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Contents

Foreword

This Record contains rail transportation research papers on a variety of topics. The papers by Allport and Brown, Dawson, Uzarski et al., and Raymond and Cai were presented at the TRB Annual Meeting in January 1993. All six papers were peer reviewed by TRB standing committees in the rail transportation area.

Allport and Brown report on an enhanced method of evaluating the economic benefits of the European High-Speed Rail Network. The focus of the method is the additional benefits that will accrue to business travelers, which had not previously been incorporated into the conventional economic evaluation of this network. The results suggest that the additional impacts are potentially a significant source of economic benefits.

Dawson reviews rail ridership and service in the Philadelphia-Lancaster-Harrisburg area of Pennsylvania. The reasons for declining patronage and the changing market for rail travel in this corridor are discussed. The relative and changing roles of the intercity carrier (Amtrak) and the local Philadelphia service (Southeastern Pennsylvania Transportation Authority) are also noted, along with potential organizational restructuring to improve service.

Schneider examines the station location, number, and intermodal connection needs of small magplane systems. The assumption is that a second-generation maglev system will be developed in the United States that will feature many small magplanes operating at high speeds and short headways over a national system of magways. The author finds that there is a major trade-off between maglev switching speed and station cost and that use of many small stations offers the possibility of providing travel times competitive with air travel by making deep cuts in ground access and airport terminal waiting times.

The four-state area of Iowa, Kansas, Missouri, and Nebraska lost about 5,000 railway mi in the 1980s. These system changes are described in detail by Maze et al. Changes in the agricultural industry, major railroad mergers, bankruptcies, and reorganizations are identified. Network rationalization, public assistance programs, and intermodal facilities developments are also assessed. Expected trends for the 1990s are identified.

The final two papers concern track condition and loading. The U.S. Army Construction Engineering Research Laboratory in conjunction with the University of Illinois developed condition indexes for rail, joint, and fastenings; ties; and ballast, subgrade, and roadway component groups. An overall composite condition index for railroad track, as a whole, was also developed. Uzarski et al. describe the development of these condition indexes for low-volume railroad trackage.

Using an analytical dynamic wheel/rail and track interaction model, Raymond and Cai examine the effects of heavier axle loads and faster speeds on the increase of wheel/rail forces, rail seat loads, and ballast/subgrade pressures. The axle loads input include those of typical 50-, 70-, 100-, and 125-ton cars complete with unsprung masses. Also included is a projection of what might be expected in the future should 150-ton cars become acceptable.

Economic Benefits of the European High-Speed Rail Network

ROGER J. ALLPORT AND MARK BROWN

Amid growing business opportunities and major social change, an extensive high-speed rail (HSR) network is being developed to link the main cities of the European Community. In addition to providing an alternative mode for intercity travel, the 24 000 km of new and upgraded HSR track will facilitate and support major social and economic change. A conventional economic evaluation of this network has been undertaken using a coarse, strategic multimode model and quantifying time and operating cost savings as measures of economic benefit. An enhanced method for evaluating the economic benefits of the European HSR network is described. The focus of the method is the additional benefits that would accrue to business travelers. A survey of European companies revealed additional economic impacts, not so far considered in the evaluation of the European HSR network, that are perceived and valued by business travelers. An approach is developed to value the additional impacts and to incorporate them into the conventional economic evaluation of the HSR network. The results suggest that the additional impacts are potentially a significant source of economic benefits. It is probable that the application of this approach would identify substantial benefits accruing to nonbusiness travelers too. This has important implications for how the European HSR network is evaluated and priorities are set for its implementation.

A study, "Socio Economic Impact of the European High Speed Rail (HSR) Network," was undertaken for the Transport Directorate (DGVII) of the European Commission during 1991–1992. The study was undertaken by a group of consultants led by Halcrow Fox and Associates and including PA-Cambridge Economic Consultants, Leeds University Institute for Transport Studies, and Accent Marketing and Research.

The purpose of the paper is to describe and discuss one of the important findings of the study—that there are expected to be large and important "extra" economic benefits attributable to the European HSR network, which are not incorporated in a conventional cost benefit analysis (CBA). This conclusion follows from an analysis of the opportunities created by HSR and a survey of the likely responses of European businesses.

EUROPE IN TRANSITION

Change, Uncertainty, and Opportunity

Europe was defined for this study as the 12 states of the European Community (EC). It represents one of the largest concentrations of population and wealth in the world, with a population of 330 million—the largest grouping after China and India, and an economic output equal to that of the United States.

Moreover, Europe is in transition. With the completion of the Single European Market (SEM) in 1992, European businesses will have undergone or face profound change:

- Many companies have been reappraising and changing their European branch plant structure. New production plants are being established closer to major markets, particularly markets where growth is expected to be most rapid. In some cases plant restructuring is reducing the number of plants to take advantage of scale economies.
- A geographical widening of suppliers is occurring, and new trading relationships are being established with much less reliance on indigenous suppliers. At the same time, the number of suppliers is being reduced, particularly where small firms are involved.
- Intensifying competition is giving a renewed impetus to the forging of transnational alliances, coalitions, acquisitions, and other forms of collaboration. In many cases relationships mature to become full mergers.

These trends will be strengthened by the expected development of a single financial system across Europe incorporating a common currency and a central European bank. Recent developments in Eastern Europe are already having a profound impact on the EC, and there is much uncertainty about the outcome. The future for Europe is, in summary, characterized by dynamic change, uncertainty, and opportunity.

Transport is at the heart of this transformation, impeding or facilitating the free exchange of goods and services and central to the prospects for environmental change, for better or worse. It is against this background that transport policy should be viewed.

