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3 rail transportation

subject areas
12 planning
21 facilities design

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1023

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Engineering Options for the Northeast Corridor

LOUIS T. KLAUDER, JR.

ABSTRACT

Two topics are presented in this paper. First, results of train performance integrations that show how train running times on the Northeast Corridor route would be affected by progressive increases in maximum speed up to 210 mph and by progressive increases in curve speed limits up to the corresponding tangent track maximums are presented. The results show that, for the curves that exist on the Northeast Corridor, full benefit can be derived from the high maximum speeds offered by available technology only if curve speed limits are raised along with maximum speed. Second, two approaches for achieving increased speeds on existing curves are considered. One is the well-known approach of operating tilting body vehicles on track with moderately increased superelevation. The other approach is to operate nontilting vehicles on track with dramatically increased rail superelevation. It is noted in this paper that this latter approach not only offers substantial advantages but also presents substantial problems. Methods of overcoming these problems are suggested.

The purpose of this paper is to review some basic physical constraints on and possibilities for a high-speed passenger service between New York City and Washington, D.C. (NY-W).

There are three reasons for rexamining NY-W service:

1. Of all the linearly arranged city groups in the United States, NY-W offers the best market for high-speed rail service.
2. The tide of governmental initiatives that has resulted in an improved level of service in the Northeast Corridor has almost ended; however, these initiatives were based on a sense of what was practical about 15 years ago.
3. Japan and France have demonstrated that levels of service substantially higher than those being achieved in the Northeast Corridor are technically feasible and economically attractive.

Thus, the following question is investigated: What kind of train operation will be most suitable for achieving high average speed on the NY-W corridor?

PREMISES OF THIS PAPER

This paper is based on three premises:

1. That there is a market for service with substantially shorter trip times than those now being offered.
2. That tracks for a new high-speed service would be used for that service only. This assumption is based on considerations of safety and of service optimization, including choice of curve superelevations without regard to the requirements of conventional trains. (Detailed arrangements for providing dedicated high-speed tracks while still supporting existing freight and passenger services are not considered here but will have to be worked out if an economic feasibility study is undertaken.)
3. That it would not be economically feasible to eliminate most of the curves that exist in the NY-W right-of-way. Thus, it is assumed here that initial planning should accept the curves that exist in the present right-of-way.

BASIC VARIABLES AFFECTING TRIP TIME

If high-speed service on dedicated tracks is considered, there is no reason for train speed to be routinely restricted by any factor other than safe braking before curves and station stops. Assuming that this is the case, trip time is determined by only three factors: (a) maximum speed, (b) how speed restrictions on curves are determined, and (c) the accelerating and braking power with which the vehicles are endowed. Each of these factors is examined in more detail in the following paragraphs.

The effect of maximum speed on trip time is fairly obvious. Examples of maximum speeds that have been achieved are given in Table 1. Sample maximum speeds that will be considered in this paper are 120, 150, 180, and 210 mph.

TABLE 1 Examples of Maximum Speeds Achieved on Several Rail Lines

Service	Maximum Speed (mph)	Year
Tokaido	130	1964
Congressional (6 stops)[a]	100	1967
Metroliner (6 stops)[b]	120	1969
Tohoku	150	1982
Paris-Lyon	168	1982
Test runs		
DOT test cars	150	1966
Metroliners	165	1969
Tohoku	198	1979
TGV[c]	237	1981

[a] The NY-W trip took 210 min on this train.
[b] The NY-W trip took 180 min on this train.
[c] TGV is Tres Grand Vitesse (French high-speed train).

The effect of curve speed restrictions on trip time is also fairly obvious. Although there can be some complicating considerations, speed on a given curve is determined by the superelevation of the rails and by the unbalance, which is a measure of the amount by which actual speed on a curve is allowed to exceed the equilibrium speed for the given curvature and superelevation. What determines the speed allowed on a curve is the resultant of the superelevation and unbalance. Superelevation up to 6 in. and unbalance up to 3 in. are conventional. Both figures can be increased for low center-of-gravity rolling stock, especially if passenger car bodies lean enough to reduce the unbalance felt by passengers. However, for simplicity, the resultant will be referred to as though it were due only to superelevation. The NY-W running times that are obtained with maximum permissible resultant elevations of 9, 12, 17, 22, 30, and 60 in. will be examined. (The 60-in. figure corresponds to rotation of the plane of the track by 90 degrees and means that curves impose no speed restrictions.)

The third factor that affects trip time is the power for accelerating and braking with which the vehicles are endowed. As a part of the preparation for this paper, some running times were computed to examine the effect of increasing propulsion power above levels that might be considered minimum reasonable levels. The amounts by which trip time was reduced as propulsion power was increased were slight. It was therefore decided to examine results for only one level of accelerating power for each maximum speed. The values are given in a later section.

Thus, for the route under examination, trip time is determined by only two factors: maximum speed and speeds on curves.

DETAILED ASSUMPTIONS

The computed trip times that will be presented are based on assumptions about the wayside, the vehicles, and train operation as follows.

Wayside

Three assumptions about the wayside are used for computing trip times.

1. The effect of grades is ignored.
2. Curves are assumed to be as given in the Federal Railroad Administration's report on the Northeast Corridor High Speed Rail Passenger Service Improvement Project (1).
3. Speed limits on curves are based on the stated maximum allowable resultant elevation but truncated to the next lower integral multiple of 10 mph or to the stated maximum speed, whichever is less. (Presumably there will be locations where it is not possible to realize as much superelevation as is allowed in general. For example, some reverse curves may not allow spirals as long as would be desired. Effects of limitations of this kind are not included in this paper. Analysis of spiral geometry for typical highly elevated curves and reverse curves will be reported later.)

Vehicles

The following assumptions about vehicles are used for computing trip times.

1. Train resistance is based on the traditional Davis coefficients: 1.3 lb/ton, 0.03 lb/ton/mph, and 29 lb/axle. The coefficients of the speed square terms are taken to be 0.37 lb/mph/mph for the lead car and 0.05 lb/mph/mph for trailing cars. These values give slightly more drag than values reported by the Japanese and significantly more than the values reported by the French. (For operation at high speed, there is strong incentive to reduce drag as much as possible.)
2. Values for maximum speed, acceleration at maximum speed for a 12-car train, maximum propulsion power per car at the rail (force-speed product) and vehicle weight are given in the following table.

Maximum Speed (mph)	Acceleration at Maximum Speed (mph/sec)	Force-Speed Product (lb·mph)	Car Weight (lb)
120	0.3	334,000	115,000
150	0.2	465,000	130,000
180	0.1	616,000	150,000
210	0.1	1,020,000	205,000

The values given in the table for propulsion power at the rail (force-speed product) and car weight are based on: (a) train resistance (as stated in Assumption 1 in this section) and (b) the assumption that car weight varies linearly with power at the rail (as exemplified by the Jersey Arrow I and Metroliner cars). Those two cars can be placed in the above table as follows:

	Force-Speed Product (lb·mph)	Car Weight (lb)
Jersey Arrow I	405,000	115,000
Metroliner	756,000	173,000

The stated values of power at the rail are assumed to be available from one-third of maximum speed to maximum speed. This then assumes use of alternating current drive with synchronous motors, such as recently developed by the French. Tractive effort is assumed to be constant from zero speed up through one-third of maximum speed. The car weights given are assumed to include an allowance for rotational inertia. Electrical energy consumption while accelerating is based on a propulsion system overall efficiency of 85 percent and on an auxiliary power consumption per car of 40 kW.

3. Braking effort is based on wet rail adhesion assumed to be given by the formula:

$$\text{Adhesion coefficient} = 14/(v + 109)$$

where v is in miles per hour.

4. Regenerative braking effort at any speed equals tractive effort at that speed, and net recovery amounts to 50 percent of the energy removed at the rail by the dynamic brake.

Train Operation

There are three assumptions about train operation used for computing trip times.

1. Trains consist of 12 cars, all of which are powered.
2. There is no coasting. That is, full power or constant speed is maintained until full braking effort is applied to reduce speed for a station stop or before entry into a curve.
3. Trains leave New York City and stop at Newark, Philadelphia, Wilmington, Baltimore, and Washington. The station dwell allowance at each intermediate stop is 3 min. Because actual dwell times are in the

1- to 2-min range, there are a few minutes of schedule slack.

COMPUTED TRIP TIMES

Computed times for the trip from New York City to Washington, D.C., are shown in Figures 1-3.

Figure 1 shows trip time (min) as a function of resultant elevation for each of the four sample maximum speeds. Each of the circled points gives a trip time that is 8 percent longer than the time the train would achieve if there were no speed restrictions because of curves. (The circled point on the 150-mph curve is interpolated rather than computed.) The elevations corresponding to the circled points appear to be almost optimal for the respective maximum speeds in the sense that higher elevations achieve little further reduction in trip time. Elevation of 60 in. eliminates all speed restrictions and corresponds to tangent track. It is proposed in this paper that the elevations indicated by the circled points can and should be achieved in practice.

Figure 2 shows the same set of computed trip times but uses them to show trip time as a function of maximum speed for fixed resultant elevation. If it were believed that a particular resultant elevation were practical, there might be a temptation to determine from Figure 2 the maximum speed that would be suitable for that elevation. However, various costs increase rather rapidly with maximum speed. Therefore, because Figure 2 includes no information about costs, the only conclusion that can be drawn from the figure with any confidence is that speeds faster than 150 mph will not be of value with the curves assumed if resultant elevations do not exceed 12 in.

Figure 3 shows the same data by means of curves that give superelevation as a function of maximum speed for several fixed values of trip time. (Points at which given curves intersect grid lines have been found by interpolation where the intercepts are not primary data points.) The optimal points are close to the points where the curves have a slope equal to -1. However, these points have been selected for illustration on the basis of plausible judgment rather than on the basis of a quantitative optimization.

Net energy consumption was computed along with trip time for each of the 24 cases. For maximum speeds of 120 and 150 mph, energy consumption decreased slightly with increasing resultant elevation. For maximum speeds of 180 and 210 mph, energy consumption first increased slightly and then decreased slightly as resultant elevation was increased. The effect of resultant elevation was slight for all four maximum speeds. Energy consumption values for the circled cases were computed as follows (the value for energy consumption corresponding to 150 mph was interpolated):

Maximum Speed (mph)	Energy Consumption (kWh)
120	12,170
150	16,300
180	21,122
210	29,736

It is interesting to note how incremental reductions in trip time and corresponding incremental

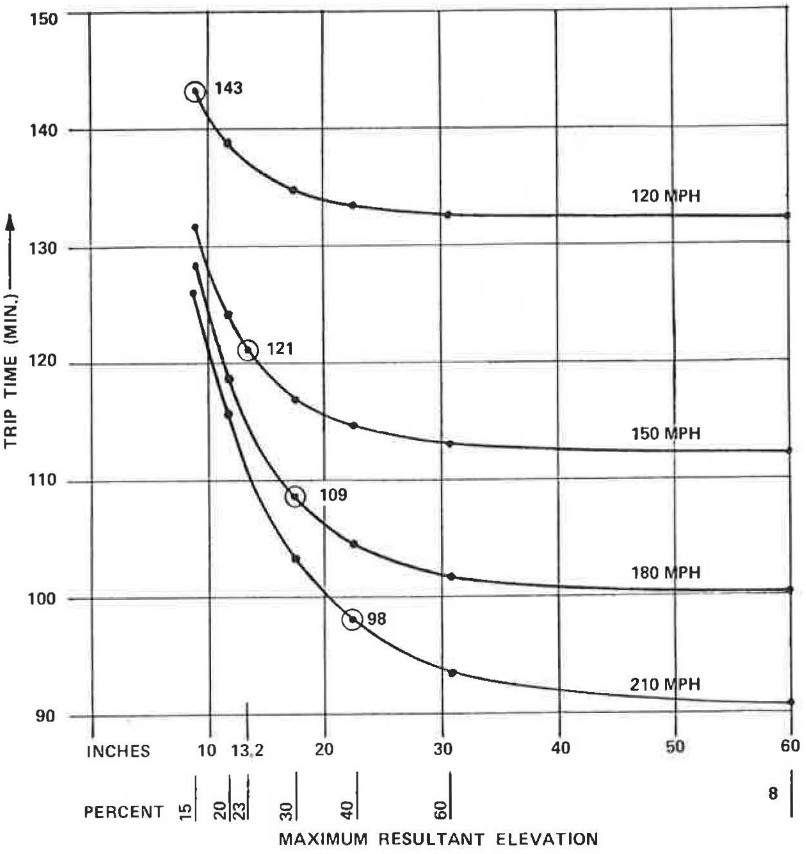

FIGURE 1 Trip time as a function of resultant elevation.

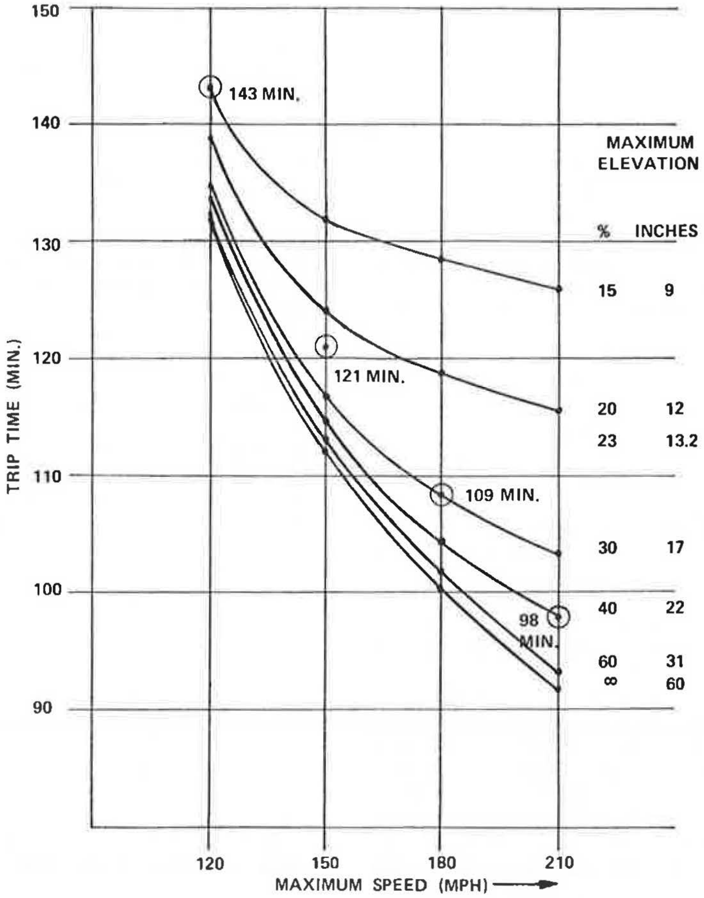

FIGURE 2 Trip time as a function of maximum speed for six values of resultant elevation.

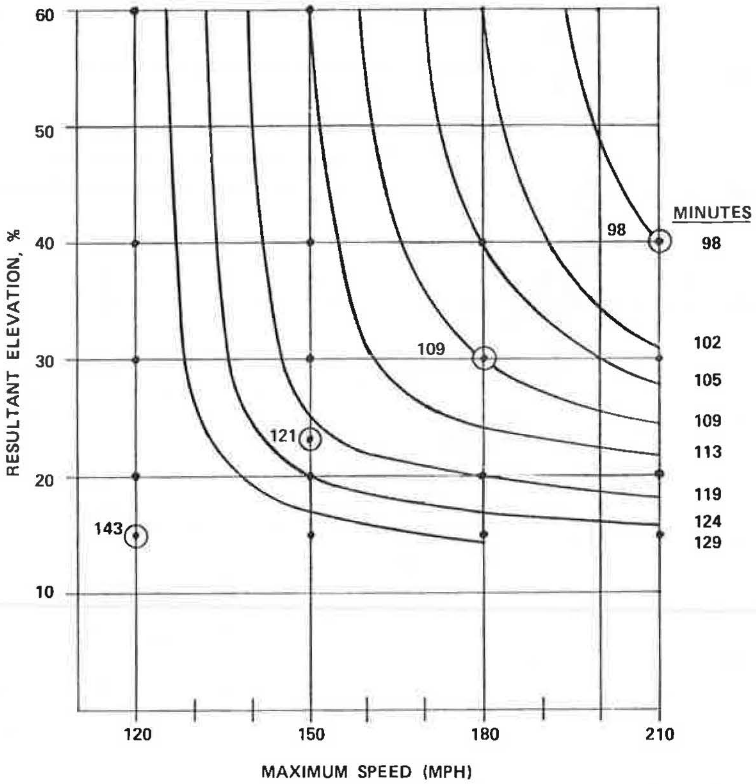

FIGURE 3 Superelevation as a function of maximum speed for fixed trip time.

increases in energy consumption compare. The relationship can be understood on an order of magnitude basis as follows. Assume that passengers who would use a premium train service are willing to spend an average of $20.00 to save 1 hour of travel time. (Passengers who now choose a Metroliner instead of a conventional train from New York to Washington spend an additional $9.00 and save about 36 min. To the extent that those passengers are paying for speed, they are valuing their travel time at $15.00 per hour. Those who prefer to pay for the Metroliner instead of an excursion fare by conventional train are valuing their travel time at $30.00 per hour. Patrons of a service providing trip times significantly shorter than those of the current Metroliner service presumably would place higher values on their time.)

Assume that a 12-car train carries an average of 600 passengers. Then trip time reduction has a value of $100.00 per minute per one-way trip. Assume that the cost per kWh of electrical energy delivered to the pantograph of a train is $0.08; then a table can be set up to compare incremental time and energy values per one-way train trip as follows:

Speed Change (mph)		Time Saved	Value of Minutes	Added	Cost of kWh
From	To	(min)	($)	kWh	($)
120	150	22	4,400	4,130	330
150	180	13	2,600	4,822	390
180	210	10	2,000	8,614	690

Energy is only one of many costs that vary with maximum speed. Some costs such as crew labor and vehicle cleaning decrease slightly with increasing speed. However, track structure, wayside power fixtures, and vehicle costs increase with maximum speed. If the cost factors assumed previously are reasonable, the increase in value of service if maximum speed is raised from 180 mph to 210 mph may or may not exceed the cost of the increase in energy usage by enough to also cover the additional capital and maintenance costs. The results would be more favorable to higher speeds if the low wind resistance values reported by the French were adopted.

A PROPOSED GOAL

On the basis of the information presented in this paper, it is argued that the U.S. passenger rail community should begin to develop a proposal for a new service between New York and Washington with parameters in the following ranges: maximum speed--180 to 210 mph; resultant elevation--17 to 22 in.; and trip time with four intermediate stops--110 to 100 min.

Design of the equipment should benefit significantly from Japanese and French experience. However, this service would introduce something new in that it would deal with curvature through engineering rather than through land acquisition that would be environmentally disruptive and economically burdensome.

Although the use of conventional steel wheels on steel-rails for support and traction is generally presupposed in this paper, the basic questions being considered here would apply equally to use of a magnetic-levitation system. That is, a magnetic-levitation system design must also deal with existing curves and with the cost of energy to overcome increasing wind resistance as speed is increased. If use of steel wheels on steel rails could not demonstrate adequate dynamic stability, durability, or adhesion, then use of magnetic levitation would have something definite to offer. However, for speeds up to 210 mph, use of steel wheels on steel rails has been found to be adequate in all three respects.

The question that remains is whether a resultant elevation in the 17 to 22 in. range is practical.

ACHIEVING RESULTANT ELEVATIONS OF 17 TO 22 INCHES

The superelevation of the track itself traditionally has been limited by the requirements that (a) a train be able to stop anywhere and (b) there should be no inconvenience when a train stops on a curve. Track superelevations have been a maximum of 6 to 7 in. partly because passengers are uncomfortable if a train stops on a curve with higher superelevation and partly to minimize the possibility of high center-of-gravity cars being overturned by strong side winds. Speeds for conventional passenger trains are usually set to limit running unbalance to 3 in. to achieve ride comfort. The discomfort that is encountered with running unbalance above 3 in. is due to the lateral suspension being held against the end of its travel and thus being unable to isolate irregularities in the alignment of the rails.

A desired resultant elevation can be achieved by using any one of a range of combinations of track superelevation and running unbalance. The unbalance is given in terms of other quantities by Equation 1:

$$U = G[\tan(R)\cos(S) - \sin(S)] \quad (1)$$

where

R = angle of resultant elevation (i.e., superelevation angle that would give zero unbalance);
S = angle of actual superelevation of the track;
G = track gauge between wheel-to-rail contact points (conventionally 60 in. for standard gauge); and
U = running unbalance (inches of track elevation on which a stationary car would experience the same lateral force as it experiences while traversing the actual curve at the design speed).

The following table gives examples of combinations of track superelevation and running unbalance all of which yield a resultant elevation of 22.3 in. [$\tan(R) = 0.4$].

Superelevation (in.)	Unbalance (in.)
11.8	11.8
14.0	9.3
16.2	6.9
18.3	4.6
20.3	2.3
22.3	0.0

So far, most efforts to achieve higher resultant elevations have been based on increasing the permissible unbalance. Danger of a vehicle overturning is controlled by reducing the height of the center of gravity of the vehicle. Discomfort that passengers would otherwise feel is reduced by making the vehicles lean into the curves and by preventing the main lateral suspension from going to the end of its travel. This general approach is usually referred to as body tilting. It is exemplified by the Spanish Talgo train, the United Aircraft Turbo Train, the British Advanced Passenger Train, and the Canadian LRC (Light Rapid Comfortable) train.