HSR Operating Environment

The impact of HSR will depend substantially on the future socioeconomic environment and on the policy environment in which it operates. The study adopted a "best estimate" for the socioeconomic environment, with economic growth averaging 2 to 3 percent per year, an increasing response to the SEM, and urban restructuring trends leading, for example, to the relocation of some service activities in the central districts of the largest "world" cities and in attractive smaller

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cities with qualified work forces and good access to major metropolitan areas.

The main study analysis adopted a Pragmatic Policy scenario, consistent with the available demand forecasts and similar to recent or existing policy. In the scenario there is little attempt to manage road and air demand by pricing, and, increasingly, infrastructure provision fails to keep up with demand. Growing congestion by road and air are the result. In this scenario rail "takes the strain" in a situation that approaches crisis for all EC travelers.

The implications of a strong Policy-Led scenario are also analyzed. Here there is convergence of national fiscal, subsidy, and competition policies; transport tariffs/prices are set to reflect social—including environmental and congestion—costs, and private-sector resources are mobilized to increase infrastructure provision and develop services more responsive to demand. Here too rail takes the strain as road and air tariffs/prices rise relative to rail.

Table 1 gives the important impacts of these scenarios on tariffs and congestion levels on Europe's transport system.

EC Transport Policy

The interplay of EC and national policy influences Europe's transport sector. In recent years EC policy has taken great strides forward and provides the direction for future change. The commission has produced railway and civil aviation policies (*1*,*2*) and will shortly produce an overall transport policy document.

Railways

The main components of EC railway policy are as follows:

- Provision and access to the EC railway infrastructure: The freedom of access to national railway infrastructure should be offered to any authorized rail transport operator. International companies should have transit rights.
- Infrastructure ownership: Member states should authorize national undertakings to own and operate infrastructure under clear conditions. The railways should pay for facilities on a basis equivalent to other modes of transport.
- Railway undertakings: Member states should lay down the requirements for the continuation or establishment of authorized railway transport or infrastructure operators, in particular ensuring their autonomy, independent management, technical ability, and adequate financial structure.
- Public railway undertakings: Member states have to provide for the institutional, economic, and financial restructuring of existing public railway undertakings, creating the conditions for their adaptation to the new situation.
- Infrastructure development: The EC should examine how different financial instruments could contribute to the achievement of high-speed network projects.
- High-speed services: The EC should promote their international development (notably a network of major axes).

The result is intended to be an efficient railway system, responsive to consumer choice and breaking down the barriers to the exchange of goods and services.

Civil Aviation

There is uncertainty about the pace and content of future change, but a plausible scenario is as follows:

- Competition between airlines will increase. Hub/spoke airports and interlining will become more common.
- However, tariffs will probably not decrease in general. The efficiency gains from deregulation and privatization will be offset by several factors: value-added tax, which will be applied but has not been hitherto; duty-free subsidies to airports, which will be removed; environmental levies; higher

TABLE 1 Impact of Scenarios on Tariffs and Congestion Levels on the EC Transport System[a]

Market/Scenario	Impact on Tariff by:			Impact on Congestion by:		
	Rail	Air	Car	Rail	Air	Car
Business Travel						
- Pragmatic scenario	+10%	+10%	+ 25%	+5%	+25%	+45%
- Policy led scenario	+30%	+70%	+110%	°	-10%[b]	-20%[b]
Non-Business Travel						
- Pragmatic scenario	+10%	+10%	+25%	°	20%	+25%
- Policy led scenario	+30%	+50%	+70%	°	-20%[b]	-20%[b]

a relative to existing tariffs and congestion levels

b traffic generation will take up some of this 'spare capacity' landing charges for increasingly scarce landing slots; and increased security costs.

- There will be continuing substantial increases in demand. The increase has been 10 percent per year during the last 2 years.
- There are a number of possible constraints on future air transport growth. Air traffic control problems are not intractable and will not be a major problem once planned European improvements are in place. Runway and terminal capacity will be a very serious constraint on air transport growth. At the five or six main hub airports in Europe there will be substantial congestion, with pricing to allocate available slots.
- There is no evidence that city center airports (like London City) will develop. The demand is not there to provide a reasonable frequency except for a very few movements (London to Paris, Amsterdam, or Frankfurt, for example), and environmental controls will constrain this.

Demand Context

The introduction of HSR is taking place against a background of rapidly growing demand by all modes (Table 2).

Car dominates the interregional travel market in Europe, whereas air has only a small market share. A small modal shift from car to HSR will therefore increase HSR demand markedly, whereas a similar shift from air will have a much smaller impact.

Rail patronage is forecast to increase substantially by 2015: up 80 percent in the "base" and 140 percent with the complete HSR network. But in the absence of HSR the market share of rail will decline by around 30 percent. The introduction of HSR will preserve this market share at around the present level.

The economic importance of HSR depends on its impact on a small proportion of business travel. Experience in Europe from other sources helps understand the behavior of this market:

- Business travel by rail is closely related to the performance of the economy, typically with an elasticity with respect to gross domestic product of 1.5.
- The most important variable for HSR is the journey time elasticity. Whereas published evidence on the elasticity of interurban rail demand to journey time is limited, an elasticity of about −1.3 is typical.
- Whereas journey time is undoubtedly the most important variable affecting mode choice, business travelers' behavior is influenced by other factors, particularly frequency, through services, and reliability. Moreover, although it is sometimes said that prices do not matter to business travelers, and although this might be true of the travelers themselves, it is certainly not true for their companies or travel managers.