Referring to the previous table, a tilt body solution could use 14 in. of track superelevation and 9.3 in. of running unbalance. Body tilting could neutralize up to 8 in. of unbalance so that passengers would routinely experience 1.5 in. of unbalance; passengers could, however, experience up to 6 in. if a train were to stop on a fully elevated curve for some reason. The center-of-gravity height would need to be kept down to about 47 in. with (a) standard gauge, (b) the traditional "middle-third" rule for overturning safety relative to the high sides of curves, and (c) center-of-gravity lateral movement limited to 2 in. This 47-in.-height is only a few inches lower than that of the original Metroliners. For this solution, the resulting gravitational force vector for a car stopped on a curve with 14-in. elevation would be about 16.5 in. to the inside of the low rail rather than the traditional minimum value of 20 in. However, dynamic forces at very low speed would be negligible, and danger from crosswinds could easily be countered by means of wind screens along the outsides of fully elevated curves.

Although the tilt body approach is well-known and generally accepted, there is a second approach that deserves consideration. This approach provides about 19 in. of actual superelevation, operates trains at about 3 in. of unbalance, and arranges signaling and dispatching so that a train would never enter a highly elevated curve unless it were cleared to go through the curve at design speed. There might still be rare cases in which a train was forced to slow down or stop unexpectedly. Protection against vehicle overturning in such cases would be provided by a combination of low center of gravity, wider track gauge, and wind screens on the outsides of curves.

Stewardesses would direct any standing passengers to be seated during the period of slowdown. Passengers would be disconcerted but would not be harmed. The possibility of rare occurrences of this kind is accepted by airline passengers, who learn at the beginning of every flight about the location of life jackets, emergency exits, emergency slides, and emergency oxygen, and who are accustomed to pressure changes that cause ear pain for some people. In the rare cases in which planes encounter strong clear air turbulence, passengers are shaken and occasionally injured. However, the basic intent for the proposed high-speed rail service is to conduct maintenance and operation so that slowdowns in highly elevated curves are rare.

The benefits of this second approach to achieving resultant elevation in the 22-in. range are that the vehicles would be simpler and lighter and that wheel and rail wear would be reduced.

The author's preference is the second approach. However, the main purpose of this paper is to encourage the beginning of a program to define, develop, and test a new dedicated track system that can follow the existing alignment between New York and Washington and provide for operation at a maximum speed between 180 and 210 mph.

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High-Speed Passenger Train Safety

MYLES B. MITCHELL

ABSTRACT

The current resurgence of high-speed rail passenger studies in the United States centers around foreign equipment with operating speeds significantly higher than those permitted by the Code of Federal Regulations. It is necessary to develop criteria and standards for a new generation of rail-passenger and magnetically levitated equipment and systems. Their quality must be consistent with the quality of the existing U.S. safety record. A series of technical workshops should be held to establish such new criteria and standards. The issues to be addressed would include structures and standards for tracks and guideways, grade-crossing protection, crashworthiness of vehicles, electrification, rolling stock, and improved emergency procedures. Because a wide variation in both design philosophy and construction criteria exists between U.S. and foreign equipment, it is essential to arrive at a technical consensus before establishing requirements and regulations.

The current resurgence of high-speed rail passenger studies in the United States centers around foreign equipment with operating speeds significantly higher than those permitted by the Code of Federal Regulations. The U.S. requirements are stringent compared with those of Europe and Japan, and any program involving departure from these standards must be approached with caution to assure that the past safety record of the United States is not compromised.

A recent Federal Railroad Administration (FRA) report to Congress on railroad passenger equipment stated, "Rail passenger service in the United States has compiled a superior safety record that can be attributed to the rail industry's operational and safety practice as well as the effect of FRA's extensive safety regulations" (1). The report further states, "FRA will convene a Special Safety Inquiry to assess the potential impact of technological changes in passenger equipment components, such as wheels, axles, bearings, and brakes."

Although some readers of the report interpret the scope of further assessment to be limited to equipment now operating over the property of the 20 rail passenger operators listed, others take a broader perspective that includes the safety assessment of new high-speed rail passenger equipment currently being evaluated for operation in the United States. It is necessary to develop criteria and standards for the new generation of rail passenger and magnetically levitated equipment and systems. Their quality must be consistent with the quality of the existing safety record in the United States.

To meet this objective it is suggested in the FRA report that a Special Safety Inquiry be set up to investigate the potential safety impact of various changes in the passenger industry that are not readily discernible. It is further suggested that a series of technical workshop sessions be held to establish criteria, requirements, and regulations for the new equipment. A wide variation in both the design philosophy and construction criteria exists between U.S. and foreign equipment. It is essential to arrive at a technical consensus before establishing meaningful and realistic practices and regulations.

Issues that should be addressed include structures and standards for tracks and guideways, grade-crossing protection, electrification, rolling stock, crashworthiness of vehicles, and improved emergency procedures. Criteria, standards, and regulations can be established for many of these elements on the basis of current engineering knowledge, supported by demonstrated operating practices and historical data. Other issues will have to be subjected to engineering analysis and verification testing.

TRACK STRUCTURES AND STANDARDS

Track structures and associated standards take on new dimensions with high-speed train operation. For cases in which current standards specify tolerances for gauge, alignment, surface of track, and elevation of the outer rail in curved track for today's equipment, a new set of criteria must be introduced for the higher speed equipment, criteria that impose tighter tolerances and control over the higher forces. A new safe limit of curve negotiation must also be established.

Class 6 track, the highest class track currently covered by standards, has the maximum allowable operating speed for passenger trains (110 mph); tolerance deviation limits are specified that require sophisticated instrumentation to monitor compliance. If the tolerance requirements were made more restrictive because of an increase in train speed from the present 110 mph to 185 mph, as proposed in Florida, by what means would FRA monitor safety compliance? Or, conversely, would it be advisable or necessary to further restrict the tolerance deviation for gauge and alignment beyond present requirements?

It is well-known that track forces vary as a function of gauge, the degree of wheel wear, and how the wheel flange contacts the rail. Perturbations, caused either by track gauge and alignment or by vehicle truck instability, will greatly increase track structure forces. Any one of these elements could compound the safety issue.

It is interesting to note that the Japanese mitigate track-imposed deviations by using direct-fixation slab-track design. Although it is possible to build and maintain close alignment tolerances by this technique of solidly bolting the rail to the concrete slab, the cost is high and the resulting noise and ground-borne vibration level is beyond an acceptable limit.

For high-speed applications the French use an alternate approach: more conventional duo-block concrete crosstie and spring-clip fasteners. Their ties are spaced 24 in. apart, compared with the U.S. practice of 21-in. spacing. This is accomplished, in part, through the use of light-weight trains that have wheel-rail forces considerably lower than equipment operating in the Northeast Corridor. They do, however, maintain track gauge and alignment tolerances about four times more stringent than U.S. practice.

It is also interesting to note that U.S. track standards are written for wood ties and spikes rather than for concrete crossties and clips such as those employed in the Northeast Corridor for the past 5 years.

To preclude derailment, the FRA imposes conservative safety measures on rail passenger trains negotiating curves. The "curved-track speed rule" limits train speeds to less than 3 in. of unbalance while negotiating a curve. Balanced speed is defined as that speed at which the resultant of the lateral centrifugal force and the gravitational force acting on the car body is normal to the floor of the car. Unbalance, or cant deficiency, is the additional superelevation (or cant) required to achieve lateral balance in a curve. Typical foreign practice is to operate at 6 to 9 in. of cant deficiency, significantly beyond current limits of acceptability in the United States.

Vehicle overturning can occur when the overturning moments of the acceleration and wind forces equal the restoring moment of the vehicle weight. The margin of safety in the United States is the Association of American Railroads (AAR) "one-third" rule, which states that the vector sum of the vertical gravitational and lateral centrifugal forces must remain within the center one-third of the track. The FRA Office of Safety has interpreted this rule conservatively to mean that the vector shall stay within 8.25 in. of the track centerline on standard gauge. Should this policy be reconsidered? If so, what should be the new criteria?

Derailment due to wheel climb results from a high value of lateral-to-vertical (L/V) wheel loading. The value of L/V that can cause derailment is a function of many factors: wheel angle of attack, flange angle, adhesion coefficient, unsprung mass of the wheel set, absolute vertical wheel load, and the lateral and torsional stiffness of the rail. Current

U.S. practice is to limit the L/V value to 1.0 for time durations greater than 50 milliseconds, compared with the European practice of using an L/V as high as 1.6 with standard four-wheel trucks. Again, this criteria should be subjected to an updated engineering review from which more definitive requirements would result.

Derailment due to rail spread, rail rollover, or lateral track panel shift must be thoroughly assessed when considering curve negotiations at high speeds. Although the FRA track safety standards for Class 6 track require good quality track structures, few data exist for train operations faster than the 110-mph limit or for high speeds in curves. In its determination to grant a waiver to the Northeast Corridor Improvement Project on sections of the Northeast Corridor track structure, FRA conducted a limited number of vehicle and track forces measurements at high cant deficiencies. However, a complete review of these data and, in all probability, a new series of testing should be conducted. In addition, the existing formula for the maximum allowable operating speed for each curve may be judged too restrictive and additional engineering analyses may be deemed appropriate.

GRADE-CROSSING PROTECTION

Grade-crossing protection must be reexamined in the context of adequacy and reliability in high-speed corridor applications. Ideally the safest solution would be a totally dedicated and grade-separated infrastructure. In reality, this may not be financially practical or even possible for obtaining the right-of-way access into and out of large cities, which leaves the technical challenge of how best to minimize the hazard.

The Shinkansen lines in Japan were built from the onset without grade crossings. This is more easily accomplished during construction of a totally new system than when an existing line is being upgraded. Conversely, in Europe almost all of the high-speed trains operate at reduced speed over segments of track that have grade crossings. It should be noted, however, that Europeans have a more positive attitude toward railroads than people in this country, and grade crossing rules are not violated. Nevertheless, they still take extreme measures to obviate a grade-crossing incident. The newer concepts include fully automated barrier protection with television monitoring.

Significant strides have been taken toward reducing the number of grade-crossing incidents in the United States; the results have been positive. However, the increased speed of new guided ground transportation systems will impose problems on presently in-place warning and protection systems. This situation may be compounded by electromagnetic interference (EMI) with the signaling system.

Some of the more prevalent grade-crossing problems encountered in the United States are situations in which motorists run around gates that have been closed for several minutes--ahead of an oncoming train. Because grade-crossing protection devices have a history of malfunctions, the motorist often believes that he is being unduly detained when he is unable to actually see an oncoming train. This attitude accounted for a high percentage of the grade-crossing accidents in Florida last year, which points to the need for advanced technology and improved motorist safety awareness.

ELECTRIFICATION

All of the new high-speed rail and magnetic levitation (maglev) systems under investigation will rely on electrification as the primary propulsion energy source. The rail systems will use an overhead catenary, and the maglev systems will have the electric power supply buried in the guideway structure. In either case, the high-voltage system will increase the risk of injury to employees and trespassers. Several incidents have occurred in the electrified segment of the Northeast Corridor where trespassing minors have come in contact with the overhead electrical system by climbing on the roof of the train.

Significant problems arise from the relationship between mechanical and electrical clearances and overhead structures, particularly between bridges and pedestrian walkways. Not only is there a security issue of maintaining a specified physical separation (yet to be identified) but there is also an electrical arc clearance problem--something that should be addressed and covered by safety standards. EMI due to the proximity of the high-voltage power source can also produce a shock hazard to both the railroad employee and the passerby.

Two complex technical concerns with electrified systems are (a) assuring compatibility with the signaling system, and (b) reducing the effects of EMI that can seriously disturb signal and communication systems. The principal sources of EMI are:

1. Magnetic induction, which introduces noise in the signal and communication circuits that have lines parallel to the railroad;
2. Electrostatic induction, which causes high voltage to appear on electrical components near the wayside, causing potential hazards and equipment damage;
3. Ground induction, which causes current flows in conductors in ground contact near the railroad, causing corrosion and potential hazards; and
4. Radio frequency interference caused by pantograph bounce (arcing) and propulsion and power supply operation.

ROLLING STOCK

The safety issues related to rolling stock in high-speed rail and magnetically levitated vehicle operation are significantly more complex than those associated with present-day passenger train operating speeds. The situation is further compounded by foreign manufacturers who are building all new high-speed passenger trains according to criteria that are totally different from the rules, standards, and regulations of the AAR, Amtrak, and the FRA. It would be unwise to ignore the requirements developed in the United States over years of test and operational experience. However, it would also be inappropriate to assume that our foreign counterparts are not equally diligent in their technical assessments and determinations of safety criteria.

CRASHWORTHINESS

One of the more critically needed workshops would address the strength requirements related to crashworthiness of rail-car and magnetically levitated vehicles. Foreign practices permit structural strength requirements for car bodies that are much lower than those specified for service in the United States. The current AAR, National Railroad Passenger Corporation (Amtrak), and FRA recommendations include the following basic provisions, which must be met without permanent deformation of the structure except where ultimate shear values are specified.

1. The car body must resist a compressive load of 800,000 lb applied at the draft gear attachment.

2. An anticlimbing arrangement that can withstand vertical loads of 100,000 lb is required so that coupled units under full compression will not override each other.

3. The coupler carrier must be able to withstand a downward load of 100,000 lb to assist in anticlimbing protection.

4. Two collision posts will be provided at each end, each of which must have an ultimate shear strength of at least 300,000 lb at the point of attachment to the underframe. If a reinforcement is used to provide this value, it must be maintained to a point 18 in. above the point of connection with tapering strength to at least 30 in. above the point of attachment.

5. Trucks must be retained to the car body by an arrangement having an ultimate shear strength of 250,000 lb in a horizontal plane.

The precise numerical value of structural strength requirements should also be included in the in-depth study. The structural requirements cited previously were specified for multiple unit (MU) locomotives built after April 1, 1956, that are operated in trains having a total empty weight of 600,000 lb or more. The only passenger equipment operated in the United States that falls within this requirement is the original Metroliners. The newer Amtrak equipment, also referred to as Metroliners, consists of trailer coaches hauled by a single AEM-7 electric locomotive.

If the Japanese Bullet Train were contemplated for operation in the United States it would not meet the 800,000-lb buff strength requirement. The cars operate as married pairs but have a measured buff strength of only 220,000 lb. On the other hand, the French high-speed train Tres Grand Vitesse (TGV), also powered by two electric locomotives and married as an electrical pair (MU), has coach car-body buff strengths of only 337,000 lb. It could, however, possibly qualify because the locomotives are not physically mated to each other, which leads to the arguable position that the train is not of the MU type. In reality, a train that has several trailer coaches sandwiched between two heavier locomotives could be potentially more detrimental to passenger safety in collision situations and should be required to have car-end compressive strength requirements as high as, if not higher than, MU cars.

The important criteria listed previously are further complicated by the knowledge that using a high numerical value for ultimate compressive strength requirement could potentially be less effective than using crushable structures to absorb the energy of impact and lessen the impact of the "second collision."

Although the structural strength requirements of the car body were established because the United States permits mixed freight and passenger traffic, their application to passenger equipment that operates on a dedicated right-of-way is necessary when a derailment or rear-end collision occurs. In situations such as these, it is immaterial whether the equipment is operating on dedicated or mixed-traffic track structures.

It should also be considered that equipment originally designed for dedicated or noninterchange service may result in additional applications outside of its intended scope. In Japan, the Shinkansen lines are truly dedicated lines, mainly because they have a wider track gauge than the rest of the rail network throughout the country. However, it is also believed that the TGV operates on a totally dedicated and grade-separated track structure between Paris and Lyon. In reality, in the densely populated metropolitan areas of both cities and over the remaining route structure to the west the TGV operates over the same track structure used by the remaining lower speed conventional trains within the French National Railways (SNCF) rail network. British Rail (BR) of England has no dedicated track structure. It is all mixed service, including the trackage over which the Inter-City 125 and Advanced Passenger Train (APT) operate.

Couplers

The method for coupling passenger cars varies considerably among foreign countries. England and most European countries use a hook and chain in conjunction with spring buffers at the corners of adjoining cars to maintain tension in the chain. The International Union of Railways (UIC) recently adopted a standard-type coupler that is not significantly different from the three standard types used in the United States. However, until the transition to this coupler is complete it will still be necessary to address the issue as it relates to high-speed passenger trains such as the APT, TGV, and Bullet Train. [The Canadian LRC (Light Rapid Comfortable) conforms to U.S. standards and therefore is not an issue.]

The key issue regarding couplers should be their capability to help keep the passenger coaches upright if the train goes aground. The advantage of the U.S. tightlock coupler is that it almost assures that derailed cars will not overturn or telescope when a car with an H-type coupler is coupled to another car with an H-type, F-type, or controlled-slack coupler.

Although the spring-loaded buffers provide tensioning to the hook-and-chain-type coupler, nothing in the coupling system counteracts the rotational tendency of the coaches during derailment. This is potentially a serious situation. A high percentage of passenger train derailments is caused by flaws in track or train equipment; safety would be greatly enhanced if the passenger coaches were to remain upright.

Both the APT and TGV are articulated trains that have two adjacent coaches sharing a common truck. For these articulated trains the coupling of the cars is through the truck-to-car-body attachment. Although the shear strength of the attachment for the APT is not known, design changes are under way that will alter the configuration and mounting arrangement. The TGV has a truck-to-car-body shear strength of 221,000 lb, a value considerably lower than the U.S. requirement.

The Bullet Train is equipped with transit-car-type automatic hook couplers that are of inadequate design strength to satisfy the anticlimbing restraint requirements. The coupler strengths are 353,000 lb tensile and 661,000 lb compressive.

Wheels and Axles

Special attention must be paid to the safety aspects of wheels and axles used on high-speed passenger trains. The dynamic stresses in the wheel will increase considerably because of the higher rotational speed of the wheel, which will cause extremely high centripetal forces at the rim. The mean vertical dynamic loading will also increase, but fortunately this is a linear characteristic rather than the quadratic variance of centrifugally related stresses.

The unsprung mass of some high-speed trucks is increased because of the increased weight of the twin-disc brake system partially suspended from the axle. This phenomenon leads to higher internal stresses, which cause fatigue cracks in the wheel set that will have to be monitored more frequently.

The metallurgical composition of some wheels manufactured by foreign companies is also different from the basic requirement imposed in the United States. U.S. practice dictates the ingot be poured as a homogeneous bonded metallurgic structure, whereas the European practice is to use a banded (marbleized) bonding structure. It is claimed that thermal cracks caused by heating of the wheel will not propagate across a band line; thus use of a banded bonding structure will provide a safer wheel. This contention is not supported in the United States, and the use of wheels fabricated by this technique is not currently allowed in revenue service.

The United States has experienced a rash of recent failures associated with hollow axles. It has not been validated conclusively whether the problem is with the hollow axle or with the interface design of the hollow axle and wheel. The short-term recommendation of the FRA-industry task force is to continue to monitor closely the temperature in the axle bore, restrict the speed of the M-2 fleet to 55 mph, and continue the solid axle retrofit of the M-2 fleet. Longer range recommendations include developing an FRA safety inspector training program on bearings and axles, urging operators to adopt more uniform bearing assembly maintenance and inspection procedures, and urging industry to develop automated wayside or on-board detection devices for overheated inboard bearings.

Although no plans are currently being promoted to use the English APT in U.S. revenue service, it should be pointed out that its basic design has a hydrokinetic brake that is mounted inside the hollow axles of the unpowered coaches. Leakage problems in the brake system have caused the designers to abandon the tubular axle concept. In any case, it is important that the safety aspects of hollow axles be reviewed and some level of acceptable standards be established.

EMERGENCY SYSTEMS AND PROCEDURES

Another category that must receive considerable attention is passenger-car emergency safety equipment, interior appointments, egress, glazing material, material flammability, emergency lighting and communication, and so forth. Although the United States has identified several areas in which improvement is needed and has initiated changes that led to increased passenger safety, the introduction of foreign equipment into the U.S. system creates a need for explicit guidelines for all safety-related appliances and emergency conditions.

The broad spectrum of emergency procedures should be handled by a special task force. Their function would be to start with simulated emergency situations and work the problem back to a definition of equipment requirements for safe and efficient passenger egress (similar to the training program Amtrak has for its train crews on existing equipment). This would include, but not be limited to, type of emergency tools, their location, and utility; the need for and operation of emergency lighting and communications; and location and operation of emergency exits. The analyses of emergency door and window operation must consider the following: unintended or premature operation, how their operation is controlled, the need for roof-mounted escape hatches and all of the ramifications that go with its hazards, and how strong to make the window glazing. It is important for the task force to include a comprehensive review of past accidents and resultant recommendations in their work.

The passenger-car glazing material is one safety feature that requires close scrutiny. Window breakage, either from accidents or vandalism, can and does cause serious injury to the passenger and train crew. The severity of the problem will increase considerably with an increase in the speed of passenger trains. The FRA regulations requiring passenger cars built after June 30, 1980, to have improved glazing materials in all windows is more stringent than those imposed on some trains made by foreign manufacturers. Conversely, some foreign countries have safety standards similar to those of the United States but with different testing criteria, which makes it difficult to compare test results. It is suggested that an engineering analysis be conducted and a uniform safety test procedure be adopted.