HSR IN EUROPE

The study looks forward 20 to 25 years to 2015, about the time the European HSR network is targeted for completion, and assesses how economic and social activity will be affected compared with a base situation in which no HSR lines are completed beyond those now under construction.

Base Network and Completed HSR Network

Figure 1 shows the HSR network that was proposed to the commission in the report of the high-level group (*3*). It also identifies the lines under construction that are incorporated in the base network for the study: Britain, London to Edinburgh; Spain, Madrid to Sevilla; France, Paris-Lille-Calais-Dover, Paris-Tours and Le Mans, and Paris-Lyon-Valence; Italy, Roma-Firenze; and Germany, Hannover-Kassel-Wurzburg, Mannheim-Stuttgart, Hamburg-Hannover, Hamburg-Bremen-Munster, Dusseldorf-Hannover, Dusseldorf-Kassel, Frankfurt-Fulda, and Frankfurt-Mannheim.

Already HSR has had a major impact in Europe. The Paris-Lyon TGV, running for 10 years, carries 90 percent of the

TABLE 2 Increase in EC Interregional Passenger Demand, 1987–2015[a] (millions of passengers) (*8*)

Mode	1987		2015 Base [b]			2015 Complete HSR [c]		
	No.	%	No.	%	% increase	No.	Network %	% increase
Car	2750	(79)	7650	(84)	+180	7400	(81)	+170
Bus	150	(4)	300	(3)	+100	300	(3)	+100
Air	150	(4)	400	(4)	+170	350	(4)	+130
Rail	450	(13)	800	(9)	+80	1100	(12)	+140
Total	3500	(100)	9150	(100)	+160	9150	(100)	+160

a Pragmatic Policy Scenario

b Defined as the complete HSR network excluding 14 cross-border 'missing links' (reference 3)

c Figures exclude traffic generated by the introduction of HSR.

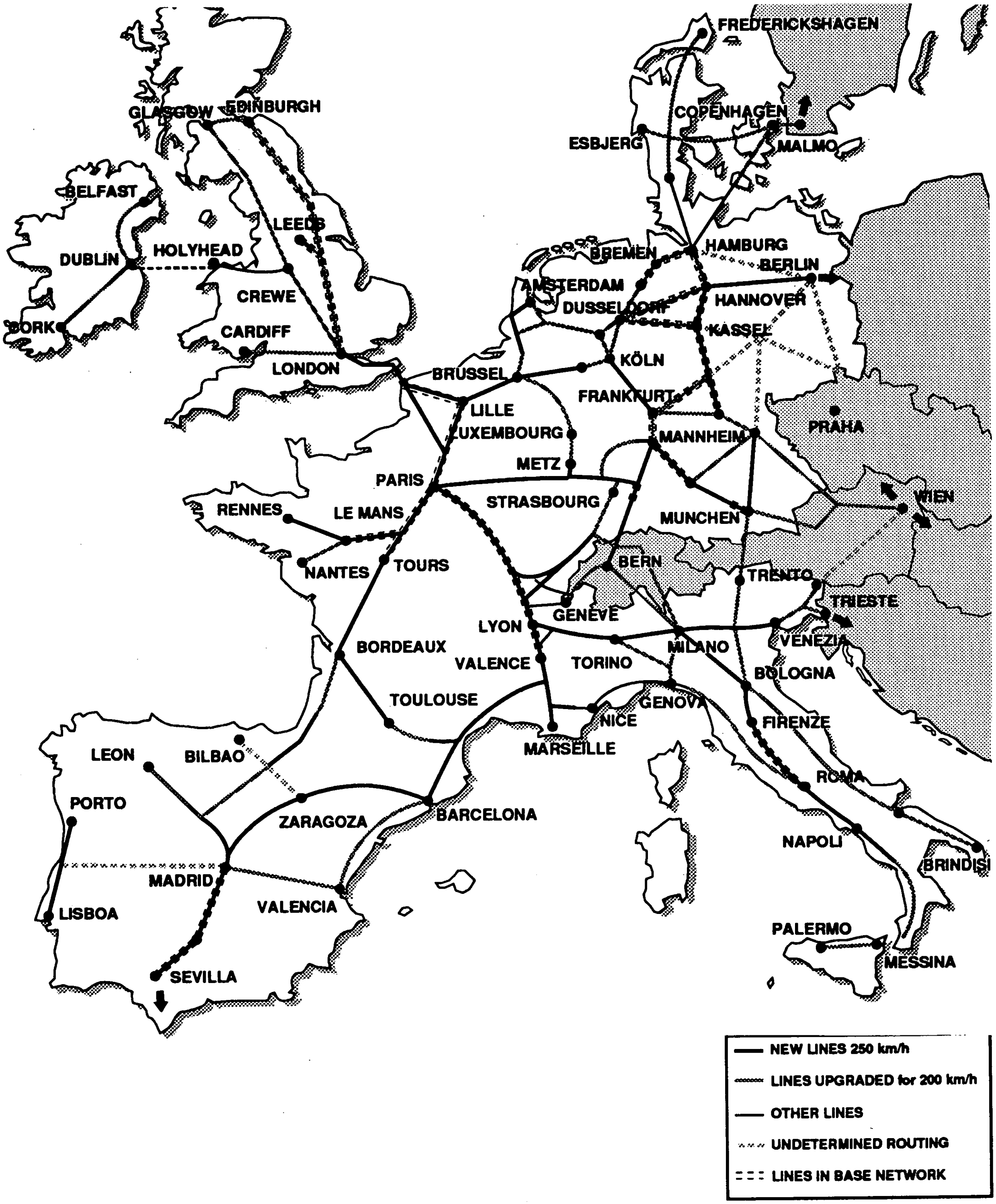


FIGURE 1 HSR network.

public transport market (air carries just 10 percent) and achieves the 427-km journey in just 2 hr. Half the trips were newly generated, one-third were air passengers, and one-sixth were car occupants.

The integrated European HSR system comprises a 24 000-km network, including 9000 km of new track and 15 000 km of upgraded track. It would permit international trains traveling at speeds between 200 and 350 km/hr to link Europe's major cities.

Technical Harmonization

In this study the fully integrated HSR network is assumed to be implemented, accommodating through-running services across all national frontiers. No operational constraints imposed by different rail technologies are assumed. This is a major assumption that deserves comment.

The Short Term

In the next 5 years or so the proliferation of different technologies in train control systems will move the national railways further away from technical harmonization. The implications for through running of international HSR services are that the next generation of rolling stock will need to be multivoltage and multisignaled.

In terms of types of high-speed service that will be offered, the diversity of on-board equipment required will almost certainly limit international services to a few key corridors where demand is sufficient to justify the expenditure and complexity of the train equipment. This is likely to be to the detriment of international services between provincial centers off the main high-speed trunk network.

Longer Term

In the longer term the trends toward greater integration and harmonization among Europe's industries and the forging of closer links between the peoples of Europe, coupled with congestion and capacity problems for competing modes, are expected to lead to a significant growth in both the volume and the geographical spread of demand for HSR travel. This should help provide the financial impetus toward achieving, if not full technical harmonization, at least a significant degree of harmonization, enabling high-speed trains from one country to operate over the tracks of another part of the EC.

In technical terms the main contribution to this is likely to be the trend toward greater portability of train control equipment, leading in time to the widespread use of radio-based on-board train signaling. By progressively freeing the railways from the need to install expensive cabling and trackside equipment when they expand their HSR network, high-speed services may be able to achieve greater market penetration at lower cost by using conventional tracks (subject to any other technology constraints). This may not become widespread for 15 to 20 years.

IMPACT OF HSR ON EUROPEAN BUSINESSES

Access to Business Opportunities

The results of accessibility analyses carried out for the study indicate that the completion of the HSR network would create significant new opportunities for individuals and organizations to participate in business activities. The opportunities, or accessibility benefits, are generated from two principal sources: (*a*) a reduction in journey times, particularly below certain critical thresholds, and (*b*) the linking of population centers within a single HSR network, thereby increasing the potential market area that can be served from a given location.

Journey Time Reductions

Benefits to businesses are most likely when day trips become possible, implying one-way door-to-door journey times of under 4.5 hr—typically 3 hr on the train in the case of rail travel, or 1 hr on the plane for air travel. HSR would bring about considerable reductions in rail journey times below this threshold, thereby creating new opportunities for day-return business trips.

Significant travel time reductions below the 4.5-hr threshold would take place on densely populated corridors throughout the EC, but this impact would be especially great in the "core" area of the Northern States (an area bordered by London, Amsterdam, Dusseldorf, Koln, Stuttgart, and Paris—see Figure 1).