The interior design and appointments of the passenger coach are important in ensuring safety of the passenger. A rugged car body is essential in case of an accident; and equal attention should be devoted to the design and securement of seats, luggage, food service galleys, and any other item that could become a projectile if it came loose from its mount. Consideration should also be given to sharp corners, protruding objects, loose floor mats, table edges, and so forth.

Car body interior material toxicity and flammability has recently received much attention from Amtrak and FRA. Further research and development are needed to establish safety criteria leading to specifications. The Federal Aviation Administration's knowledge of and test experience on the flammability of materials used in aircraft interiors should be considered.

MAGNETICALLY LEVITATED VEHICLES

Magnetic levitation (maglev) is a proven technology that has matured beyond the laboratory research phase. Proposals have now been made to implement maglev vehicle systems for revenue service in several states. The proposals stress the enhanced safety of the concept due to (a) its inherent advantage of having no moving parts in the basic propulsion and levitation systems and (b) the vehicle's captivity within the guideway structure. Although this is technically correct, some aspects of the conceptual design may need additional safeguards. To date only the experimental vehicle builders and their respective governments have examined the safety features of the overall system.

A great opportunity exists to establish meaningful design criteria for magnetically levitated systems before their implementation for revenue service in the United States. A joint government-industry task force should be assembled immediately to address key issues and implement findings in a timely and cost-effective manner.

A German Example

The German attraction concept entraps the vehicle to the guideway by wrapping it around the slab portion of the guideway; this provides a constant 1/2-in. air gap clearance when the magnets are energized. Fixed clearance is maintained at all speeds by a feedback control loop. If the control loop fails, the attractive force of the magnets will drive the air gap toward zero clearance. Likewise, if some component of the vehicle located between the vehicle and guideway becomes loose, it could become wedged if it has a thickness greater than 1/2 in. This could potentially cause severe damage to either the vehicle or guideway, or both, or worse yet, cause the vehicle to come to a sudden stop from a very high speed.

A Japanese Example

The Japanese approach uses the repulsion magnetic concept, which causes the air gap to increase with increased vehicle speed, reaching a 4-in. clearance at 300 mph. The vehicle is entrapped in a U-shaped guideway and supposedly cannot escape. A loss of power would cause the vehicle to drop down onto wheel sets at very high speeds.

CONCLUSION

Both the German and the Japanese concepts have advantageous technical and safety features. Only after close scrutiny can determinations be made that could lead to design modifications or additional safety provisions. Additional issues that must be addressed are the following: high-speed switching; egress from an elevated guideway during emergency conditions; use of cryogenics on the vehicles; effect of magnetic field on the human body; acceleration and deceleration rates; and all of the other typical safety issues such as vehicle structural integrity, braking, train control and communication, electromagnetic interference, and electrical hazards.

REFERENCE

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Publication of this paper sponsored by Committee on Intercity Passenger Guided Transportation.

Electrification of the Tumbler Ridge Branch Line in British Columbia, Canada

PER ERIK OLSON

ABSTRACT

The North-East Coal Development and Transportation Project in British Columbia, Canada, is a major undertaking that is costing about $2.5 billion (1983 Canadian dollars). The exploration incorporates development of large coal and mineral resources in a completely unpopulated area, founding of a new townsite, and construction of a railway branch line with long tunnels through the Rocky Mountains to haul coal almost 1000 km to a newly constructed unloading facility on the Pacific Ocean at Prince Rupert. The electrification of the Tumbler Ridge Branch Line (TRBL) and its technological spinoffs are discussed in this paper. The transportation and energy-technical background is reviewed along with the considerations leading to use of a 50 kV overhead electrification system and thyristor controlled locomotives. The technical-economic benefits and the future outlook are discussed. British Columbia Railway Company is the first railroad to electrify a heavy-haul route in North America in the past 50 years. It has used and advanced the most modern technology available in the world. The TRBL project was completed in less than 3 years, ahead of schedule and below budget.

The 50-kV, 60-Hz electrification of the 130-km main line railroad is the main topic discussed in this paper. However, the $500 million (1983 Canadian dollars) construction cost of the electrified Tumbler Ridge Branch Line (TRBL) is just a part of a $2.5 billion project for coal production that also includes upgrading 800 km of British Columbia Railway Company (BCRC) and Canadian National Railways' (CNR) connecting trackage, building a new townsite for 6,000 future inhabitants, and constructing a modern port and coal loading facilities on the North Pacific Ocean coast of British Columbia at Prince Rupert. Thus, exploration of coal resources in northeastern British Columbia is a major undertaking.

The map in Figure 1 shows the general location of this immense transportation project. It is essential to note that before the North-East Coal Development and Transportation Project was started, the entire area from Dawson Creek in the northern sector to the Fraser River in the southern sector was completely wilderness, devoid of rural roads, power transmission lines, and communication facilities. It is

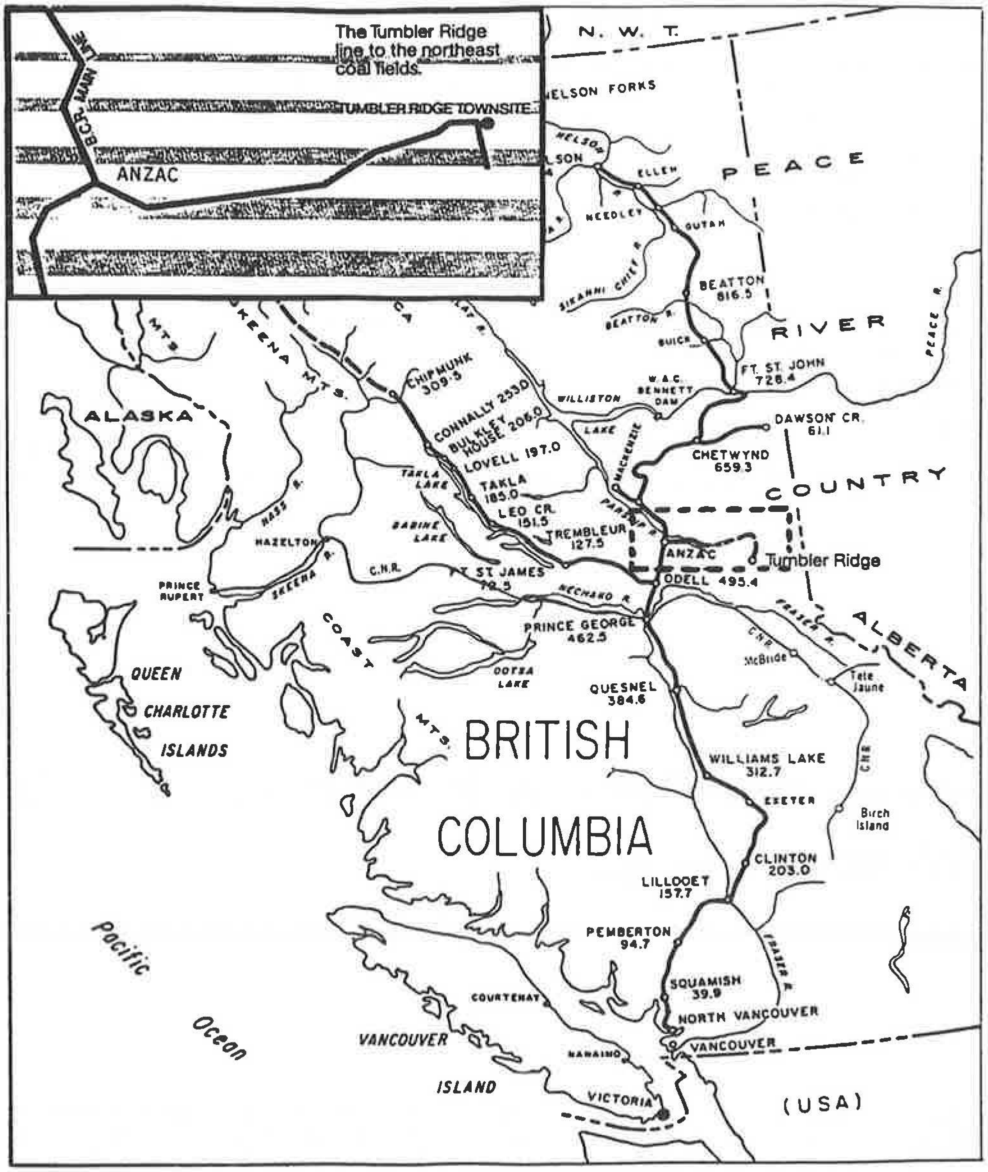


FIGURE 1 Map of British Columbia showing location of electrification project.

therefore a significant achievement to have completed the project within 3 years after the decision in early 1981 to begin; the first coal train delivery to Prince Rupert was in November 1983.

SOCIOECONOMIC BENEFIT

This enormous transportation project carried out by the government of British Columbia has resulted in major socioeconomic benefit to the area. Although the main objective was to transport coal from the mines to the port at Prince Rupert, the results have been (a) installation of a cost-effective electrified railroad, (b) mineralogical development of a vast wilderness, (c) creation of a modern city, and (d) construction of a high technology port facility on the North American Pacific coast.

As an integral part of the North-East Coal Development and Transportation Project, TRBL significantly contributes to the overall socioeconomic benefits of the transportation project. It is not only a fast, efficient, and reliable transportation link for enhancing development of mineral resources east of the Rocky Mountains, but it also uses renewable energy resources for its power. Further, this electric railway incorporates the capability for diversified freight handling as well as potential for passenger operation in the future.

TRANSPORTATION CONSIDERATIONS

Contracts for development of the north-east coal block call for mining 8 to 10 million tons of metallurgical coal annually and transporting it to the seaport of Prince Rupert on the Pacific Ocean, 1000 km from the mines. The map in Figure 1 shows the area where BCRC connects to CNR in Prince George. The new railway line stretches from Anzac to the mining area in Tumbler Ridge (see Figure 2). The new 130-km branch line passes over the continental divide near the center of the 9.1-km Table Tunnel. The length of Wolverine Tunnel is 6.4 km. The maximum gradient for a loaded train (westward) is 1.2 percent; the maximum gradient for an empty train (eastward) is 1.5 percent (see Figure 3).

To meet contract requirements, an average of

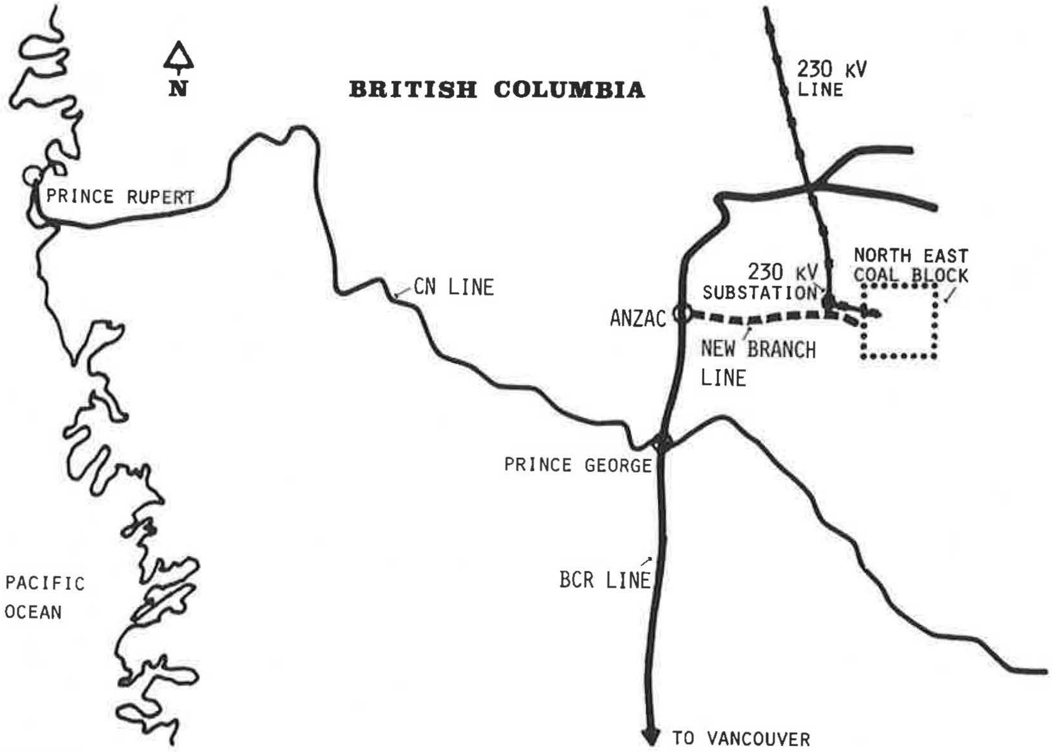


FIGURE 2 Map of northern British Columbia showing BCR and CNR lines along with the new railway line from Anzac to Tumbler Ridge.

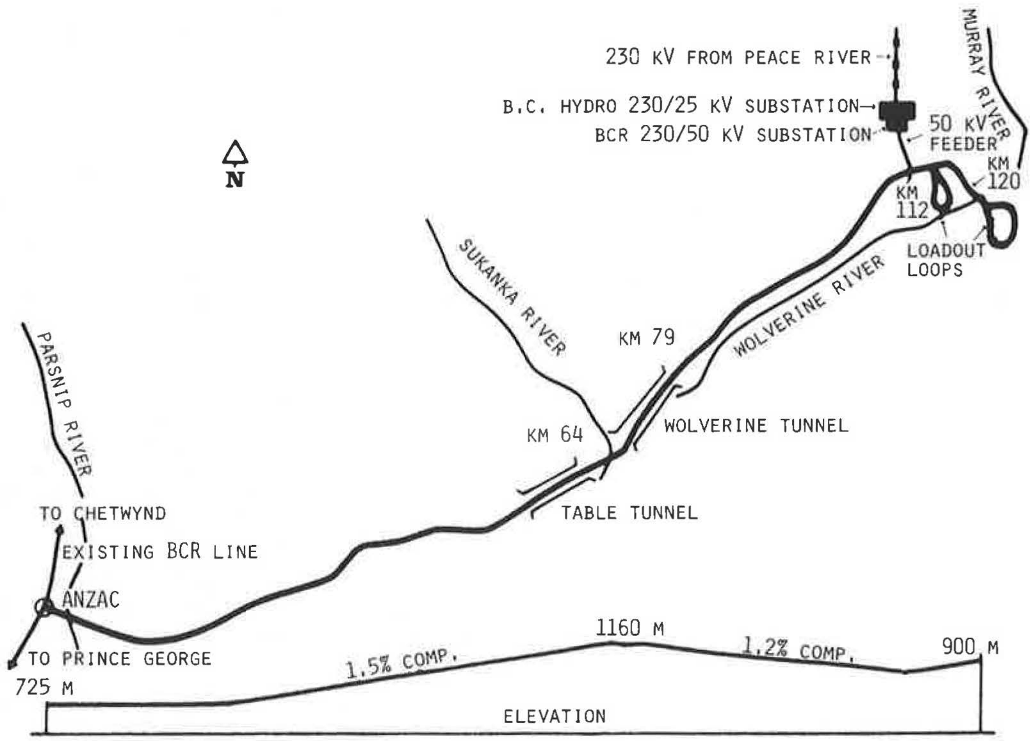


FIGURE 3 Location map and profile of Tumbler Ridge Branch Line.

33,000 tons of coal per day must be delivered. Three unit trains, each consisting of 98 cars with a loaded weight of 13,000 tons, are required. At least five six-axle, 3,000-hp diesel-electric locomotives (SD40) are required to power this train in nonelectrified territory. Each of these diesel locomotives has a total weight of approximately 200 tons. The new electric locomotives now in operation each have approximately 6,000 hp available and weigh less than 180 tons. These technical advantages of the electric locomotives over the diesels were important considerations in the decision to electrify TRBL.

However, the primary concern was the need to supply sufficient fresh air for combustion and cooling while diesel locomotives move heavy trains through long tunnels. A single diesel locomotive can develop almost full power on a heavy grade in tunnel operation. In a multiple-unit train with many diesels the temperature around the second unit and following units increases, oxygen becomes more rare, and combustion is impeded. The resulting output is thus reduced; this can cause the train to stall, which results in numerous operational complications. The health risk for the crew operating trains in tunnels was another consideration.

Therefore, the use of five or six 3,000-hp diesel-electric units in the long summit Table Tunnel would require heavy investment in ventilation equipment, electromechanical control apparatus, and power supply. The cost to operate continuously all of the ancillary support equipment in a remote area, which has limited wintertime access, was also considered. The estimated $12 million cost for this equipment was another of the major factors that influenced the decision to electrify TRBL.

PLANNING AND STUDIES

It is interesting to note that in 1909 an electrified railway summit tunnel was constructed through the Cascade Mountains in Washington State by Great Northern Railway. This electric railway in the Rocky Mountains was abandoned in 1956. In 1969 BCRC conducted a study for the electrification of 750 km of railroad that runs from North Vancouver to Prince George. At the same time CNR conducted a study for the potential electrification of its line through the Rocky Mountains.

As one step in the development procedure of British Columbia's exploration of the northeast coal block, the provincial government and BCRC conducted a feasibility study in 1976. At that time electrification was considered as an alternative and dropped. After screening various alternative routes for rail transportation, the Anzac route (Figure 2) was selected in 1977 for detailed study. In 1980 the study of the Anzac route was adopted, and the decision was made to proceed with exploration of access roads and preparation of necessary documents for construction of the first 30 km of the system. This phase of the project was budgeted at $455 million and was scheduled to be completed in 1983.

The electrification studies carried out by the Transportation Development Centre of Canada and the Railway Association of Canada early in 1981 triggered the decision to electrify TRBL. Major project milestones are listed in the following chronology of TRBL.

Date	Milestone
January 13, 1981	Access road contracts awarded
July 20, 1981	Preliminary grade work started
December 8, 1981	Major tunnel contracts awarded
March 16, 1982	First blast in Wolverine Tunnel completed
April 5, 1982	First blast in Table Tunnel completed
August 5, 1982	Decision to electrify ratified
August 20, 1982	Short tunnel contracts awarded
December 1, 1982	Mile-50 Tunnel holed-through
December 11, 1982	Mile-53 Tunnel holed-through
May 28, 1983	Wolverine Tunnel holed-through
August 21, 1983	Table Tunnel holed-through
September 9, 1983	Grade construction completed
October 21, 1983	Last rail bolted
November 1, 1983	Last spike driven
November 1, 1983	First diesel coal train operated
November 16, 1983	First electric locomotive (No. 6001) delivered
December 1, 1983	Electric locomotive trials began
March 1, 1984	Electric train operations began
June 6, 1984	Formal inauguration of TRBL took place

ELECTRIFICATION

Main line railroads in North America have been subjected to electrification feasibility studies ever since the Northeast Corridor system was electrified early in the century. BCRC is the first main line railroad to electrify since the 1930s. With the exception of the narrow gauge iron-ore railway in South Africa (Sishen-Saldana), the TRBL electrification is the first 50-kV, 60-Hz (industry-frequency) railway installation in the world.

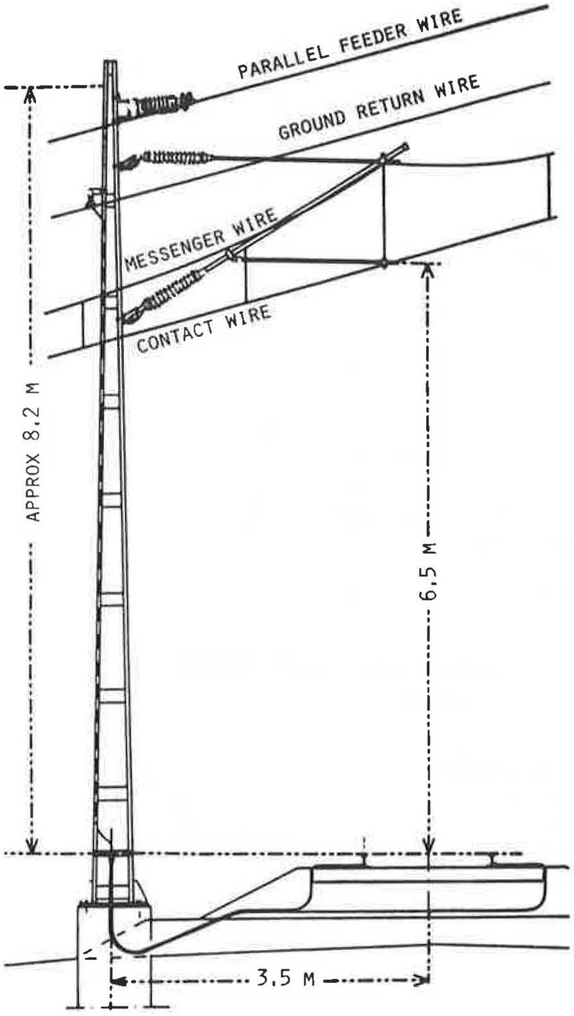
The approach of the TRBL railway was to install an electrification system based on proven concepts, incorporating the most advanced engineering design available. This was necessitated by the climate of the area that TRBL was penetrating: an area in the Rocky Mountains with heavy winter snowstorms, generally characterized by an arctic climate. The power distribution system--the overhead catenary system (OCS)--was derived from the Swedish State Railways' (SJ) design, originally installed in 1914 north of the polar circle in Scandinavian Lapland. The electric locomotive was also derived from accepted solid state technology as a result of close cooperation between North American and Swedish railroad industry suppliers. The specific electrotechnical aspects of the design of electrification have been reviewed during several sessions of the Institute of Electrical and Electronics Engineers (1-3).