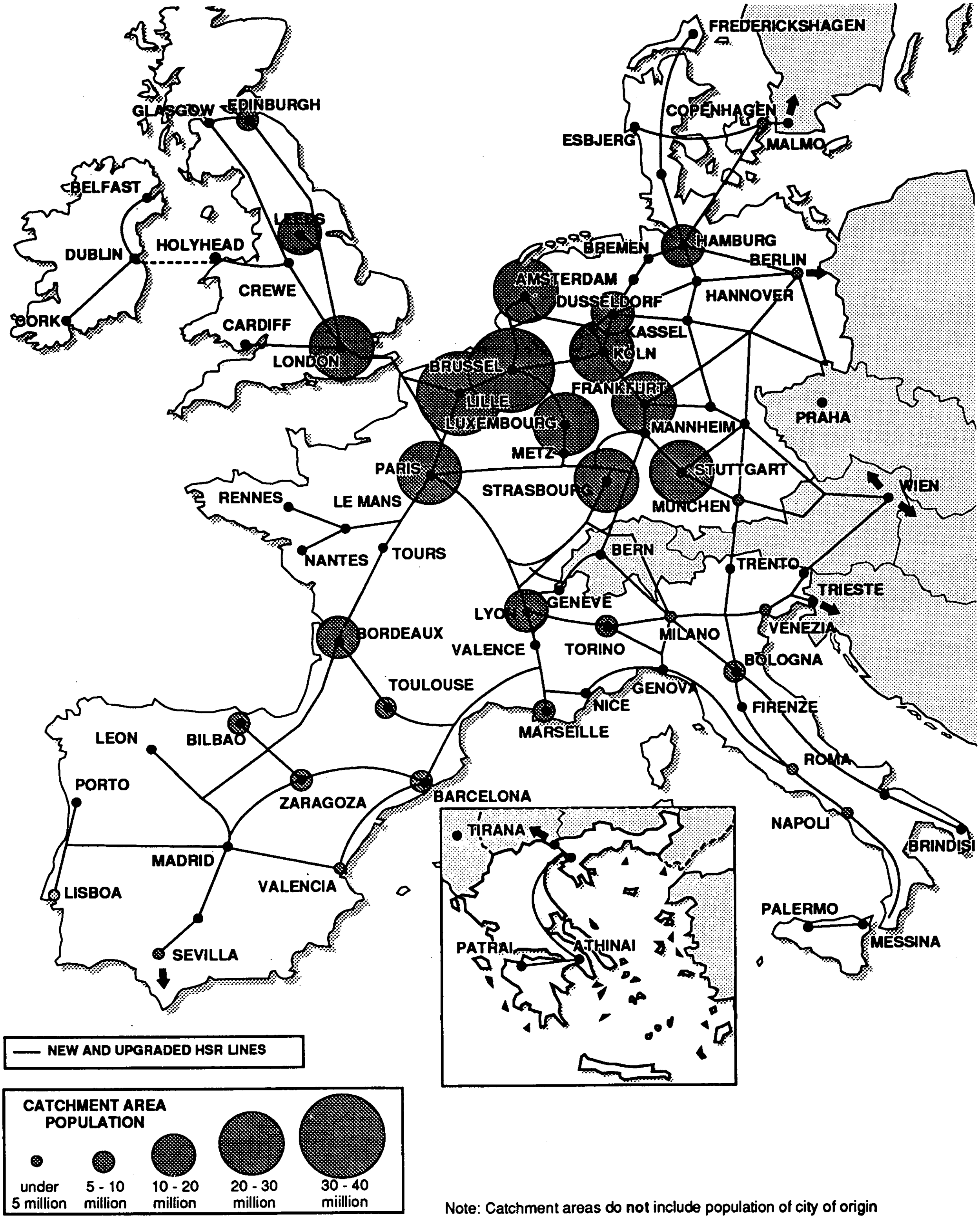
Catchment Area Increase

The introduction of an integrated HSR network would result in very large increases in the urban population catchments of many European cities. Figure 2 shows the rail population catchment of cities within 4.5 hr (door-to-door) of travel by HSR.

Increases in population catchments would be particularly great in the core area of the Northern States. The population (and markets) accessible by HSR from major conurbations in this area would compare favorably with those currently reached by air within a similar 4.5-hr (day-return threshold) travel time.

The greatest relative change in accessibility due to HSR would take place in smaller cities (those with a population of around 1 million or less) rather than in the larger conurbations. For example, Strasbourg, which is located on the border of France and Germany (population 400,000), would experience a 540 percent growth in its rail population catchment from 6 million to 28 million.

There are two sources of these accessibility benefits: (*a*) smaller cities are not so well served by air, with few and infrequent flights, whereas HSR would provide a minimum 2-hr service frequency, and (*b*) the time required for access to and egress from the HSR network in smaller cities is very low, both in comparison with access times for airports and those of rail stations in major cities, hence door-to-door travel times are reduced.



Note: Catchment areas do not include population of city of origin

FIGURE 2 City population catchments within 4.5 hr of travel by HSR.

Changes in levels of accessibility indicate the extent to which new opportunities for business activities will emerge from the introduction of HSR. The extent to which European business travelers are likely to perceive and exploit such opportunities and the resultant economic benefits are described below.

Business Responses to HSR—Additional Sources of Economic Benefit

In-depth interviews were carried out with senior executives of more than 50 major European business corporations. In addition, postal questionnaires were distributed to more than 6,000 smaller enterprises. The results of these surveys have revealed the perceptions of business people toward travel by HSR and its potential benefits.

In particular, the surveys have identified impacts of HSR that have implications for business efficiency (that is, that reduce the opportunity cost of travel or for which a willingness to pay can be deduced).

Nine journey attributes have emerged from analysis of the survey results that would be perceived by business executives as either "relevant," "important," or "of critical importance" in the decision to travel by HSR. Clearly the benefits of HSR go well beyond the gains from higher speeds alone. In order of declining importance these are time saving (the most important), ability to make outward and return journeys on the same day, reliability, proximity of rail terminus to trip origin/destination (access time), service frequency, perceptions of safety, price, comfort, and opportunity for in-travel work.

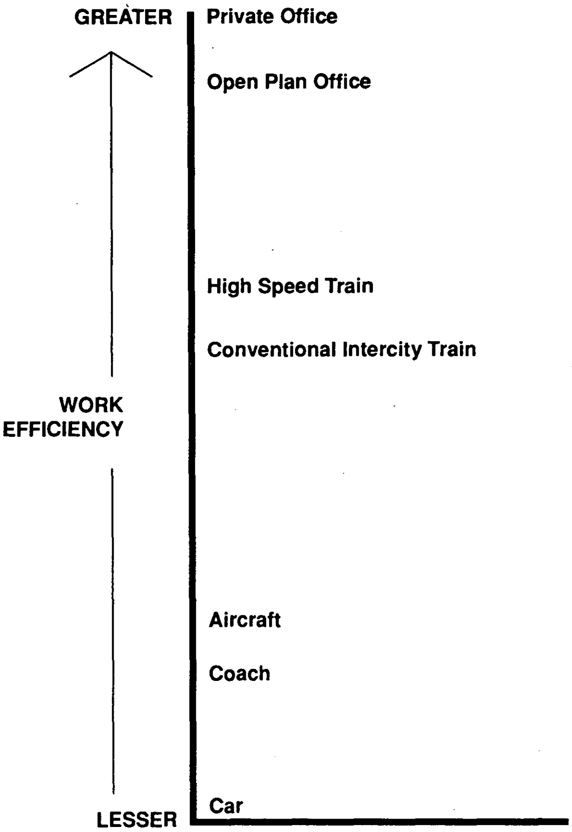
Attributes that appear to have been formally included in the demand forecasts and conventional evaluation of the European HSR network are time savings and price (a determinant of demand, and a transfer payment in economic evaluation). That the impacts of the remaining attributes appear not to have been formally incorporated in demand forecasts or valued provides the basis for this paper. To the extent that these attributes result in increased demand (service frequency, access time, and the facility for day-return trips will each have this effect) and economic output, they should correctly be incorporated in economic evaluation. To the extent that large extra benefits result, they should be center-stage in decision making.