One of the major reasons for choosing 50 kV as the line voltage was the option to use an existing 230-kV power line to supply all energy necessary for the 130-km, heavy-duty freight railroad. This option reduced significantly the investment cost for the power supply. The decision to use 50-kV power was supported by computer simulations of power demand, voltage drop, and capacity under various operating criteria. The rationale for feeding power to the railroad from its extreme northeastern end and adding to a series capacitor to compensate for the 30-percent catenary impedance at the center of the line has been justified in full scale testing and in service operation.

Figure 4 shows a typical catenary system cross section and Figure 5 shows a 6,000-hp GF6C locomotive. In the chart in Figure 6 characteristics of a GF6C locomotive are given together with a tractive effort versus speed curve. The technical and operating management at BCRC suggest that one GF6C locomotive is operationally equivalent to two 3,000-hp diesel-electric SD40 locomotives.

A test program to validate the contracted values was carried out simultaneously with electric operation in early 1984. So far these tests have verified the specified acceleration, capacity, power factor, and so forth. Further, system response to perturbations and harmonic feedback from the 50-kV catenary to the 230-kV power line network has been studied and results were satisfactory.

The OCS uses a solid copper contact wire and a stranded copper messenger wire. The construction has proved to be adequate for speeds up to 100 km/hr and is designed to handle four pantographs simultaneously. A 50-kV feeder wire mounted on the catenary poles is parallel with the catenary system. The ground return circuits consist of the earth, the rails, and a ground return conductor installed on



Wire arrangement of the OCS.

MESSENGER WIRE	70 MM^2	COPPER
CONTACT WIRE	107 MM^2	COPPER
PARALLEL FEEDER WIRE	125 MM^2	ACSR
GROUND RETURN WIRE	125 MM^2	ACSR

FIGURE 4 Typical catenary cross section.

the outside of the catenary poles. Because there are no long cables or open wires, the system does not employ booster transformers (Figure 7).

The OCS is divided into sections over its entire length with remote-local disconnects. This enables sections of the system to be isolated for maintenance while allowing other sections, the loadout loops for example, to remain energized (see Figure 7).

DESIGN AND COST OF OVERHEAD CONTACT SYSTEM

Of primary concern in the electrification of a specific railroad is the energy supply and distribution to the motive power along the line. In the case of TRBL as mentioned earlier, it was possible to energize the total system from one location, thereby minimizing the cost of expensive high-voltage (230-kV) feeder lines. Therefore, attention was concentrated on the OCS to optimize its design, construction, and maintenance requirements.

The concept of the overhead contact system was based on designs tried and proven by SJ in climatic conditions similar to those in northeastern British Columbia. During the detailed design phase, the Swedish designs were adapted wherever possible to North American standards as well as to the specific requirements of TRBL.

FIGURE 5 6,000-hp GF6C locomotive.

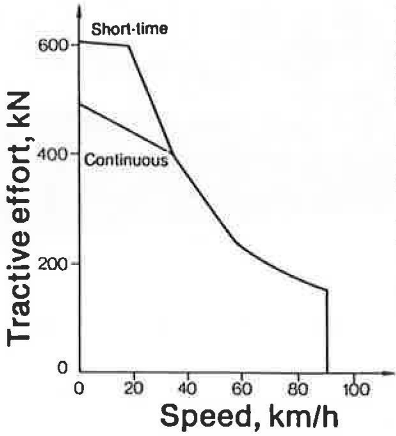
The overhead contact system is composed of two major subsystems: the mechanical subsystem, which consists of poles, cantilevers, and tensioning devices; and the electrical subsystem, which consists of the contact wire, the ground wire that is electrically connected to the track, and the messenger-dropper system that maintains the contact wire at the correct height above the rail as well as forms part of the electrical circuitry. [This is described in detail in Andersson et al. (2).] Generally approved construction methods were used in most cases. However, for foundations, a unique method was used for all but a few of the catenary masts.

The BCRC Engineering Department undertook design of the foundation. Because of the newly filled subgrade and high cost of concrete at the construction site, there was reluctance to recommend poured concrete foundations in holes augered or dug with a backhoe. Driven steel piles or precast concrete foundations were considered potentially suitable and tests were carried out by loading prototype foundations with the structures bolted to them. The driven steel pile was found to be satisfactory, which enabled the design to proceed with one standard length of mast for each of four different mast cross sections. The steel piles were driven into the subgrade by a truck-mounted pile driver. This pile driver proved capable of installing between 20 and 50 foundations per day; it could thereby cover from 1.0 to 2.5 km per day for a single-track catenary.

The newly designed 50-kV catenary system penetrates an area where severe climatic conditions and operating demands that required special design arrangements had to be considered. Some interesting OCS design features of this installation are those used for:

- Section insulator and neutral sections,
- Weight tensioning,
- Insulated overlaps,
- OCS at load-out loops, and
- Tunnel design.

Some of these features and their arrangements at the coal load-out silos are shown in Figure 8. The OCS arrangement to facilitate loading the coal cars is shown in Figure 8(a), and the OCS arrangement at the coal loading hopper is shown in Figure 8(b). Coal and train handling in the loading area will be fully



Main data

First delivery		1983
Line voltage	kV	50
Line frequency	Hz	60
Gauge	mm	1435
Driving wheel diameter (new)	mm	1067
Bogie wheelbase	mm	4162
Total wheelbase	mm	17,420
Height over pantograph, down	mm	5029
Max. width	mm	3245
Length over couplers	mm	20,980
Max. speed	km/h	90
Continuous transformer rating excluding auxiliaries	kVA	6480
Rating as per IEC 349	kW	4400
Max. starting effort	kN	605
Axle load max.	kg	29,690
Weight, total	kg	178,000
Number of traction motors		6
Traction motor control	Thyristors	
Transmission	E88 nose suspended motors	
Auxiliary machines	60 Hz, 3-phase	
Brake system	Dynamic brake combined with tread brake	

The locomotives are provided with a thyristor switched power factor correction system and a radar-based speed measuring unit to regulate the power to each axle so that slip occurs under control, permitting the maximum use of available adhesion.

FIGURE 6 Tractive effort versus speed curve and GF6C locomotive characteristics.

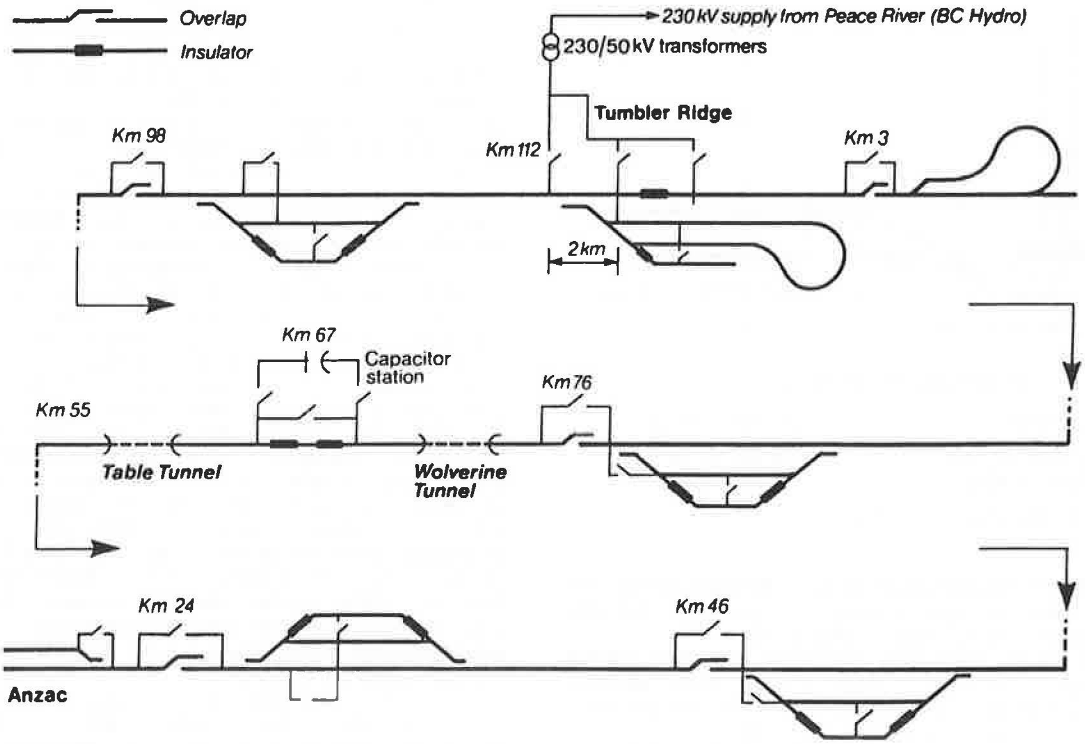


FIGURE 7 General arrangement of power feed to the catenary and the sectioning of the system.

automatic and controlled by advanced computer systems.

For the total OCS at TRBL some of the typical procurement and installation costs were as follows (1982-1983 Canadian dollars):

Supporting Structure	Cost ($)
H-beam steel piles	378-397
Precast concrete pedestals	500-555
Installation of steel piles	237
Installation of concrete pedestals	475
Steel masts	341-882
Erection of masts	70
Total cost of one mast	948-1,862
Portal structures (material)	2,275-2,459

Mechanical Components and Assembly	Cost ($)
Special casting and fabrications	951,000
Insulators	666,000
Cantilever tubing	111,000
Tunnel supports	154,000
Nuts and bolts	143,000
Other items	119,000
Subtotal	2,144,000

Electrical Components and Assembly	Cost ($)
Contact wire	875,000
Messenger wire	632,000
Earth and feeder wire	251,000
Other fittings	381,000
Subtotal	2,139,000

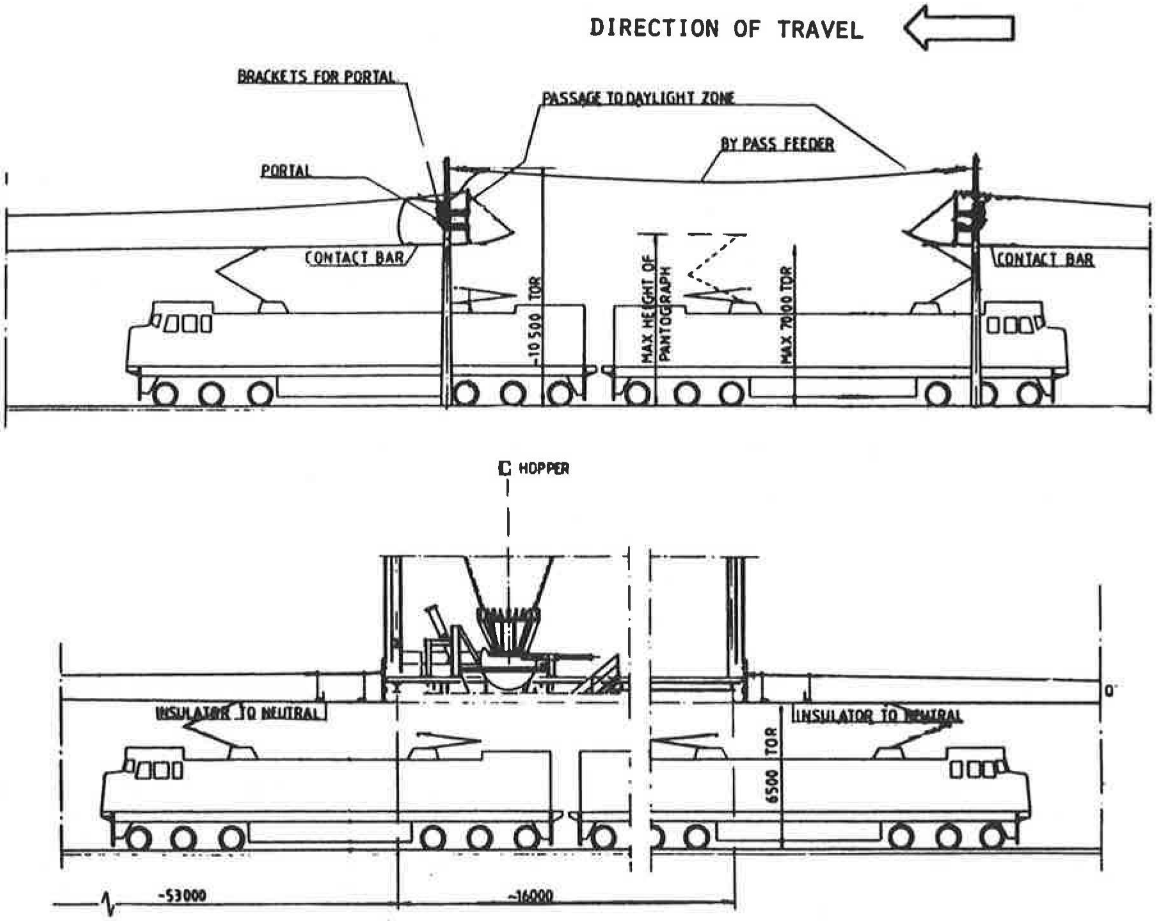


FIGURE 8 Some design features of OCS and arrangement at coal load-out silo.

The installation cost--excluding substations, the capacitor station, and 50-kV feeder line from the substation--is approximately $100,000 per single track kilometer. There are about 168 km of single track OCS.

ECONOMIC BENEFITS: ENERGY AND TECHNICAL ASPECTS

There are two principal energy-related benefits now being derived from the electrified operation of TRBL: the efficient use of energy to transport coal from the mines to the BCRC main line and the use of hydrogenerated electricity instead of nonrenewable fossil fuel. Additional benefits are obtained from reduced locomotive maintenance and elimination of the need for tunnel ventilation systems. Using the electrical system is also environmentally cleaner and less noisy than using diesel power, and requires only nominal maintenance effort.

The energy consumption estimates presented in this section were derived from a series of computer analyses based on the number of locomotives, train length, train weight, and track gradient. The figures show the projected energy use during the coming years. Field data collected and analyzed thus far have shown good agreement with the computer analyses. Converting from diesel to electrical energy is expected to provide an annual saving of approximately $1 million (1982 dollars) by 1986, when the mines will be producing coal at their planned capacity of 8 to 9 million tons per annum.

Use of electrical energy instead of diesel energy will reduce energy consumption by 63 percent, which will make use of electrical energy almost three times as efficient as use of diesel fuel. It is estimated that during a 10-year period the electric locomotives will save almost 100 million liters of high-grade diesel fuel in transporting 80 to 90 million tons of coal through the Rocky Mountains. Translation of energy efficiency between different types of internal combustion and electric prime movers is a complex process. Efficiencies of various types of transportation equipment are presented in Table 1.

The diesel engine energy efficiency is 23 percent, compared with 90 percent for the compensated, thyristor-controlled electric locomotive. The BCRC has conservatively calculated an efficiency of 27 percent for the diesel electric locomotive and 75 percent for the electric locomotive. The BCRC fuel consumption estimates shown here are based on projected annual tonnages.

Year	Trips	Diesel Fuel (L)	Diesel Fuel (GJ)	Electricity (kw/hr)	Electricity (GJ)
1984	700	6,540,000	252,000	25,900,000	93,000
1985	881	8,823,000	317,160	32,597,000	117,175
1986	953	8,903,000	343,080	35,261,000	126,750

The annual fuel savings are calculated to be $289,000 in 1984, $603,000 in 1985, and--when the mines are delivering coal at their contracted capacity from 1986 on--$729,000. Estimated annual savings from using electric power rather than diesel fuel are shown in Table 2. The data in Table 2 indicate that substantial savings in fuel cost can be realized from the use of electrically powered locomotives.

There are many other cost benefits to be realized

TABLE 1 Comparison of Transportation Equipment Efficiencies

	Diesel Oil From:		Petrol From:		Electricity from Oil, Coal, Nuclear Power		
	Oil	Coal	Oil	Coal	Condensing	Backpressure[a]	Hydro Power
Efficiency of conversion to usable energy (percent)	94	33	94	33	35	85	100
Efficiency of refueling, charging-discharging (percent)	100	100	100	100	66[b]-90	66[b]-90	66[b]-90
Efficiency of engine and motor (percent)	23	23	17	17	75[c]-90	75[c]-90	75[c]-90
Efficiency of transmission engine and motor wheels (percent)	85	85	85	85	85-95	85-95	85-95
Total energy remaining for propulsion (percent)	18	7	14	5	15-27	36-65	42-77
Regeneration, 20 percent of total efficiency	18	7	14	5	18-32	43-78	50-92

[a] Including heat.
[b] Accumulator.
[c] Contactor-resistor system.

TABLE 2 Estimated Annual Savings of Diesel Fuel Compared with Electric Power

			Cost of Electric Power			
Year	No. of Trips	Cost of Diesel Fuel ($000s)	Energy Charge ($000s)	Demand Charge ($000s)	Total Cost of Electric Power ($000s)	Savings ($000s)
1984	700	1,793	581	923	1,504	289
1985	881	2,257	731	923	1,654	603
1986	953	2,443	791	923	1,714	729

from use of electrification. First, locomotive maintenance costs are expected to be reduced by $350,000 per year (compared with maintenance costs of using diesel-powered locomotives). Elimination of the requirement for tunnel ventilation systems will result in a further operating-cost reduction of $200,000 per year. Assuming the maintenance cost of the electrical power system to be $300,000 per year, the net savings for 1986 and succeeding years will be about $250,000. This, together with fuel cost savings, yields a total saving of almost $1 million per year in 1986 and in succeeding years, when the mines are delivering coal at their contracted capacity.

By examining the capital cost figures it can be observed that the electrification of the line has resulted in an additional cost of $12 million. BCRC estimates that this cost will be recovered in 13 years. If the energy savings credits are included, the cost will be recovered in 8 years.

SUMMARY AND OUTLOOK

Electrification of TRBL represents only 5 percent of BCRC's 20 percent involvement in the $2.5 billion North-East Coal Development and Transportation Project in British Columbia. Nevertheless, electrification is a major technical achievement that can provide significant cost benefits in the future. The project was carried out in a short time period and was completed ahead of schedule and below budget. The introduction of high-voltage electrification and modern solid-state controlled electric locomotives will provide the railroad industry in North America a valuable data base for performance of a modern electrified railroad operation for heavy loads under adverse conditions. It is too early to draw conclusions from the TRBL operation, but so far the tests and operating experience have been favorable. Many technical questions will arise and their resolution will serve as guidelines for future railroad electrification development in North America.

ACKNOWLEDGMENT

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Computerized Interactive Videodisc Railroad-Worker Training in Houston, Texas

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ABSTRACT

In May 1983 computerized interactive videodisc (CIV) training was offered to 50 railroad workers on the Port Terminal Railroad Association (PTRA) in Houston, Texas. CIV combines the control capabilities of a microcomputer with the sound and video strengths of a videodisc. This project was cooperatively funded by the PTRA and the Office of Safety, Federal Railroad Administration (FRA). Its purpose was to test (a) railroad employee response to this type of training, and (b) CIV equipment capability in a live railroad training exercise. Six different CIV courses were developed and implemented. The courses were presented using a microcomputer, keyboard, a videodisc player, and a color monitor. Course material was contained on floppy disks and a videodisc. From comments supplied by employees and the on-site monitor from the company that developed the CIV, a number of conclusions were drawn, including: (a) railroad employees respond favorably to this type of on-site training; the amount of classroom training could decrease significantly if supplemented by CIV; (b) the ideal location for on-site training is one with little disturbance and yet that is not isolated; (c) hard disks are preferred over floppy disks and videodiscs; (d) railroad workers consider refresher training, such as CIV, an effective tool in increasing safety awareness; (e) the keyboard was cumbersome to a few employees; an alternative may be desirable; (f) employees prefer simple, direct, and concise features of course design, and employee enthusiasm decreases as degree of difficulty increases; (g) there appears to be direct correlation between interest of management and enthusiasm of employees.

Computerized interactive videodisc (CIV) training has been offered to railroad workers on the Port Terminal Railroad Association (PTRA) in Houston, Texas, since May 1983. CIV combines the control capabilities of a microcomputer with the sound and video strengths of a videodisc. This effort is cooperatively funded by the PTRA and the Office of Safety, Federal Railroad Administration. The results of an initial evaluation conducted with 50 railroad workers to determine their receptivity to this type of training and to establish guidelines for future direction of the course are summarized in this paper.

COURSE MATERIAL

Course material focused on railroad operating rules and safety procedures and was contained on floppy disks and a videodisc. Courses were presented by using a microcomputer, keyboard, videodisc player, and color monitor. Six different CIV courses were developed and implemented:

1. Train Yard Safety: a general training exercise designed to reinforce train-yard safety habits. This course is applicable to all craftsmen and managers working in a train yard.
2. Blue Signal: a course designed to teach proper blue-signal placement and recognition. This course is designed primarily for teaching mechanical craftsmen. It also is a practical method by which to familiarize operating craftsmen (train and enginemen and yard masters) with the purpose of blue-signal display.
3. Air and Hand Brake: a course designed to describe safe practices when working with hand and air brakes. Both operating craftsmen and mechanical craftsmen will benefit from the exercises contained in this course.
4. Hazardous Material Handling: a course designed to teach engine service and ground crews their responsibilities in situations in which they are confronted with hazardous material, such as leaking cars, derailments, hazardous material accidents, and so forth. The PTRA serves the Houston petrochemical complex.
5. Coupler Safety: a course used as an example of how CIV training can be used to teach safety and operating rules. Employees witness other employees, through scenes on the videodisc, in obvious violation of rules relating to coupler operation. The employee is asked to identify the rules being violated. This course is primarily designed for operating craftsmen.
6. Employee Injuries: a generic course designed to describe predominant employee injuries. Statistics and video sequences are used to stress importance of constant alertness when working in a train yard, particularly around moving equipment. Clerks, workers in operating crafts, maintenance of way, mechanical departments, and management can all benefit from this course.