In-Travel Work Capacity

HSR will provide a comfortable, spacious, well-equipped, and undisturbed environment in which to work. The creation of greater opportunities for productive work while traveling will thus reduce the opportunity cost of travel for passengers who transfer to HSR. Figure 3 shows the hypothetical levels of work efficiency associated with different environments.

Whereas the levels remain to be empirically tested, Figure 3 illustrates the point that the work efficiency of HSR passengers is likely to be considerably higher than that of air, coach, and car travelers. It may well be higher than on conventional trains.

Furthermore, passengers who transfer from air and car to HSR not only benefit from improved work efficiency, but also from being able to work for a greater proportion of their journey. HSR passengers spend more time on board the vehicle and less time accessing the terminus and checking in than air travelers.



Note: these are hypothesised, illustrative figures

FIGURE 3 Working efficiency in different environments.

Another of the additional six attributes of HSR is increased comfort. This may have similar connotations for business travelers as the opportunity for in-travel work, and attempts to value each separately could result in double counting. In the absence of more detailed research, it is prudent to regard them as having the same efficiency impact.

Access Time Saving Between Plane/Train and Origin/Final Destination

HSR passengers spend most of their door-to-door journey on the train, whereas short-haul air travelers spend up to 75 percent of total travel time going to and from the airport; negotiating check-in, security, and various other procedures; and walking up to 1 mi through the airport terminal to the aircraft. Research has found that passengers place different values on an equivalent time saving, depending on whether it is saved while on board the main mode of travel (HSR train/plane) or while accessing the vehicle (walk/interchange/wait time, etc). This reflects the higher level of stress and reduced comfort associated with travel between the main transit mode and the trip origin or destination (*4*). Passengers who transfer from air to HSR will experience a significant benefit from a reduction in this total access, check-in, and wait time and are likely to be willing to pay a premium for the saving.

New Opportunities for Day-Return Trips

One of the main impacts of HSR will be to provide business travelers with the opportunity to make a return trip within a single day. In the absence of HSR, some would be compelled to make an overnight stay before completing their trip. Passengers who transfer from the car mode, together with existing rail travelers, all stand to gain.

The benefit to travelers is likely to go beyond that represented by the net travel time reduction (which is represented in a conventional CBA). By making a return trip within the same day, business travelers release the whole of the following day for alternative, productive activities and are able to spend the night at their home rather than in a hotel. There will be a willingness to pay for the utility gains from both impacts.

Higher Service Frequencies

The frequencies of HSR services are likely to be consistently high throughout the network, and a minimum headway of 2 hr is likely to be achieved throughout a 16-hr operational day. This contrasts with air services, which only achieve a comparable frequency on shuttle operations between major city pairs.

Service frequency affects business efficiency through changes in the defer time of travel, that is, the difference between the preferred and the scheduled travel time.

Greater Service Reliability

In 1989, 24 percent of short- and medium-haul flights in Europe were delayed by more than 15 min (*5*). This risk of delay represents a significant increase in the opportunity cost of air journeys to the business traveler. Moreover, it is unlikely that reliability of air services will improve, with projections by the Association of European Airlines suggesting that 11 of the 46 major airports in Europe will exceed their runway capacities and 17 their terminal design capacities by 2000 (*6*).

In contrast, HSR travelers should, because of the greater operational reliability of rail systems, experience no systematic service delays (i.e., more than 15 min) on a consistent basis. Hence, air passengers who transfer to HSR should experience significant benefits, both from real reductions in delay and from reduced risks of delay.

ECONOMIC BENEFITS OF HIGH SPEED RAIL

Conventional CBA

A conventional CBA of HSR in Europe has recently been carried out elsewhere on behalf of the European Commission. It considered the economic impact of constructing 14 key HSR lines across national borders, thereby linking the isolated national networks and forming a pan-European HSR system. The conventional CBA evaluated the following impacts: net travel time savings to travelers, operating cost savings to operators of the transport system, rolling-stock costs, and infrastructure capital costs. Standard economic values for unit travel time and operating cost savings were drawn from previous CBAs within Europe.

Demand forecasts were derived using a four-stage transportation model from which the diversion of passengers to HSR from other modes (car, bus, air, and conventional rail) could be estimated. The model also provided estimates of the total travel time and operating cost savings due to HSR.

Enhanced Evaluation

The conventional economic evaluation of the 14 international HSR links, outlined above, was repeated using an enhanced evaluation framework.

Identification of Impacts

The enhanced framework incorporates traditional economic impacts (travel time savings, operating cost savings, accident cost savings, and capital and maintenance costs) along with the five additional quality impacts experienced by business travelers. Table 3 summarizes them and describes the nature of the efficiency gain generated by each.

Prediction of Impacts

The enhanced evaluation has not involved new demand modeling. The prediction of the magnitude of the additional impacts on business travelers has relied entirely on the travel forecasts used in the conventional CBA. Relevant information was abstracted on the number of passengers who transfer from car, coach, and air to HSR following completion of the cross-border key links. It is likely that the data underestimate the true diversion to HSR because the five new quality impacts are not represented in the demand models.

Valuation of Impacts

The valuation of the additional economic impacts relies on somewhat less conventional techniques than those used in a traditional CBA of infrastructure investment. Whereas the valuation techniques used have a sound theoretical basis, the unit values do not always have the advantage of empirical validation. It has been necessary to make assumptions based largely on economic valuation research into domestic intercity or urban travel (*4,7*). Values are expressed in constant 1990 U.S. dollars, converted from Ecus at the rate of $1 U.S. = 0.725 Ecu.