Each of the preceding courses was designed with various combinations of digital displays and audio-video sequences. The audio-video sequences were contained on a videodisc that was produced from videotapes supplied by the PTRA. The Author Learning System controlled interaction between the equipment and the student. Courses were selected and developed with the assistance of the PTRA Director of Safety.

The Houston Labor/Management Project provided technical guidance and coordination with rail labor and local management.

Based on the results of this initial test, a more intensive program has been initiated. The PTRA has been joined in the current effort by the Southern Pacific Transportation Company; they are now the two principal carriers evaluating CIV courses.

A total of 14 modules will be available when the project is completed. The new courses also focus on railroad operating rules and safety procedures, but are more intensive than the original courses and include the full spectrum of rail operations. The courses will run on a computerized work station that consists of an IBM personal computer, a Pioneer LDV-1000 videodisc player, an Amdek color monitor, a printer, and headsets.

CHARACTERISTICS OF A CIV

Description of a CIV

CIV represents a merger of two technologies: computer-assisted instruction (CAI) and videodisc. Equipped with a computer, an interface to control the videodisc player, and a monitor, the user is provided the high visual impact and graphic capability of video and the responsiveness, flexibility, and power of the computer.

CIV incorporates all of the recognized advantages of CAI: self-paced individualized instruction, complex branching, feedback, testing, and record keeping. CIV's major advantage, however, is that it permits the user to randomly access or branch to specific visual images that are stored on a videodisc.

A videodisc is a mass storage medium, generally the size of an LP record. It contains analog, digital information, or both, that represent text, audio, video, and computer programming. A noncontact or optical disc can store 54,000 frames of information, which is recorded as microscopic pits that vary in length and density on each side.

The videodisc is read by using a low power laser; information contained in the microscopic pits is converted to visuals (pictures), audio (voice, music, or other sounds), text, or program logic. Each track contains information for a separate video image, giving a per-side equivalent of 675 carousel slide trays of pictures, or one-half hour of motion. Because the videodisc is read by a laser beam, there is no physical contact with the disc; therefore each image can be read over and over without causing wear and tear to the disc. This makes it possible to use the freeze- or still-frame feature as well as slow motion. Users can directly access any track in 2 to 6 seconds, depending on the player used.

Two audio channels are available. They can be used in bilingual programs, to provide multiple strategies for instruction, or to produce stereo. For example, in the current effort under way in Houston, the Maintenance of Way course will be in both English and Spanish to accommodate the Spanish-speaking railroad population.

With a computer, interactive instructional programs may be implemented. This interaction allows branching to visual motion, visual still, audio, or computer text graphics, on the basis of student response. Learner control as well as system control is possible. Tracking performance allows evaluation of the student as well as the program. Motion sequences can be shown in slow motion or still frame to observe critical details. Overlaying computer text and graphics on top of projected videodisc images allows highlighting, cueing, and other visual techniques. There is also the possibility of using a given visual image for multiple purposes and captioning for non-English speaking persons or the hearing impaired. Thus, CIV offers unlimited possibilities for use in education and training.

Effectiveness of Computer-Assisted Instruction

CAI has been evaluated in a number of different settings and its efficacy as an instructional delivery system has been determined. Results of research in the military, where most of this type of training is under way, show that CAI is an effective instructional method. Specifically, it reduces learning time, increases achievement, and produces favorable attitudes toward learning.

Most studies of military technical training courses demonstrate that CAI saves a significant amount of time needed by trainees to complete courses. Although the median value of time savings is 30 percent, the value varies with the type of course. For example, trainees in courses on electronics and electricity saved up to 60 percent in learning time when using CAI methods compared with learning time when using conventional instruction. Reducing learning time, however, did not reduce achievement. In the military studies, in almost all situations, trainee achievement when using CAI was the same or better than when using conventional instruction.

Data evaluating the effectiveness of CIV are not yet available from railroad companies. However, the following conclusions can be drawn from this initial test on the PTRA:

1. CIV reduced from days to hours the amount of time railroad workers required for taking refresher courses on operating rules.
2. As part of an overall management plan, CIV contributed to the complete reversal of the accident and injury record. That is, among railroads within the same classification, the PTRA went from having the worst safety record in 1980 to having the best safety record in 1983. The PTRA received the 1983 Gold Harriman Award for being the safest railroad in its class of service.

The followup effort will be statistically evaluated to determine its effectiveness relative to the results of the initial test. It will also include cost comparisons with more traditional forms of training. Further information will be available from PTRA in 1985.

DETAILS OF PILOT TEST

Scheduling and Personnel

For five full days, beginning on Monday, May 23, 1983, PTRA employees were exposed to the six different courses. On the first day the system was set up in the employee lunchroom of the PTRA North Yard main office. For one day a large concentration of PTRA's operating craftsmen and mechanical craftsmen were given an opportunity to inspect the equipment. Word spread quickly throughout PTRA that such a system was in place. This led to other employees coming to see firsthand the type of training being offered. This was a good step in acquainting employees with the new system.

On the second day and for the rest of the week the equipment was set up in the PTRA North Yard rip track office. This was a better location because it was smaller, more accessible by mechanical and operating forces, had fewer distractions than the lunch room, and the equipment could be left overnight without security problems.

Fifty railroad employees participated in the pilot test. The sequence was as follows: Day 1, 9 employees; Day 2, 10 employees; Day 3, 14 employees; Day 4, 8 employees; Day 5, 9 employees; total, 50 employees. The employees represented the following crafts: management, 9; car men or machinists, 26; maintenance-of-way workers, 4; clerks, 1; operating craftsmen (train and enginemen), 10; total, 50.

Management representatives took all six courses. Car men and machinists completed the four courses dealing with train yard safety, blue signal, air brake, and employee injuries. Operating craftsmen completed the four courses on train yard safety, hazardous material, coupler safety, and employee injuries. Maintenance-of-way representatives concentrated on two courses: train yard safety and employee injuries.

Course Design and Variation

A procedural document about the course was prepared. The course procedure was explained to each employee before he began. PTRA's Director of Safety was also briefed on the system and conducted start-up sessions.

Each course required approximately 20 minutes, depending on the knowledge of each trainee. No pressure was exerted to hurry the trainees; they were permitted to progress at their own pace. The courses were not designed as tests that an employee could pass or fail. They were designed as refresher learning exercises on operating rules and safety procedures.

The six courses were prepared with different combinations of audio-video scenes and questions. In one design set, audio-video scenes were used to generate questions. Employees were asked to respond to questions on audiovisual material they had just reviewed. In another design set, trainees were presented with continuous digital questions. If each of these was answered correctly, the student progressed to the next question. If the question was answered incorrectly, video scenes were used to present the correct procedure.

In another design set, a series of questions was presented sequentially. Following the series of questions, regardless of how well or how poorly the student performed, important reminder audio-video scenes were presented as reinforcing mechanisms.

Three levels of branching were used throughout all the courses in this pilot program. If the student failed to respond correctly on the second tier of branching, he was told in the third branching mode to see his safety director for assistance on that particular subject matter. After discussions with the safety director, the student was required to repeat the course. Flow charts of the two prevalent course designs are shown in Figures 1 and 2.

EVALUATION

Evaluation Criteria

On completion of the training session, each employee was asked to fill out a short questionnaire. Forty-six evaluation forms were completed. The numbers of representatives of different positions who filled out the questionnaires were as follows: management, 8; nonoperating union workers, 29; and operating craftsmen, 9. ("Nonoperating" positions include (clerks, shop people, car men, mechanics, and track-

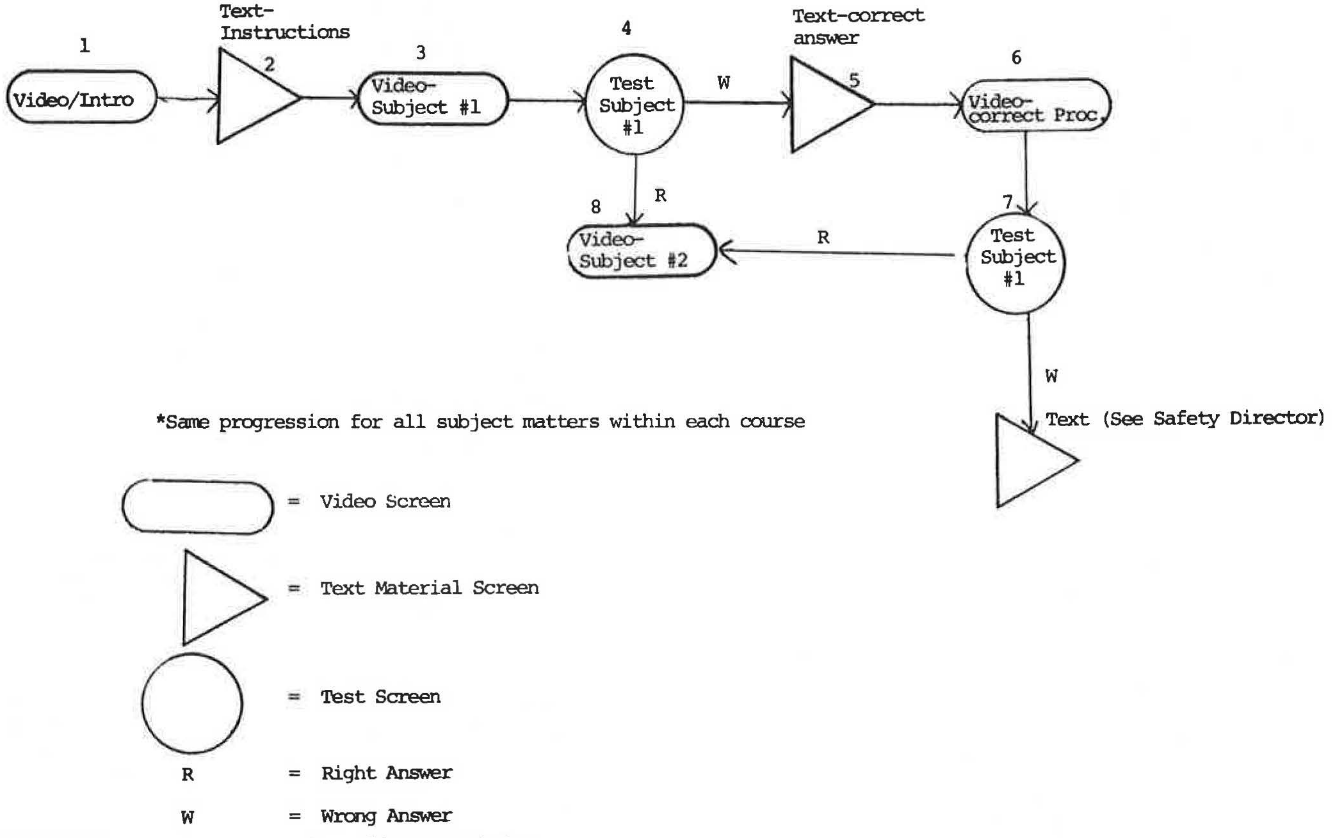

FIGURE 1 Flowchart of one of two CAI course designs.

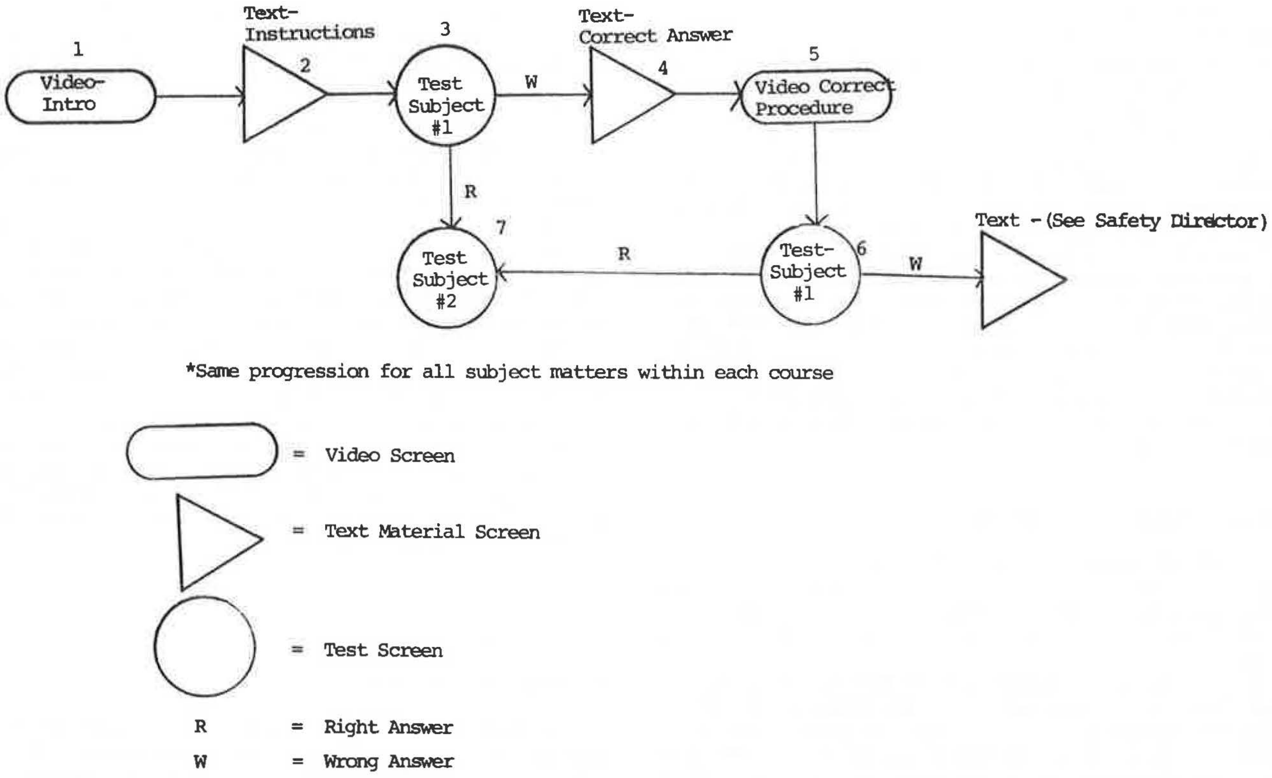

FIGURE 2 Flowchart of the second CAI course design.

men. "Operating" positions include train and enginemen and yard masters.)

The form was designed to:

1. Extract information on employees' reactions to this training delivery system;
2. Identify system weaknesses;
3. Gain comments on the individual courses, paying particular attention to course design; and
4. Evaluate logistics such as training location and ease of use.

Evaluation Results

Nine questions were asked. The questions and the tabulated results are listed here.

QUESTION 1: Your overall reaction to this approach in training is:

Favorable	46
Unfavorable	-
Total	46

QUESTION 2: Did you find the system:

Hard to use	1
Easy to use	43
Between hard and easy	2
Total	46

Three employees noted some concern about start-up and operation in working with the system. According to comments received, this could have been due to their unfamiliarity with a typewriter keyboard, their inability to read (either because they forgot their glasses or because they cannot read), belief that the floppy disk was too delicate, or some combination of these. The majority of the employees found the system easy to use.

QUESTION 3: Do you believe you could learn more:

Through CIV than through safety classes	22
Through classroom and on-the-job training	7
Through some combination	17
Total	46

QUESTION 4: On the following list, please write a 1 beside the course you liked best, and a 2 beside the course you liked second best.

Course	No. of First-Choice Votes	No. of Second-Choice Votes	Total Votes
Employee Injuries	13	13	26
Blue Signal	17	4	21
Train Yard Safety	14	3	17
Air and Hand Brake	12	4	16
Hazardous Material	8	4	12
Coupler Safety	3	8	11

This question was designed to extract some employee reaction to the different combinations of presenting audio-video scenes and digital information. It also was structured to gain insight into employee reaction to the degree of difficulty of different courses.

On the first issue, it appears that railroad employees favor sequences in which audio-video scenes generate questions. The following four courses featured structured audio-video scenes in which railroad employees were shown properly or improperly performing tasks: Train Yard Safety, Blue Signal, Air and Hand Brake, and Employee Injuries. Following the scenes, employees were asked questions pertaining to the material they had just received. Initially, the other two courses, in which digital information was presented without video material, were rated lower than these four courses.

Hazardous Material Handling and Coupler Safety--in their original design in which digital information was presented without video material--were the two most difficult courses. In these courses employees needed a good grasp of safety rules pertaining to the subject matter before they participated in the training. Of all six courses, these two received the fewest first-choice and second-choice votes. As the degree of difficulty increases, employees' favorable reaction appears to decrease slightly. Of the 50 taking the courses, only two employees (one from management and one car man) finished with a perfect score on all the courses. This indicates that all the courses were somewhat difficult.

QUESTION 5: What areas of railroad training lend themselves to this computerized approach?

Area	No. of Votes
Safety	36
Rules	24
Technical training	10
Clerical training	10
Management training	8
Other	6

Of the six votes cast for Other, five employees indicated that all training could benefit from a computerized approach, and one employee indicated that yardmaster training could benefit. The two areas Safety and Rules received the largest numbers of votes. This was probably influenced by the orientation of the six courses in the training exercise to these subjects. Employees appeared impressed with the effectiveness of the computerized approach as a learning mechanism for safety procedures and railroad rules. In addition, many employees considered this computerized approach suitable for use throughout the broad spectrum of railroad training.

QUESTION 6: Did you find it hard to set up the system and get started?

Response	No.
Yes	1
No	41
Total	42

Of those responding to this question, only one employee found the setup difficult. This employee's comment was that he was not accustomed to machines. In most instances, an on-site staff member of the agency that developed the CIV courses assisted each employee with the insertion of the floppy disk and the videodisc. However, those employees who were following the digital instructions without assistance mastered the technique rapidly.

QUESTION 7: Did you find the environment (re: on-site training) conducive to learning?

Response	No.
Yes	32
No	10
Total	42

Employees appeared to support on-site training. However, provisions need to be made to minimize disturbances and the number of onlookers. During most of the day, the rip-track location was an ideal spot for the training. Employees could totally concentrate on the course with few distractions. However, at lunch time or during a change of shift, it would be preferable not to train anyone at that location because of the commotion. An ideal situation would be one in which an employee does not feel isolated, the system is easily accessible, and the area is free from distractions.

QUESTION 8: Did you notice any problems in scheduling your session?

Response	No.
Yes	1
No	42
Total	43

The one positive response was given as a criticism of the constant movement of people into and out of the rip-track office. All of the employees who participated in the exercise were being paid and were removed from their regular assignments. Employees were scheduled to take courses by either the Safety Director, the Assistant Superintendent, the car foreman, or the lead car man.

QUESTION 9: Do you believe you are a safer employee with a better understanding of certain rules as a result of this pilot program?

Response	No.
Yes	41
No	-
Total	41

CONCLUSIONS

A number of conclusions about the entire training exercise can be drawn from comments supplied by the employees and from observations by the technical teams. These conclusions are presented in the following paragraphs.

Railroad employees respond favorably to this type of on-site training. In general they favor it as a supplement to, not a replacement for, classroom training. However, the amount of classroom training could decrease significantly with a CIV backup.

The ideal location for on-site training is one that has little disturbance and yet is not isolated. Employees like to be seen taking the courses but not disturbed while they do.

The insertion of floppy disks and a videodisc is not a mechanical problem. Employees will do it. However, the floppy disks do not appear rugged enough for the industrial environment. The hard disk is the preferred alternative.

Railroad workers believe that refresher training, like CIV, is an effective tool in increasing safety awareness.

The keyboard was somewhat cumbersome to a few employees. These employees admitted that they were not familiar with typewriter keyboards. An alternative design may be desirable.

Railroad workers prefer a course design that features video scenes generating questions. As the degree of difficulty of a course increases, employees' enthusiasm decreases slightly. These workers believe that more in-depth handling of the subject matter would be preferable.

Some solutions to the problems of scheduling this type of training need to be found. This may be approached differently by each railroad and within each class and craft of employees.

Video sequences and digital material must be concise and to the point. Too much material confuses the employees. Some workers had trouble reading the material. Sentences shorter than those presented in the current design would facilitate understanding.

There appears to be a direct correlation between the interest of management and the enthusiasm of employees. Management needs to make a solid commitment to this type of training for it to be successful.

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Comparison of Freeway and Railroad Rights-of-Way for High-Speed Trains in the Texas Triangle

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ABSTRACT

Alternative rights-of-way for high-speed trains operating in the Texas Triangle, which connects Dallas-Fort Worth, Houston, and San Antonio, are described and compared in this paper. These alternatives include medians of Interstate highways and the former Rock Island right-of-way. It is concluded that cross-sectional geometry would allow construction of a high-speed rail line on the majority of the two types of rights-of-way. Two different microcomputer simulation programs were applied to the Texas Triangle to investigate different types of high-speed train technologies operating in Interstate highway medians and along the former Rock Island right-of-way. The simulation runs demonstrated that comfort and curvature limitations prevented full utilization of a 350-mph speed, and that lower speeds (150 to 200 mph) would appear more effective given the existing geometric constraints. In addition to operating characteristics, the Texas Railroad Company simulation provided estimates of energy requirements. The investigations demonstrated that 200-mph high-speed rail passenger service is technically feasible along existing rights-of-way in Texas.