The following values of time, consistent with previous CBAs for the European Commission, have been used: work time,

TABLE 3 Additional Economic Impacts on Business Travelers

ECONOMIC IMPACT	BENEFITTING GROUPS	SOURCE OF BENEFIT	EFFICIENCY GAIN
(1) In-travel work capability	ex. car passengers ex. air passengers	Creation of greater opportunities for productive work whilst travelling	Reduced opportunity cost of travel
(2) Access time saving	ex. air passengers	The value of one hour saved travelling between home/office and plane/train is greater than a similar saving whilst on board the plane/train	Willingness to pay premium for a reduction in access time.
(3) New opportunities for Day Return trips	ex. car passengers ex. rail passengers	Reduction in journey times below the threshold that permits return trips within the same day	Willingness to pay to spend evening at home/whole of following day available for productive activities.
(4) Higher service frequencies	ex. air passengers	Significantly higher HSR frequencies on certain routes compared with air	Reduced opportunity cost of travel due to lower defer time.
(5) Greater service reliability	ex. air passengers	Greater reliability of scheduled HSR sercices compared with air	Reduced opportunity cost of travel due to lower risk of delay.

$39.70/hr; nonwork time, $9.90/hr. The approach to valuation is as follows.

For in-travel work capability,

- Benefits accrue to all business passengers who transfer from car and air (information currently available does not enable a firm conclusion to be drawn on whether existing rail passengers also benefit);
- The benefits arise from a combination of two factors: extra time during which work can be undertaken and higher productivity of work that is carried out;
- Car travelers benefit from 100 min work time per trip, air passengers by an extra 60 min (this recognizes that passengers spend a larger proportion of HSR journeys working and that the average in-vehicle time is longer on HSR trips); and
- The value of this additional in-travel work time is assumed to be $13.80/hr. This is a conservative estimate, which recognizes that whereas HSR passengers may achieve a high level of productive efficiency, the time "saved" may not necessarily be devoted to work activities. This would benefit from empirical clarification.

For access time savings,

- Benefits accrue to all business passengers who transfer from air;
- Access time savings take account of travel to the airport/HSR station, wait times, interchange and check-in times, and egress time from the airport/station to the final destination;
- Access time savings for each city are weighted by the city population in order to develop a mean time saving per person for each major urban center;
- The mean weighted access time saving between air and HSR is 51 min per trip; and
- The value of this saving is estimated to be $8.40/trip.

For opportunities for day-return journeys,

- Benefits accrue to business travelers who divert from car and to rail passengers;
- Estimates of the number of travelers to benefit are based on trip length distribution data, which identify rail journeys reduced below a 4.5-hr travel time threshold; and
- Valuation of the benefit considers the willingness to pay to spend an additional evening at home or to have a complete day in which to schedule business activities following the day-return trip (the net time saving is already included in the conventional CBA). A value equivalent to 4 hr of nonwork time (i.e., one evening) or 1 hr of work time, $39.70, is assumed.

For higher service frequencies,

- Benefits accrue to passengers diverted from air;
- 75 percent of these passengers are estimated to benefit from significantly higher frequencies than would be achieved on the alternative air services;
- Excluding air services between major cities, which enjoy relatively high frequencies, the mean frequency per air route is estimated as 2.5 flights per day. The associated mean defer time is 1 hr per flight; and
- The value of defer time is assumed to be the average value of work time previously used in studies for the commission ($39.70/hr). Thus the average benefit per passenger is $39.70/hr.

For greater service reliability,

- Benefits accrue to passengers who divert from air;
- 24 percent of air passengers are delayed by an assumed average of 25 min ("at least" 15 min) per trip; and
- The value of this delay, per passenger, amounts to $16.60.

Evaluation Results

The benefits from these five economic impacts are summarized in Table 4. Net Present Benefits (NPBs) are discounted over 30 years and are expressed in constant 1990 dollars.

The total additional efficiency benefits to business travelers amount to an extra U.S. $35.3 billion. This represents an increase in NPB over that of a traditional CBA of 25 percent.

When the additional business traveler benefits are combined with the results of the conventional CBA, the additional benefits more than double the NPV of the HSR network, and the benefit-cost ratio of the HSR network increases from 1.3 to 1.6.

Implications

These results have great significance for a number of reasons. First, they indicate that the economic benefits of HSR are much greater than was originally thought. Second, they demonstrate that these wider economic benefits can be quantified and evaluated in monetary terms. Third, they suggest a broader approach to the evaluation of HSR projects, which could be developed into a standard appraisal methodology for such schemes.

The additional efficiency benefits reflect a general improvement in the quality of travel. They are likely to have a direct economic impact on the performance of European businesses and their staff.

Furthermore, it is likely that they represent minimum levels of benefit. First, the extra impacts of HSR are not reflected in the models used to forecast travel demand, and a conservative approach to valuation has, in the absence of empirical evidence, been adopted. Second, it is likely that, following further research, additional economic benefits to various categories of leisure traveler could also be identified and valued.

Whereas the evaluation is based on sound theoretical principles, further empirical work is required to establish empirical values. Because the majority of additional benefits accrue from the ability to make a day-return trip and from in-travel work opportunities, priority should be given to researching these impacts.

CONCLUSIONS

The European HSR network is being planned and constructed in a period of great change and growing business opportunities. The success of HSR will, in part, be determined by the extent to which it exploits and supports these opportunities.