Proposed routes for high-speed rail service generally use three types of right-of-way: (a) existing railroads, (b) existing highways, and (c) new alignments. Each provides a different set of benefits and problems.

Travel time, an important factor in attracting riders, is affected by the combination of physical route and performance characteristics of the trains. Human factors and mechanical limitations determine the maximum speeds at which a train can traverse curves and grades. Vertical and horizontal curves combine with train operation and performance characteristics to determine the time and distance necessary to accelerate and decelerate the train (1).

Use of computer simulations of train operation over proposed routes can yield information that is needed to make early policy decisions about appropriate technology and engineering designs, but multiple detailed mainframe computer simulations can be expensive. Microcomputers provide the ability to run low-cost, simplified simulations for sketch-planning purposes, which can help with comparisons of predicted performances of high-speed trains on various types of routes.

The studies described in this paper were directed toward assessing the physical practicality of implementing high-speed rail passenger service on existing highway and railroad rights-of-way in Texas. This paper does not include an investigation of market potential or a detailed analysis of the financial or legal feasibility of implementing and operating high-speed rail service in the Texas Triangle.

POSSIBLE HIGH-SPEED RAIL LOCATIONS IN TEXAS

One major U.S. corridor that has been considered for high-speed rail service is the 750-mile Texas Triangle, which connects Dallas-Fort Worth, San Antonio, and Houston (Figure 1). Investigations of potential routes for implementing high-speed rail passenger service in Texas have concentrated on using existing freeway and railroad rights-of-way. These routes were examined for physical and geometric

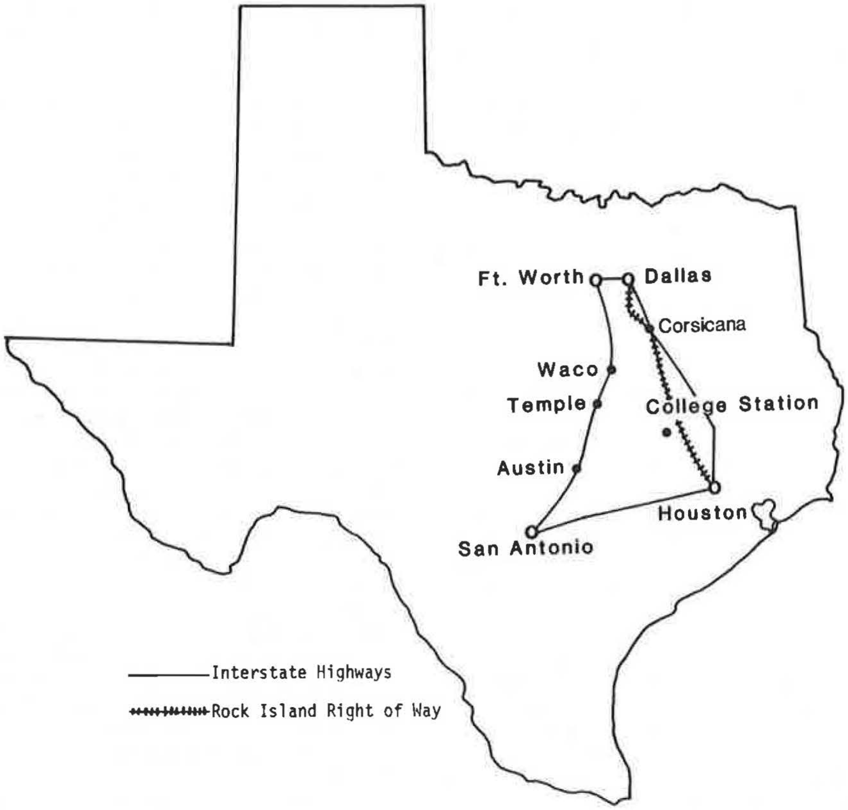

FIGURE 1 Map of the Texas Triangle.

features relevant to implementing high-speed rail passenger service within the right-of-way cross sections. A range of rail technologies, extending from operation at 120 mph to operation at 350 mph, were then superimposed on the longitudinal geometries of the right-of-way to determine their respective performance characteristics.

Interstate Highway Medians

A Texas Transportation Institute (TTI) research team surveyed 730 miles of the five Interstate highways in the Texas Triangle. Information recorded in the field included the following: (a) bridge structures, (b) overpasses, (c) vertical clearances, (d) major transmission lines, (e) milepost numbers, and (f) general observations. In addition, horizontal curve data were estimated from aerial photographs and county maps. Outside urban areas, the number of potential obstructions averages almost one per mile. The survey also considered weighted average surface width, roadbed width, and right-of-way width. To simplify the sketch-planning simulations, only horizontal curve data were used in the computer simulation program run by TTI.

Rural freeways in Texas are fairly straight and have relatively wide medians. Adequate median width exists along most of the route to allow construction of a high-speed rail system; such a system could be implemented at grade between the traveled lanes in a large portion of the Triangle. Medians 96 ft or wider would provide sufficient lateral clearance for double tracks while maintaining the 30-ft clear zone recommended by AASHTO. Considering safety along with noise and visual impacts, it may be desirable to construct barriers to shield the high-speed trains from adjacent traffic. At-grade construction, with appropriate protective devices, is feasible for two-way operation if median width is approximately 50 ft or more. Vertical clearances for an overhead power distribution system would be a problem at some locations.

Because of the variable design requirements associated with different high-speed rail systems and the geometric characteristics found at certain locations along the Interstate facilities (such as at major interchanges), it may be necessary or desirable to elevate portions of the guideway. Reasons to deviate from the at-grade construction could include topographic features (e.g., rivers), narrow medians, unsuitable horizontal or vertical curvatures, insufficient clearances, freeway structures, or some combination of these.

In urban areas, other problems can be expected. For example, in Houston the freeway medians have been dedicated to other uses, such as high-occupancy-vehicle lanes, and would not be available. Although more costly than an elevated guideway, a subway might be feasible; the exact configuration and dimensions of the tunnels would be determined by the high-speed rail technology selected.

Existing Burlington Northern-Rock Island Railroad Right-of-Way

The Burlington Northern-Chicago, Rock Island and Pacific Railroad Company (Rock Island Railroad) line is 240 miles long and runs between Houston and Dallas. Each party owns 50 percent of undivided interest in the southern 211 miles of the line from Houston to Waxahachie. The northern 29 miles of the line, from Waxahachie to Dallas, is owned by Missouri-Kansas-Texas Railroad Company and is operated by both Burlington Northern and Rock Island Railroad. Nine additional miles of the high-speed line are proposed, which would be on other rights-of-way.

The Texas Railroad Company has signed a contract to purchase Rock Island Railroad's interest in this line, which now has 96 bridges, 34 inactive railroad stations, and 122 turnouts and crosses 64 private roads, 224 state or county roads, and one major river (Trinity River in Dallas County). There are 123 curves with various radii; the total length is 33.40 miles, or 14 percent of the total mileage of the railroad; and the maximum grade is 1.00 percent. In general, the railroad right-of-way is 100 ft wide or more; this width is adequate for construction of three or four parallel tracks and drainage structures.

These rail-line characteristics are different from those of a highway right-of-way. Because the line already carries railroad traffic, it can be expected that the objections to noise and visual intrusion may be fewer than objections to noise and visual intrusion that would result from using a highway right-of-way. The problem of clearances will be less along an existing railroad right-of-way than along a highway right-of-way. On the other hand, Burlington Northern will insist on being kept whole, which will necessitate reconstruction of freight railroad tracks to one side and provision for access to (or compensation for) blocked industries. The railroad line as it now exists has many highway-railroad crossings at grade that must be upgraded to grade-separated crossings. Interstate highways bypass many towns, but railroads pass through their centers; either grade separation or, more likely, acquisition of new rights-of-way to bypass these towns will be necessary.

GEOMETRICS AND TRAVEL TIME

Most of the rights-of-way that were investigated have adequate cross-sectional geometry for construction of the high-speed rail lines. The feasibility of using existing rights-of-way for high-speed rail service also depends in part on longitudinal alignment. Freight railroads and freeways were designed for much lower speeds than those of high-speed rail systems; therefore, existing alignments constrain high-speed train operation. Vertical curves have an impact on project and energy costs but can be discounted in a preliminary analysis; grades of freeway rights-of-way are generally smooth and less than 5 percent, and railroad grades are much less than those of freeways. Horizontal alignment, however, can significantly affect grade separation, the need for extra right-of-way, and traffic disruption (2).

Restrictions on high speeds of trains at curves are largely the result of an effort to ensure passenger comfort rather than the inability of the train to negotiate curves at high speeds. One way to attain greater comfort when the train travels at high speeds through horizontal curves is to superelevate, or raise, the outside rail. For any given speed the degree of curvature and superelevation must be controlled to maintain lateral passenger acceleration and its rate of change (jerk) at a level that does not affect comfort. Although the Federal Railroad Administration (FRA) specifies a maximum of 3 in. of unbalanced superelevation (the extra superelevation that would be required to achieve equilibrium), recent studies (3,4) demonstrate the feasibility of using up to 4.5 in. of unbalanced superelevation in passenger trains that are equipped with stiffer suspension, without significantly affecting comfort. The French railroads have allowed for the use of a maximum of 6.3 in. of unbalanced superelevation in their Tres Grand Vitesse (TGV) train, even though in practice the unbalanced superelevation of the new Paris-Lyon line is less than 4 in. (5). At present, FRA regulations limit actual superelevation to 6 in., although in the past superelevations of 8 in. or more were used on North American railroads (6,7). Thus, train speeds on curves will be limited by unbalanced superelevation plus actual superelevation.

Another way of achieving balanced forces on the passengers is to tilt the passenger cars as done by the Swedish experimental train (8,9), the British Advanced Passenger Train (APT) (10-12), the Swiss (13), the Canadian Light Rapid Comfortable (LRC) (13), and the Italian State Railways (10,13). For example, a train could operate with 8 in. of actual superelevation plus 6 degrees of tilt (approximating 6 in. of additional superelevation) plus 4 in. of unbalance, which would provide a total of 18 in. of superelevation and thus higher curve speeds. It may be possible to add as much as 12 in. of track superelevation plus 6 degrees of tilt plus 6 in. of unbalance (which would give 24 in. of total superelevation) without inflicting undue discomfort on passengers who are either moving or stopped.

Magnetically levitated (maglev) trains could possibly achieve higher speeds. Although this emerging technology has not yet been placed in revenue service, maglev vehicles could be capable of greater superelevation angles; an actual equivalent superelevation of 20 in. could be feasible, but passenger mobility problems could arise if a maglev train were to stop on a curve with such tilt. Unbalance of 4 in. plus 20 equivalent in. of actual superelevation would provide a total superelevation of 24 in.

Unless it can be assumed that all curves have large enough radii that speed restrictions do not need to be imposed, curves along a selected right-of-way become important in simulation of train operations. By using the given geometric information, a computer program can determine controlling speeds on curves and thus develop an estimate of travel time.

SIMULATIONS

Two different deterministic simulation programs were used to "operate" high-speed trains in the Texas Triangle. One program, used by TTI and run on a Radio Shack Model III microcomputer, was designed to print a detailed velocity profile of train performance each 0.25 mile, but it did not consider grades or energy. To increase program running speed, the TTI program used a table lookup to determine at what point to begin deceleration. The second program, used by the Texas Railroad Transportation Company [now the Texas Railroad Company (TRC)], was run on an Apple IIe microcomputer. It did not print details of the velocity profile along the line, but used real-time calculations to consider overall energy requirements. Recall that the TTI program considered curves but did not consider grades; the TRC program considered grades and curves, but did not slow trains down to travel around curves. Yet when the TTI program was run with the Rock Island data and with assumptions of large radius curves, the travel times were essentially the same.

TTI simulations of both the Interstate highway rights-of-way and railroad rights-of-way assumed that the high-speed rail terminals were located at the interchanges of the Interstate highways. This is approximately the location of the Amtrak terminal in Houston, that is, just north of the downtown area. The Dallas terminal is located just east of the central business district.

Technologies Investigated

Three types of conventional steel-wheel-on-steel-rail technologies were simulated by traveling along the existing rights-of-way. Performance characteristics of these trains were estimated and used in the computer simulations.

The first set of rail parameters was estimated for a modern Amtrak train that consisted of 7 Amcar coaches pulled by an electric locomotive (Electric EMD AEM-7, 7,000 hp).

The second set of rail parameters was estimated to approximate the performance of a high-speed conventional electric train such as the German IC-E (Intercity Experimental) train of the French TGV with all axles powered, both with and without the ability to tilt up to 6 degrees on curves (approximating an additional superelevation of 6 in.).

The third set of operating parameters was estimated for a theoretical train. These theoretical capabilities have not, and may never be, attained in general operation with flanged steel wheels on steel rails, but they may represent a possible set of estimated operating parameters for maglev trains.

The Amtrak train was the lowest-performance option, and the theoretical train (or maglev) was used to represent the highest-performance rail option. The conventional diesel-powered passenger train operating on shared-freight railroad tracks was not included in the analysis.

A fourth set of ultra-maglev parameters, which resemble those of an amusement park ride or a jet airplane when taking off or landing, was also included to investigate their effects on travel time reduction. However, such operating parameters would require that the traveling public remain seated and belted throughout the run, which may not be acceptable in practice.

Except for the 120-mph maximum Amtrak speed, which was based on actual operation, maximum speeds of 200 and 350 mph were chosen to be representative of a general range of technologies. To facilitate comparisons, these three speeds were the only ones used on highway medians by the TTI program. Additional speeds were used on the Rock Island right-of-way. It should be noted that selection and use of these speeds in no way constitutes a recommendation or feasibility analysis.

Superelevations were matched to the maximum speeds allowed and the rail technology that was being examined. Except for the ultra-maglev system, maximum superelevation used was 24 in., which was composed of 12 in. of actual superelevation plus 6 degrees of vehicle tilt plus 6 in. of unbalanced superelevation. Although feasible, this amount of superelevation would make it difficult if not impossible to use highway medians because of the amount of spiral offset that would be required when entering and leaving curves. For the Amtrak technology, superelevation was assumed to be a total of 12 in., which is the sum of 4 in. of unbalanced superelevation plus 8 in. of actual superelevation for a standard gauge track of 4 ft 8-1/2 in. The 18-in. total superelevation assumed the same 8 in. of actual superelevation plus 4 in. of unbalanced superelevation, but with an additional 6-degree tilt capability of the train car bodies.

TTI Simulation of Highway Medians

A deterministic train performance simulation program was written in BASIC to generate train performance velocity profiles, travel time, and other data by reading route characteristics from a disk file.

Because the program operates on a small microcomputer and is quite slow, the program was kept as simple as possible to minimize run time. Table lookup was used to initiate deceleration, acceleration curves were approximated by straight-line segments, and performance was averaged over each 0.25 mile. Because analysis indicated that grades would have minimal effects on high-speed train operation over relatively flat terrain, such as that in the Texas Triangle, grades were not used (14). These limitations can allow for potential performance inaccuracies of plus or minus 0.25 mile and plus or minus a few minutes, with the possibility of a train entering a speed restriction at 1 or 2 mph over the speed restriction. These inaccuracies were considered more acceptable for the desired performance requirements than the alternative of increasing program complexity and run time.

It is important to note that train travel time is minimized by the TTI simulation program, and no attempt is made to save energy. If the train is not traveling at maximum speed (considering speed restrictions), and if it is not necessary to decelerate before an upcoming speed restriction or stop, then the train is accelerating at the maximum rate for its current speed range. This often leads to a constant acceleration-deceleration velocity profile that would waste energy; this is not the operating mode of commercial trains.

The TTI program was also used to investigate the effects of reducing curvature to allow higher operating speeds. For a high-speed train to travel at speeds faster than would be possible on freeway median curves, wider radius curves may be used; however, these curves may encroach on the main lanes. The highway alignment could then be modified or the railroad could be grade separated (15).

Reverse curves, such as those found on I-45 near Corsicana, Texas, may further complicate curve widening. The need for adequate spirals for smooth transitions between curves and tangents in the railroad alignments may increase the total lengths of two adjacent railroad curves to an amount such that the tracks may run away from the freeway median, and may even leave the Interstate right-of-way.

A train operating with a total of 18 in. of superelevation that is going around a 1.5-degree curve at or below 131 mph can follow the alignment of the freeway median curves shown in Figure 2. Traveling at a speed of 185 mph requires wider curves than are available in the freeway median; this alignment requires shallow angle crossings over freeway main lanes and departure from the existing right-of-way at the center of each curve. Such alignment still begins and ends in the freeway median. For a train to travel at 227 mph the tracks must be constructed completely outside of the freeway median and right-of-way, along the curve.

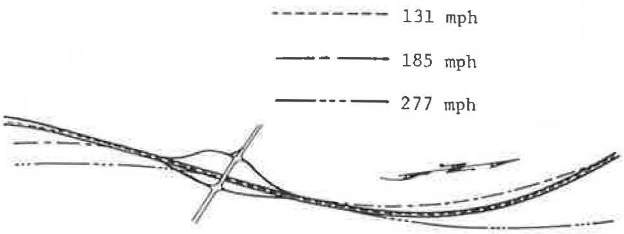

FIGURE 2 High-speed rail alignment through a reverse curve on I-45 near Corsicana, Texas.

TABLE 1 TTI Simulation Results of Trip Times of 9 Trains on Routes in Texas (min)

			Route				
			Houston-Dallas				
Type of Train	Speed (mph)	Superelevation (in.)	I-45	Rock Island	Dallas-Ft. Worth	Ft. Worth-San Antonio	Houston-San Antonio
Amtrak	120	12	130.5	144.5	17.5	130.9	110.7
IC-E/TGV	200	12	94.0	121.8	13.5	96.7	78.5
IC-E/TGV/Tilt	200	18	86.5	108.6	12.3	87.0	72.6
Theoretical	200	18	82.4	102.5	11.6	85.6	69.4
Theoretical	350	18[a]	74.1	99.4	10.7	78.6	58.8
Theoretical	200	24	79.6	92.7	11.4	80.7	67.3
Theoretical	350	24	68.7	89.4	10.1	69.6	55.2
Ultra maglev	350	36	52.6	65.6	7.4	52.8	44.0

[a] Three special runs were made with this train; the trip times (min) are as follows: Ft. Worth to Austin, 55.6; Austin to San Antonio, 23.6; Houston to Dallas (Corsicana curves reduced), 72.0. Total trip time from Ft. Worth to San Antonio was 79.2 min plus station dwell time.

To test the effect of widening horizontal curves on travel time, a reduction of all curves to 0.5 degree over a 20-mile stretch of track near Corsicana was simulated. The results showed a total time savings of only 2.1 min for the complete Houston to Dallas simulation run. Because this was not considered significant, all other runs on Interstate highways were simulated with the tracks following the curves of the freeway medians. The slowing effects of curves are more pronounced on the railroad right-of-way, and would have a greater overall effect on schedule operation.

Results of TTI simulations of high-speed trains traveling in highway medians (15) are given in Table 1. These results suggest that traveling on the Amtrak train at a maximum speed of 120 mph would require less passenger travel time than would traveling by automobile, but would take significantly more passenger travel time that traveling by the available air mode. At the other extreme, the theoretical train (or maglev), which has a top speed of 350 mph, would reduce the amount of travel time to less than the amount of time required to travel by air. Yet it would save less than 18 min per run compared with the 200-mph German IC-E train or the French TGV train with all axles powered, but at higher construction costs and operation costs.

The ultra-maglev train saved almost 30 min on the Houston to Dallas run traveling at 200 mph compared with the theoretical train (or regular maglev), and more than 41 min compared with the nontilting high-speed train on the same run. However, it is questionable whether the seated and belted passengers would find the extreme accelerations and decelerations comfortable.

Within the limits of the TTI simulation program (deterministic assumptions, ±0.25 mile, and time errors of a few minutes), the following generalizations may be made:

1. Horizontal curvature on all routes prevents maintaining a constant speed of 350 mph. The majority of the time is spent accelerating and decelerating when the maximum speed is 350 mph.
2. Time savings between a 350-mph theoretical train (or maglev) at a 24-in. superelevation and a high-speed train with tilt at an 18-in. superelevation is less than 18 min, or 25 percent, on any route. The savings are most pronounced on the Houston to San Antonio route on which fewer curves are encountered along the route length.
3. Time savings between a 200-mph theoretical train at an 18-in. superelevation and a conventional high-speed train with tilt was 4 min or less per run.
4. A stop in Austin on the Fort Worth to San Antonio run added only 0.5 min (plus dwell time) to the time per run of the 350-mph train at 18-in. superelevation, because of the need to slow for curves in the Austin area.
5. Removing the 6-degree tilt of the high-speed train added 7.6 min to the Houston to Dallas run.
6. The Amtrak train was significantly slower for all runs, but it was faster than Amtrak passenger service scheduled in the past (e.g., 260 min on Burlington Northern from Houston to Dallas in 1963, and 335 min from Houston to Fort Worth on Amtrak in 1972).
7. The testing of curve easing over a single section of a route had only a minor effect on overall schedule performance. Reduction of all curves to 0.5 degree of tilt or less over a 20-mile stretch of track near Corsicana, south of Dallas on I-45, had only a 2.14-min effect on running time. (Note that this implication holds only for trains traveling in the highway median; widening of some, if not all, of the curvature on the Rock Island right-of-way would result in significantly greater time savings.)
8. With straight rights-of-way and a 350-mph top speed, travel time over the "perfect" 250-mile route from Houston to Dallas would be about 45 min per run.

TRC Simulation of the Rock Island Right-of-Way

High-speed train operation over the right-of-way alignment of the Rock Island Railroad line between Houston and Dallas was simulated by the Texas Railroad Company (TRC). The design and operating characteristics of the high-speed French TGV train were used as the basis for calculation because of the availability of data about this train.

Because it was found that it would be impossible to run trains at a constant speed of 150 mph or more over the line with its existing geometric characteristics, TRC's simulation assumed that curves would be modified by widening them to a minimum radius of 11,155 ft. This would cause no speed restrictions at 150 mph if 6 in. of actual superelevation plus 6 in. of unbalanced superelevation were used.

The trade-off between saving time and saving energy was investigated. Basic energy consumption depends on the configuration (geometry) of the right-of-way and the design of the rolling stock. The French TGV train (or a similar German or Japanese train) represents one of the most advanced technologies in the field and is energy efficient. The French railway industry has investigated intensively the configurations of the propulsion system and the aerodynamic shape of the rolling stock (16). On a per-passenger basis, a TGV train traveling at 160 mph consumes less energy than a conventional train traveling at 100 mph.

An initial microcomputer analysis was conducted by TRC to determine expected performance of the high-speed train in the Houston-Dallas intercity corridor. Technical data on the French TGV were used when available to calculate tractive effort and train motion resistance (16-18). The TRC simulation assumptions included:

1. Standard M-8-M train set of 418 tons and 385 seats;
2. No speed restrictions;
3. Specific acceleration of 2 km/hr/sec or 1.25 mph/sec;
4. Specific deceleration of 2.8 km/hr/sec or 1.75 mph/sec;
5. Propulsion system efficiency of 0.80;
6. Catenary efficiency of 0.85;
7. Electrical substation efficiency of 0.85;
8. Power transport line efficiency of 0.85;
9. Power plant efficiency of 0.30;
10. Specific cost of \$0.05/kWh, and
11. Auxiliary devices power of 3.5 percent of propulsion system.

The TRC simulation program combined the mathematical models of energy consumption, train resistance, and schedule time. Power on the train must overcome resistance to motion, accelerate the train, decelerate the train, and power auxiliary devices.

Resistance to train motion arises from mechanical resistance due to the rolling of the wheel on the rail and internal friction and oscillation and air resistance, which depends on speed and the surface of the maximum cross section and on the effects of friction along the sides of the train.

By using the tractive effort developed by the propulsion system, which depends on speed and trainset resistance, the TRC computer simulation program integrated the train motion equation. Given train velocity and train position at the beginning of the time interval, the program simulated the next train position at the end of that interval. The program generated the step-by-step speed-time-position trajectory of the train and the power consumed.

Output of the TRC program gives schedule performance, energy consumption, peak power demand, specific energy consumption, and cost of energy for 44 train sets per day between Houston and Dallas. General results include:

1. Running time is 101 min between Houston and Dallas, there are no intermediate stops, and the average speed is 146 mph (over a slightly shorter route of 246.5 miles with widened curves that do not require speed restrictions).
2. Energy use for a single standard M-8-M train set (motor unit, 8 cars, motor unit) over the route was 7,031 kWh at the substation, or 0.0921 kWh per passenger mile based on 80 percent occupancy of the 385-seat train.
3. Energy-use increase at higher train speeds is approximately proportional to speed increase raised to the 1.8 power.

According to French experience, the most economic speed appears to be in the range of 140 to 165 mph. The simulation runs support this; how longer travel times affect the attraction of passengers to rail travel was not simulated, however.

TTI Simulations of the Rock Island Right-of-Way

For comparison, the TTI simulation program was run without curve restrictions at a speed of 150 mph, which gave essentially a trip time of 101.5 min between Houston and Dallas; this compares to the TRC simulation program time of 101 min. In addition, the simulation runs by high-speed trains were performed over the existing curvature (see Table 1). The theoretical train at 24 in. of superelevation was able to operate at the maximum speed of 350 mph for only 1.5 miles during the 249-mile trip (less than 1 percent) because of curves. Thus, the TRC simulation assumption that curve smoothing is necessary to increase train speed was validated.

IMPLICATIONS OF THE SIMULATIONS

One significant implication of the simulation runs is the suggestion that a maximum speed of 350 mph along highway medians or existing railroad routes may not be cost-effective. Maximum time savings would be only 18 min, whereas the increase in construction, vehicle, and operating costs would be disproportionately high. Assuming a riding population of 6,000 passengers per day, with the value of their time at \$7.00 per hour, the 18-min time savings would result in a value savings of \$3,276,000 per year. This savings would cover the interest on \$32,276,000 of capital at 10 percent, if all additional energy costs are ignored, which is much less than the capital investment required to smooth curves over the entire route. Analysis of the velocity profiles that were generated show that the 350-mph train would not be able to maintain maximum speed over the majority of the routes.

Houston to Dallas trip times along the I-45 right-of-way plotted as a function of maximum train speed can be seen in Figure 3. Increases in speeds above approximately 200 mph do not result in significant travel time reductions; the curve in the figure shows that minimum trip time for an existing route is approached at 350 mph. The spread of points at 200 mph and 350 mph is due to the points representing different technologies and superelevations. It is important to note that this curve is for a single existing alignment, and the curve should not be directly applied to any other route. Nevertheless, assuming that the TRC energy-use calculations for the Rock Island right-of-way would be similar for the I-45 right-of-way, it can be seen that an increase in maximum speed to 350 mph would result in a significant increase in energy consumption without a concurrent reduction in trip time. Because of the amount and degree of curvature on this route, the 350-mph trains were unable to operate at maximum speed over most of the route.

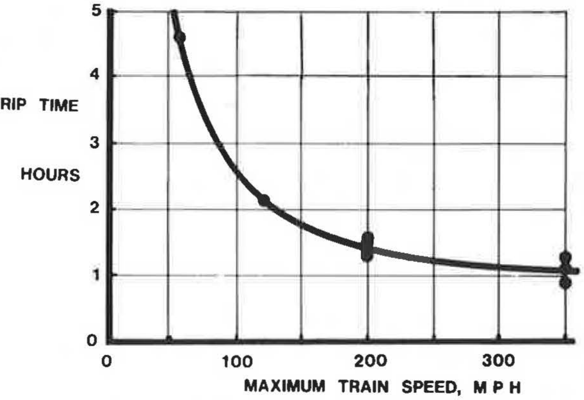

FIGURE 3 Houston-Dallas trip time on I-45 versus maximum speed.

The 200-mph German IC-E train or French TGV train with all axles powered, on the other hand, were able to operate at maximum speed for a significant portion of time. This type of train took only 94 min to go from Houston to Dallas along the highway median at 200 mph, operating with no tilt, 101 min over the Rock Island right-of-way at 150 mph with no curve speed restrictions, and 108.6 min operating with tilt and a top speed of 200 mph over the existing Rock Island right-of-way. If airport access-boarding time of 30 plus 20 min is added to flight time, downtown-to-downtown train travel time is essentially the same as air travel time between these two cities. The 86.5-min travel time that is possible with a German IC-E train or a French TGV train operating with tilt is quicker than the total central-business-district to central-business-district air travel time. Assuming that train fares would be lower than air fares, the existing TGV-type of technology (possibly with 6 degrees of tilt added) should be adequate to cause a significant diversion of passengers from other modes to the train.

The 200-mph speed used with the high-speed trains was arbitrarily chosen; although 200 mph appears to be close to the most effective speed needed to attract significant numbers of airplane passengers, no sensitivity analysis was made. Thus, 200 mph must not be considered a magic number; it was merely a convenient number for this preliminary analysis, a number the use of which gave good results. The TRC simulations suggested that 150 mph might be more economical in energy usage, but it may range downward or upward by a considerable amount. The significantly longer travel times required by the Amtrak train could result in less diversion of intercity traffic, which would make this option less effective than the higher speed 200-mph trains.

Use of microcomputers to simulate the operation of high-speed trains on the Texas Triangle by using BASIC programs was a success. Although the results were not as sophisticated or accurate as those that might be obtained from a mainframe simulation, the results were adequate for defining the relative effectiveness of different types of technologies over an available route, by estimating travel times and other parameters with a minimum of input requirements and an acceptable degree of accuracy.

SUMMARY

The studies and simulations suggested that a conventional high-speed train similar to the West German IC-E or French TGV (or maglev), operating at a maximum speed of 150 to 200 mph, would be capable of operating on the former Rock Island railroad route, or over existing highway rights-of-way, at scheduled speeds and with time savings capable of attracting passengers from other travel modes, using a reasonable level of energy consumption. The TTI simulation detailed speed bottlenecks, and the TRC program calculated energy requirements.

These findings, which were an outcome of sketch planning, were derived by using microcomputers. The simulations proved valuable in establishing the directions of further studies, and in defining the engineering problems and technology that could be pursued.

ACKNOWLEDGMENTS

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Analysis of Urban Rail-Service Alternatives

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ABSTRACT

A segment of rail line running through Memphis, Tennessee, along the Mississippi River is owned by the city and leased to Illinois Central Gulf (ICG) Railroad Company. The operation is perceived by proponents of downtown redevelopment to be a retardant to new commercial and residential development that is now being experienced in the downtown area. This study was performed to assist public officials in making a decision concerning renewal of the rail line lease, which expires in 1986. A wide range of rail-service alternatives were considered, many of which were eliminated in a preliminary screening analysis. Those remaining were examined in detail. The study analyzed the impacts of all of the alternatives on ICG, Memphis users of ICG, Memphis development, and the public. A benefit-cost analysis was also performed. Although results of the analysis are given in this paper, the study did not identify a best alternative, because such a selection is the responsibility of public officials and not a responsibility of this analysis.

On May 1, 1986, a 100-year lease agreement between the city of Memphis, Tennessee, and the Illinois Central Gulf (ICG) Railroad Company for property through the downtown area along the Mississippi Riverfront will expire. The ICG maintains trackage and operates trains in this 2.3-mile corridor extending from Saffarans Avenue in the north to Calhoun Street in the south (Figure 1).

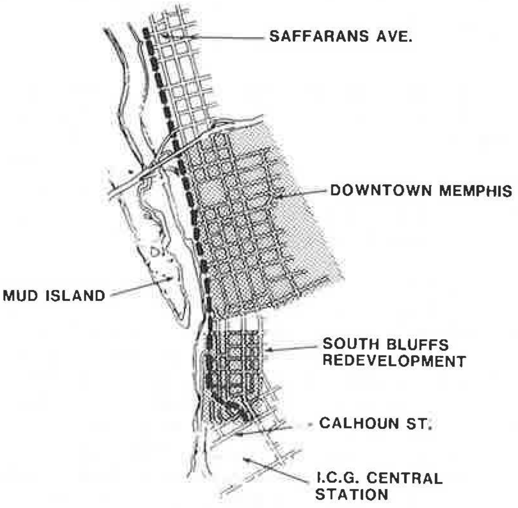

FIGURE 1 The riverfront corridor.

In recent years redevelopment activities in downtown Memphis and along the Mississippi River bluff south of downtown have accelerated. This development is occurring adjacent to the rail corridor, and attention has been focused on the impact that continued rail operations within the corridor will have on future commercial and residential development along the riverfront. Proposals have been made by developers and proponents of downtown redevelopment that (a) the lease not be renewed in 1986, (b) the tracks be abandoned, and (c) the train traffic currently using the Riverfront Rail Corridor be diverted to other portions of the Memphis rail network. An opposing view, that the elimination of this rail link will severely affect users and will result in a degradation of rail service in and through Memphis, especially to customers within the corridor and to industries north of the downtown area, has been presented by companies served by ICG and the railroad.

The objectives of this investigation were to develop an evaluation methodology and to evaluate the various alternatives to renewing the ICG lease and continuing to allow the line to operate as it has in the past. Included in the set of alternatives was the no-action alternative, that is, continuing the lease in its present form. The evaluation included an analysis of the capital, operating and maintenance, and road user costs for each alternative. Additional evaluation measures included environmental impacts and effects on rail customer service. Economic analyses of the costs and benefits associated with each alternative were also conducted.

THE MEMPHIS RAIL NETWORK

There are five Class I railroads that serve Memphis: ICG Railroad, Burlington Northern railroad (formerly Frisco), Seaboard Coast Line Railroad Company (formerly Louisville and Nashville), Union Pacific Railroad (formerly Missouri Pacific), and Norfolk Southern Railway Company (formerly Southern). The locations of these railroads are shown in Figure 2. ICG serves Memphis from the north and south. At the northern end of the urban area at Woodstock ICG branches into two lines, one single track line proceeding along the Mississippi River through the Driving Park Industrial Area, into the downtown (double track) area, and south through the ICG South Yard where another branch is made. One branch extends to the west of Johnston Yard, which is the railroad's major maintenance and classification facility in Memphis. This line connects with the South Main line and extends into Mississippi. The second branch at the South Yard is to the east of the Johnston yard and becomes the Grenada Main, extending south into Mississippi. The second branch at Woodstock is dual track and proceeds directly to

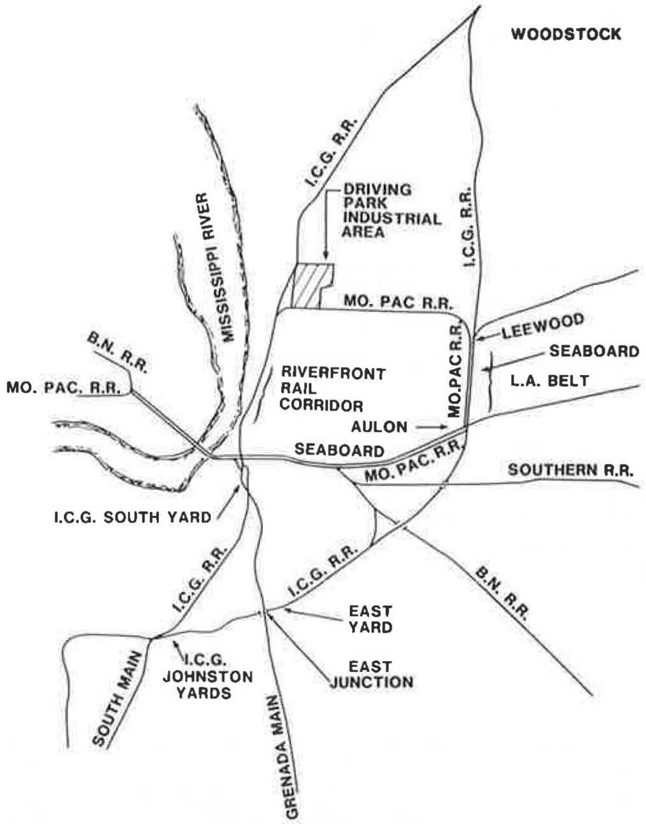

FIGURE 2 The Memphis rail network.

Leewood Junction, where the ICG operates on track owned by Seaboard for a length of approximately 2 miles to Aulon Junction. At this point the ICG has dual track leading southwest to Johnston Yard. No direct connection currently exists between this line and the Grenada Main.

Seaboard enters Memphis from the east. At Leewood this line is double track that proceeds in a southerly direction to Aulon. Seaboard facilities continue to the west. Norfolk Southern also serves Memphis from the east. Its operations terminate in Memphis.

Burlington Northern enters Memphis from Arkansas, south of downtown, and heads in a southeasterly direction toward Alabama. Union Pacific (MOPAC) also enters from Arkansas south of downtown and proceeds to its Sargent Yard facility, which is located in the central part of the city. MOPAC operates a single track circumferential route that first proceeds eastward, then travels northward (paralleling the Seaboard tracks in the Leewood-Aulon corridor), and then turns west and travels toward the Driving Park Industrial Area.

PRESENT OPERATIONS--ICG SYSTEM

Within the dual-track Riverfront Rail Corridor, the area in which it has been proposed to abandon operations, there is currently an average of 9 train movements per day. These include two scheduled Amtrak trains that use the passenger station located at the southern end of the downtown area, 5 through trailer-on-flat-car (TOFC) trains, and 2 transfers between the Driving Park Industrial Area and the ICG South Yard. TOFC trains use this corridor because it has direct connection to the Grenada Main. All through the corridor, mixed freight operations use the alternative eastern route. This route is known as the LA Belt.

IDENTIFICATION OF RAIL-SERVICE ALTERNATIVES

The initial task in this study consisted of identifying all options proposed for providing rail service subsequent to the end of the present ICG lease for use of the Riverfront Rail Corridor. The emphasis at this level of analysis was to generate a wide range of options without regard to the feasibility of each option.

The rail-service options developed were grouped into 7 categories. Category 1 contained a single element--the no-action alternative in which the lease would be renewed without any changes in physical layout or operating practices in the Riverfront Rail Corridor. The options in Category 2 contained physical changes that could be made in the Riverfront Rail Corridor. Category 3 contained a list of modifications to operating practices that could be implemented in the Riverfront Rail Corridor. Revisions to operating practices along the LA Belt and on the portions of the Memphis rail network were continued in the Category 4 options. Category 5 consisted of options based on physical changes in the railroad right-of-way owned by ICG. Improvements within the right-of-way owned by other railroads in Memphis were listed in Category 6. Category 7 was composed of additional alternatives that involved significant railroad construction in new corridors or major changes in the transportation system.

ALTERNATIVES CONSIDERED FOR DETAILED ANALYSIS

Four alternatives were selected to be evaluated in detail after completion of a preliminary screening analysis, which was conducted to eliminate alternatives that were not feasible or that were dominated by other alternatives. This screening was based on consideration of the following two factors:

1. Economic comparison of one alternative with other alternatives that could provide similar levels of service; and
2. Analysis of whether this alternative was dominated by other alternatives that could provide equal or better levels of service with less disruption, less construction, or lower operating costs.

The selected alternatives were developed by synthesizing the options being considered into concepts that combined the physical and operational changes required to maximize rail system capacity and level of service to users given existing constraints, such as the necessity of routing trains over longer distances and of using the tracks of other railroads.

It became apparent as the study progressed that the objective of providing system users, especially those in the Driving Park Industrial Area, with a level of service equal to what they were currently receiving could not be achieved by using viable alternatives (including abandonment of the Riverfront Rail Corridor) without major new construction and system disruption. Several alternatives that would provide service comparable to the current level were considered, but the associated costs and other negative impacts were judged unacceptable. For example, one concept that had been developed included expansion of the ICG East Yard near East Junction, addition of a third main track along the LA Belt from Leewood to East Yard, and installation of centralized traffic control (CTC) along the entire length of the LA Belt. This would provide a major improvement in the efficiency of transfer and through movements, but the capital expenditures that would be required were estimated to exceed $25 million.

Even if funds were available to provide these extensive physical improvements, there are other constraints that limit the provision of a level of service equal to the current level. The primary factor is that for any alternative that does not include use of the Riverfront line, ICG trains would be forced to use trackage of other railroads for all through and transfer movements. Although there are existing agreements permitting trains from one line to use tracks of another railroad, it is important to note that the railroad that owns the right-of-way and physical plant sets the priority of use. For example, if ICG operates over the tracks of other railroads, its access will be limited to avoid its interfering with the operation of the railroad whose line ICG is using.

This situation exists today along the LA Belt: ICG trains use the segment from Leewood to Aulon, which is owned by Seaboard. Informal conversations with Seaboard personnel revealed that ICG may pay up to 60 percent of the cost to operate and maintain the corridor through transfer fees collected by Seaboard. In spite of this, Seaboard trains--even switching operations--have priority over ICG through trains in this section. It has been reported that ICG trains may wait an hour or more to receive permission to proceed while Seaboard switching activities are taking place.

Given this constraint, the approach taken in developing alternatives for detailed analysis was to weigh the capital costs required for the improvements and to define alternatives that would provide maximum service within the limitations imposed by the existing railroad system, which consists of the properties of several railroads. This resulted in the generation of alternatives that would provide adequate service, although the level of service might not be equal to the level that is currently being provided with the Riverfront Rail Corridor in its existing form.

On the basis of an analysis of all available information and a review of the alternatives' feasibility and constraints, four alternatives were selected for detailed analysis. These are:

1. No change in physical layout or operating practices in the Riverfront Rail Corridor;
2. Enhanced Riverfront Rail Corridor;
3. Use of the existing MOPAC trackage for transfer movements and the LA Belt for through ICG trains; and
4. Transfer of all ICG operations to the LA Belt.

The extent of improvements that are necessary for each alternative is described in detail in the following sections.

No-Action Alternative

The "no-action" alternative assumes that the lease between the city of Memphis and ICG Railroad will be renewed in 1986. Two tracks will remain in the corridor, and no major changes will be made in train schedules, physical conditions in the corridor, or other operating practices.

Enhanced-Riverfront-Rail-Corridor Alternative

This alternative includes renewal of a modified lease in the Riverfront Rail Corridor by ICG Railroad. Corridor modifications to be considered include:

1. Removing one track in the corridor,
2. Replacing the existing rail on the remaining track with continuous welded rail,
3. Improving the highway grade crossings at major streets with rubberized surfaces, and
4. Landscaping the corridor.

Additional operational improvements that may be implemented include prohibiting blowing of whistles and ringing of bells and rescheduling train movements to minimize conflicts with peak street traffic volumes and evening operations.

The examination of this alternative will include an evaluation of the incremental costs and benefits associated with the proposed modifications.

Use of Existing MOPAC Trackage for Transfer Movements and the LA Belt for ICG Through Trains

Existing MOPAC trackage from the Driving Park Industrial Area to the LA Belt and parallel to the LA Belt and to Aulon will be used for transfer movements to the ICG South Yard. These transfer movements will use Seaboard or MOPAC tracks along Broadway to Kentucky Street and existing wye-shaped trackage to South Yard. Through trains will use the LA Belt from Woodstock and a new wye at East Junction to connect to the Grenada main line. The Riverfront Rail Corridor tracks will be abandoned and a new Amtrak station will be built. Specific modifications will include:

1. Rehabilitating the existing Missouri-Pacific track from the Driving Park Industrial Area east to the MOPAC North Yard near Leewood and south to Aulon, including replacement of turnouts and grade-crossing improvements;
2. Constructing a new Amtrak station along the LA Belt;
3. Constructing a new wye at East Junction; and
4. Constructing new track at East Yard to connect with the new wye.

Transfer All ICG Operations to the LA Belt

All train movements that use the Riverfront Rail Corridor will be transferred to the LA Belt. Specific improvements to be included are:

1. Constructing a new wye at East Junction,
2. Constructing new track at East Yard to connect with the new wye,
3. Purchasing existing right-of-way and track for the wye in the northeast quadrant at East Junction,
4. Constructing a 1-mile passing track and required crossovers along the LA Belt,
5. Constructing a 1,000-ft passing track and required crossovers in the Leewood to Aulon segment,
6. Constructing a 0.25-mile lead track at Woodstock,
7. Constructing a new Amtrak Station along the LA Belt,
8. Installing a new signal system from Aulon to East Yard, and
9. Improving signals from Leewood to Aulon.

ANALYSIS OF CAPITAL, OPERATING, AND MAINTENANCE COSTS

A principal component of the evaluation process was the development of estimates for the capital, operating, and maintenance costs associated with each of the alternatives that were being considered. The following cost elements were included in this analysis:

1. Capital costs for new construction or rehabilitation;
2. Additional maintenance costs or maintenance cost savings attributed to each alternative;
3. Additional operating and delay costs to ICG trains that formerly used the Riverfront Rail Corridor; and
4. Additional operating and delay costs to other train movements (both ICG and other railroads) on the Memphis Rail Network, which are a result of the increased train volumes on the existing system.

Documents prepared for estimating engineering cost estimates were used to determine railroad capital expenditures. An additional source of information was a 1974 publication of the Federal Railroad Administration, Guidebook for Planning to Alleviate Urban Railroad Problems (1). This document contains procedures for determining operations costs and maintenance costs based on consideration of time, distance, and delay factors. Figures from this publication were updated to a 1983 base by using cost-index data provided by the Association of American Railroads.

In preparing the cost estimates it was assumed that no additional right-of-way purchases would be needed at Woodstock, along MOPAC trackage, or along the LA Belt, and that modification to the existing system could be made within present rights-of-way. It was further assumed that land would be provided at no cost to the ICG Railroad to construct the wye in the southwest quadrant at East Junction, and that the privately owned wye that is in place in the northwest quadrant at East Junction would be purchased for $100,000. Tables 1-3 give lists of the recommended improvements and associated costs for the three alternatives. Table 4 gives a summary of the capital, maintenance, and operating and delay costs for all alternatives.

TABLE 1 Recommended Improvements to and Associated Costs of the Enhanced-Riverfront-Rail-Corridor Alternative

Recommended Capital Improvement	Cost ($)
Welded rail	560,000
Grade-crossing improvement	200,000
Landscaping	100,000
Total	860,000
Annual Maintenance	
Track maintenance	18,000 (savings)
Landscaping	40,000
Total	22,000/year

TABLE 2 Recommended Improvements to and Associated Costs of Missouri-Pacific-Transfer Alternative

Recommended Capital Improvement	Cost ($)
Track rehabilitation	1,350,000
Turnouts	225,000
Grade-crossing rehabilitation	105,000
Amtrak station	250,000
Wye at East Junction	368,000
Track at East Yard	110,000
Total	2,408,000
Annual Maintenance	
Abandon riverfront	60,000 (savings)
Additional	31,200 (LA Belt) 18,000 (MOPAC)
Total	10,800 (savings)
Annual Operation and Delay	
ICG trains diverted	1,107,209
Other train traffic	1,136,610
Total	2,243,819

TABLE 3 Recommended Improvements to and Associated Costs of LA-Belt-Woodstock-to-East-Junction Alternative

Recommended Capital Improvement	Cost ($)
East Junction Wye	
SE quadrant	368,000
NE quadrant—land	100,000
Passing track	
Airways to Cincinnati	1,344,000
Leewood to Aulon	260,000
Lead track, Woodstock	219,000
Track at East Yard	110,000
Amtrak station	250,000
Signals, Aulon to East Yard	419,000
Signal improvement (Leewood to Aulon)	50,000
Total	3,120,000
Annual Maintenance	
Abandon riverfront	60,000 (savings)
Additional maintenance	50,000 (new track) 31,200 (LA Belt)
Total	21,200
Annual Operation and Delay	
ICG trains diverted	1,967,058
Other train traffic	1,441,841
Total	3,408,899

Analysis of Impacts on the Road User

Several measures of effectiveness (MOEs) were used to describe impacts on the road user both inside and outside of the study area. These were:

- Average delay per vehicle at railroad grade crossings,
- Number of vehicles per day that experienced delay,
- Total vehicle-hours of delay (per year),
- Excess fuel consumption due to railroad grade crossings (gal/yr),
- Costs to the road user due to delay and fuel consumption ($/yr), and
- Expected potential accident conflicts (which is referred to as the safety index).

The values of these MOEs were obtained from several computer programs that were developed for this project. These programs considered train length, time of train arrival, street traffic volume at that time of day, and anticipated traffic growth between the years 1986 and 2000. These impacts are summarized in Table 5 for those alternatives that were selected for detailed analysis.

Impacts on the road user are the same for the do-nothing and enhanced-Riverfront-Rail-Corridor alternatives. Considering anticipated growth of street traffic in the study area, an average of 519 vehicles per day would be delayed an average of 71.3 sec each for these two alternatives. This would be an average of 3,753 vehicle-hr of delay each year. The total equivalent uniform annual costs to the road user

TABLE 4 Summary of Railroad Capital, Maintenance, and Operation and Delay Costs for All Rail-Service Alternatives

Alternative	Capital ($)	Maintenance ($/yr)	Operation and Delay ($/yr)
No action	0	0	0
Enhanced riverfront rail corridor	860,000	22,000	0
Missouri-Pacific transfer	2,408,000	10,800 (savings)	2,243,819
LA Belt-Woodstock to East Junction transfer	3,120,000	21,200	3,408,899

(considering the costs of delay and fuel consumption) for these two alternatives would be $23,590 per year.

These impacts on the road user would be eliminated if the riverfront line were removed. However, increased impact on the road user would occur outside of the study area because rail traffic currently using the riverfront line would be crossing different streets (and these streets would therefore carry increased amounts of traffic).

Both alternatives associated with removal of the riverfront line include routing through trains from East Junction to Woodstock via the LA Belt. The difference between these two alternatives is the manner in which transfers would take place. For ICG transfers made by using the MOPAC tracks, an average of 1,918 additional vehicles would be delayed an average of 76.9 sec each, which would amount to 14,957 vehicle-hr of delay per year. The total equivalent uniform cost to the road user would be $93,645 per year. If ICG transfers were to take place via East Junction and Woodstock, the additional number of motorists delayed would be 1,331 per day, which would result in an average of 10,373 vehicle-hr of delay per year. The equivalent uniform annual cost to the road user for this alternative would be $62,974 per year.

Comparing the two alternatives associated with removal of the riverfront rail line with those alternatives in which at least one track remains in place, the savings to the road user from removal of the rail line are more than offset by increased costs to the road user elsewhere in the city. By using the MOPAC tracks to accomplish ICG transfers, the number of additional vehicles delayed would be 3.7 times the number for which delay would be eliminated in the study area. This ratio would be approximately 2.6 if the transfers were made via East Junction and Woodstock. Similarly, total delay increases outside of the study area would exceed savings in the study area by a factor of 4 for the MOPAC alternative and by a factor of 2.8 for the East Junction-Woodstock alternative. The respective ratios for equivalent uniform annual costs to the road user would be 4.0 and 2.7.

ANALYSIS OF IMPACTS ON SAFETY

The impacts on safety for each alternative were assessed using a safety index, which represents the potential for a highway vehicle-train conflict. The conflicts occur when a vehicle attempts to cross tracks when grade-crossing controls prohibit crossings because of the approach or presence of a train. These conflicts may or may not result in an accident, depending on whether the motorist is successful in crossing the tracks. Nevertheless, a crossing accident will have a conflict associated with it. The potential for these conflicts (or safety index) is the number of times per year that at least one vehicle is present in each line while grade-crossing controls prohibit crossing. The values for the safety index of each alternative are given in the last column of Figure 5. It is emphasized that these values cannot be used to forecast accidents. They merely indicate that for the city as a whole, the do-nothing and enhanced-Riverfront-Rail-Corridor alternatives are likely to be the safest alternatives for providing the desired level of service.

ANALYSIS OF IMPACTS ON INDUSTRY

A survey of selected Memphis industries was conducted to determine the perceived impacts on economics and employment that would result from shipping delays that were expected to occur if the Riverfront Corridor was abandoned. The industries that were surveyed were those listed in the 1980 report entitled Memphis Riverfront Rail Impact Analysis (2). Each firm was asked to estimate the economic impact and the projected number of jobs lost for two conditions, a 24- to 36-hr shipping delay and a 2-hr shipping delay; a decrease in shipping reliability was assumed for both situations. An attempt was made to contact the 21 firms listed in the earlier survey. However, because some of the companies were no longer in operation in Memphis, it was only possible to contact 18 companies.

The results of the survey indicated that the estimates contained in the previous report of job losses resulting from a 24- to 36-hr shipping delay were still considered valid by most firms. For delays of this magnitude, a total of 300 jobs were projected to be lost. The majority of these lost jobs would not be existing jobs, but rather would be jobs that are never created, because the poor transportation service would cause firms to look for other locations in which to expand operation.

The estimates of the dollar value of the economic impacts to affected firms were highly variable because most of the industries that were surveyed included the value of future jobs lost, as well as extra shipping charges. However, based on the data supplied in the survey, an estimate of the minimum extra costs that would be incurred by industries as a result of 24- to 36-hr shipping delays would be about $750,000 per year.

Most of the firms surveyed believed that 2-hr shipping delays would not affect employment. However, a few firms indicated that any delays would mean decreased shipping reliability, which could influence decisions about future expansion. The total number of jobs projected to be lost by 11 industries was 100.

The majority of companies indicated that the

TABLE 5 Summary of Impacts of All Rail-Service Alternatives on Road Users

Alternative	Avg Delay/Vehicle (sec)	No. of Delayed Vehicles/Day	Annual Vehicle-Hr of Delay	Excess Fuel/Year (gal)	Annual Road User Costs ($)	Safety Index
No action	71.3	519	3,753	4,079	23,590	53,518
Enhanced riverfront rail corridor	71.3	519	3,753	4,079	23,590	53,518
Missouri-Pacific transfer	76.9	1,918	14,957	15,466	93,645	91,088
LA Belt-Woodstock to East Junction transfer	76.9	1,331	10,373	10,729	62,974	67,511

economic impacts of a 2-hr shipping delay would be minimal. However, if this delay resulted in missed connections, costs would accumulate. A conservative estimate of the extra shipping costs that would be attributed to 2-hr shipping delays would be approximately $100,000 per year.

The dollar value of the loss of jobs that would result from abandoning the Riverfront Rail Corridor was calculated by using the estimates provided for number of jobs lost, salary data, and information collected on train schedule reliability. The expected loss per year was computed to be $2,317,700. This was based on the following assumptions:

1. An average salary of $21,070 per year, and
2. A probability distribution of delays with a 95 percent probability of 2-hr delay and a 5 percent probability of 24-hr delay.

Based on these assumptions, the expected value of loss per year was computed in the following manner:

.05 x 300 jobs @ $21,070 + .95 x 100 jobs @ $21,070 = $2,317,700.

BENEFIT-COST ANALYSIS

An incremental benefit-cost analysis was used in the economic analysis of the alternatives. Capital costs, annual operating and maintenance costs, and annual costs to the road user were discussed in preceding sections of this paper. A separate study, Downtown Development Potential Analysis (3), was conducted by Memphis State University's Regional Economic Development Center to determine the land development potential and resultant benefits associated with improvement or removal of ICG tracks in the Riverfront Rail Corridor. This study developed estimates of employment gain and tax benefits that would occur if the railroad operations were eliminated or reduced in the downtown area.

A summary of the costs and benefits associated with each alternative is given in Table 6. The column labeled Annual Employment Gains gives the value of jobs that are gained from removal or reduction in rail service in the corridor. The Annual Employment Losses column gives estimates of the value of jobs lost by industry as a result of reduction in the level of service provided by the railroad. To provide consistency of units, capital costs are multiplied by a capital recovery factor to provide units of $/yr.

For the first comparison, the alternative with the lowest capital cost is the base alternative and that with the next lowest capital cost is the proposed alternative. For the proposed alternative to be economically superior to the base alternative, a benefit/cost (B/C) greater than 1 (a positive value) is required. For this comparison, the calculated B/C value was -0.09. This negative value of B/C indicates that the base alternative is superior to the proposed alternative. Thus, the enhanced corridor alternative was eliminated from further economic consideration.

For the next comparison, the proposed alternative involves transfers via MOPAC tracks. The do-nothing alternative is again the base. The B/C that was calculated was -14.5. Again, the do-nothing alternative is economically superior. It also serves as the base for the final comparison--that for which the proposed alternative assumes that transfers are accomplished via East Junction and Woodstock. The B/C for this comparison was -14.6. The do-nothing alternative is once again economically superior; therefore, from an economic perspective, it is the best of the entire set of alternatives. Note that this same conclusion would be reached even if there were no jobs lost by removal of the riverfront line. The benefit-cost ratios, however, would have different magnitudes.

CONCLUSIONS

This study was an in-depth investigation of the costs, benefits, and other impacts of alternative methods of providing rail service in Memphis if the present lease between the city of Memphis and ICG Railroad for the Riverfront Rail Corridor is not renewed in its existing form in 1986. A detailed study of feasible options for maintaining service at the current level has been conducted, and the costs (and their impacts) associated with each option have been calculated. The results of this study are intended to guide the mayor's committee in formulating a recommendation about renewal of the ICG lease.

No specific recommendations concerning the best alternative were developed; however, several conclusions are made as a result of this study. The first conclusion is that the recurring annual costs for maintenance and operations for all of the alternatives that were selected for detailed analysis were more significant than the capital costs for the improvements. This was especially true for the alternatives that included costs to the railroads for additional travel distances and time delays.

A second conclusion is that the trade-off among benefits must be considered for each alternative. For example, abandonment of the Riverfront Rail Corridor will benefit employment opportunities in the South Bluff Area, but will have a negative impact on the number of potential jobs in the Driving Park Industrial area. Likewise, reductions in delays to motorists in the downtown area that would result from removal of train traffic would be outweighed by the increased delays to vehicles that would be caused by additional trains traveling on other portions of the rail network.

A final conclusion is that any resolution of the current problem will require cooperation among all affected railroads. These railroads should not be expected to agree to rail system modifications unless it is demonstrated that the railroads will

TABLE 6 Summary of Costs and Benefits of All Rail-Service Alternatives ($/yr)

Alternative	I x CR	K	U	Annual Employment Gains	Annual Employment Losses	E	T
No action	0	0	23,590	0	0	0	0
Enhanced riverfront rail corridor	108,841	22,000	23,590	(-)9,738	0	(-)9,738	2,469
Missouri-Pacific transfer	298,684	2,233,019	93,645	(-)221,077	2,317,700	2,095,923	(-)76,115
LA Belt-Woodstock to East Junction	376,081	3,430,099	62,976	(-)221,077	2,317,700	2,095,923	(-)76,115

Notes: Benefits are indicated by a negative sign. 1 = capital improvement cost; K = equivalent uniform annual operating and maintenance costs (relative to the no-action alternative); U = equivalent uniform annual road user costs; E = equivalent uniform annual net employment costs; T = equivalent uniform annual taxes; and CR = capital recovery factor.

benefit and that their operations will not suffer as a result of recommended changes.

ACKNOWLEDGMENTS

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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

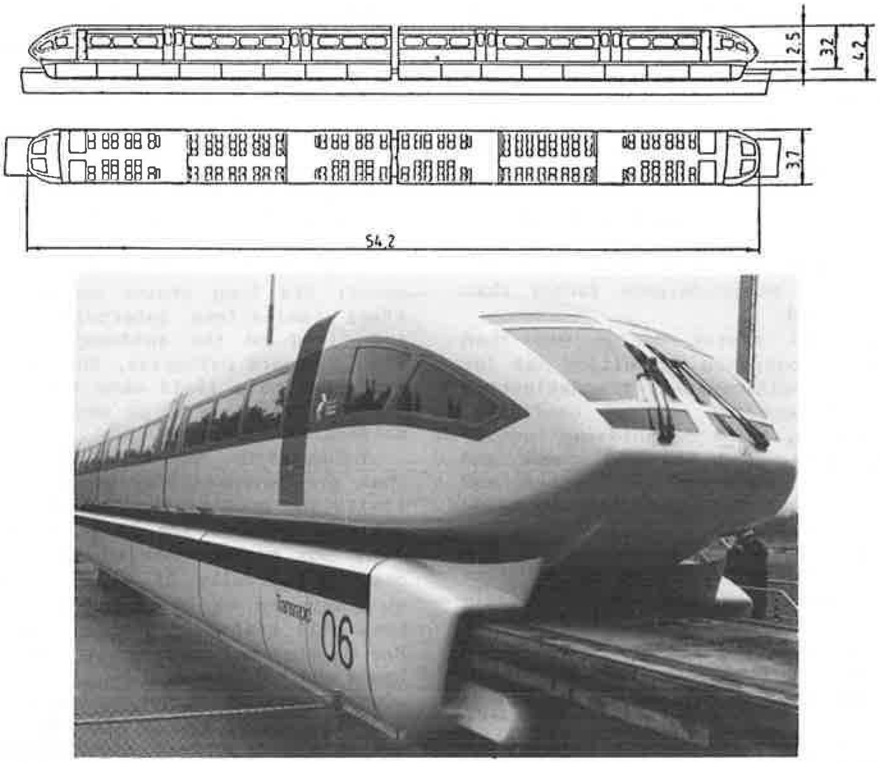

FIGURE 2 Maglev vehicle, main dimensions and general view.

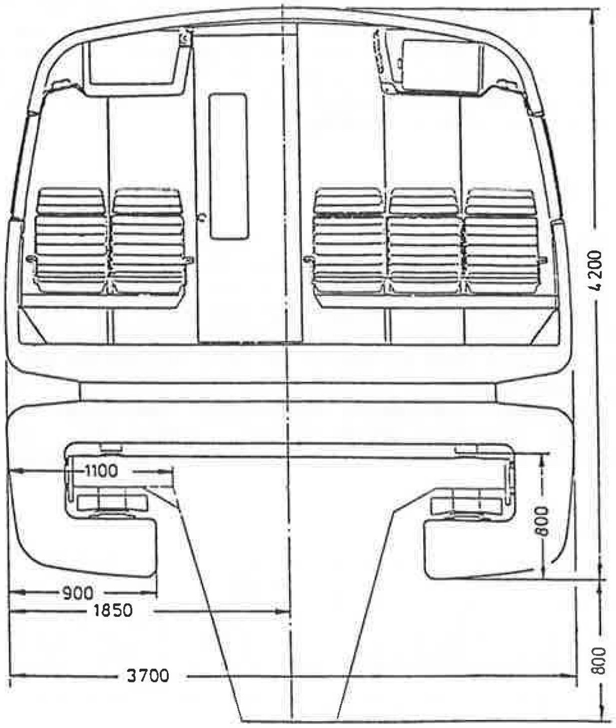

FIGURE 3 Cross section of Maglev vehicle on guideway.

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.

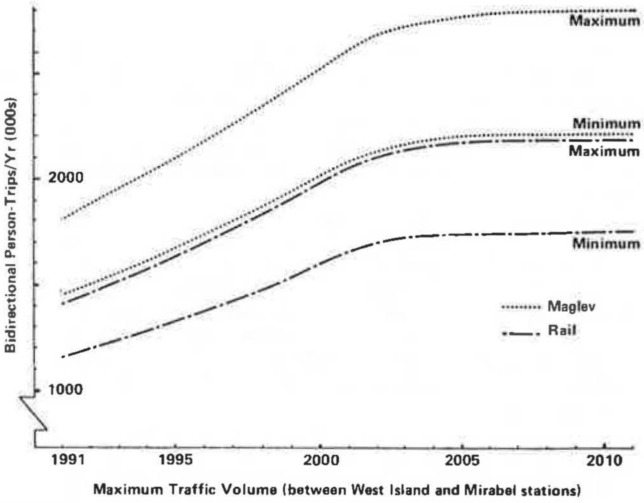

FIGURE 4 Forecasts of total future levels of traffic for Maglev system and Rail system.

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

	Capital Costs (relative to Rail costs)		
Item	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

	Annaul Cost (relative to Rail costs)		
Component	Maglev	Rail	Rationale for Difference
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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