TABLE 4 Summary Economic Evaluation of the HSR Network

(millions Ecus/$)

ECONOMIC IMPACTS	Costs/Benefits from traditional evaluation		Traditional Costs/Benefits + additional business traveller benefits	
	Ecus	$	Ecus	$
Travel Time Cost Savings (previous CBA)	84,000	116,000	84,000	116,000
Operating Cost Savings (previous CBA)	15,500	21,500	15,500	21,500
In-Travel Productive Time Benefits (New)	-	-	15,300	21,100
Access Time Savings Premium (New)	-	-	700	1,000
Day-Return Opportunity Benefits (New)	-	-	7,400	10,200
Service Frequency Gains (New)	-	-	2,500	2,500
Service Reliability Gains (New)	-	-	300	500
Infrastructure and Rolling Stock Costs (previous CBA)	(77,500)	(107,000)	(77,500)	(107,000)
Net Present Benefits (NPB)	99,500	137,500	125,700	172,800
Net Present Value (NPV)	22,000	30,500	48,200	65,800

All costs and benefits are discounted present values. Parentheses denote costs.

Completion of the network would create significant accessibility benefits for business travelers. Most important among these would be the many new opportunities to make return trips within 1 day, thus reducing the need for overnight stays.

The greatest relative impact of HSR is likely to occur in smaller cities rather than in the major metropolitan areas. These cities are less well served by air, with relatively few and infrequent flights, whereas the time required to access the HSR network is comparatively low.

Additional economic impacts of HSR that are not normally included within the investment appraisal of rail infrastructure have been identified. They are all perceived and valued by business travelers and relate to the enhanced quality of service provided by HSR. The addition of these new impacts to the travel time and operating cost savings estimated by a conventional CBA increases the NPB of the HSR network by 25 percent and doubles the NPV.

This finding has important implications. The CBAs of the European HSR network carried out to date, based on travel time and operating cost savings alone, are unlikely to be an appropriate basis for appraising the full range of impacts of this new transport mode. Rather these other, quality factors will improve decision making: in determining the value for money viability of HSR, in setting priorities for implementation, and in system specification and design.

ACKNOWLEDGMENTS

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Rail Ridership, Service, and Markets in the Keystone Corridor

John A. Dawson

During the 1980s ridership on Amtrak's Keystone trains between Philadelphia and Harrisburg declined by 67 percent. The reasons for the decline and the changing market for rail travel in the corridor are discussed. Whereas service cuts, increased travel times, and higher fares undoubtedly played a role, patronage shifts to an expanding local (Southeastern Pennsylvania Transportation Authority) service on the eastern end of the line also had a significant effect. Amtrak's markets were analyzed and segmented by geography and time of day. In 1983, when all local Philadelphia service terminated at Paoli, 48 percent of Amtrak passengers were traveling only on the eastern portion of the line (Philadelphia to Parkesburg), but by 1990 this share had declined to 16 percent. During the same period the share of trips between the Philadelphia area and Lancaster or Harrisburg increased from 48 to 78 percent. Most of the regular Amtrak commuters to Philadelphia are now coming from Lancaster County, which is beyond the reach of local service. These indications are all consistent with the conjecture that a patronage shift has occurred. However, this raises the questions of whether markets on the western end of the line (Lancaster and Harrisburg) are adequately served and what the proper role for Amtrak in the corridor is. One or two new stations would help tap a growing market in eastern Lancaster County. In addition, it may now make sense to restructure the service by transferring operation of the Keystone trains to a state or regional agency.

Philadelphia-Harrisburg passenger trains, collectively named the Keystone Service, have been operated by Amtrak since 1971 with financial assistance from the Commonwealth of Pennsylvania. The service was originally part of an extensive network of passenger trains operated by the Pennsylvania Railroad (PRR) and was continued by the Penn Central Railroad after it was formed from the merger of the PRR with the New York Central in 1968. Before the Amtrak takeover in 1971, service to Harrisburg consisted of 10 weekday trains, 8 Philadelphia-Harrisburg trains supplemented by 2 long-haul trains, in each direction. As of early 1992, service consisted of seven weekday trains in each direction [six local trains plus the Pennsylvanian (New York–Pittsburgh)] and five on weekends and holidays. Only trains with traffic rights between Philadelphia and Harrisburg are counted. Information in this paper is current to May 1992.

As recently as 1980, more than 1 million passenger trips per year were carried by the Keystone trains, but throughout most of the 1980s ridership fell steadily, reaching 317,000 in 1989. Several reasons for the loss of ridership have been suggested, including service cuts, patronage shifts to an expanding local service operated by the Southeastern Pennsylvania Transportation Authority (SEPTA) on the eastern end of the line, and changing markets for rail travel. The quality of service and less-than-inspired marketing have also received their share of the blame.

This paper examines some of the reasons for the ridership decline, the changing market for rail travel in the corridor, and the resulting impact on ridership since 1980 and suggests institutional changes that could place the service on a sounder footing. It is part of a larger study that the Delaware Valley Regional Planning Commission (DVRPC) conducted for the Pennsylvania Department of Transportation (PennDOT). In that study, DVRPC was asked to assess the condition of the line, examine service patterns and ridership, determine needed improvements, and explore management and operational options for improving the service. Technical assistance was provided by R. L. Banks & Associates, Inc.; Main Line Management Services, Inc.; LTK Engineering Services; and Canby Associates.

Amtrak serves 14 stations on the 167-km (104-mi) line between Philadelphia (30th Street) and Harrisburg. Trains use the Northeast Corridor for the first 2.3 km (1.4 mi) out of 30th Street Station and then diverge at Zoo Interlocking to head west. Figure 1 shows the line with stations and connections served by Amtrak. The PRR electrified the 32 km (20 mi) between Philadelphia and Paoli for local commuter service in 1915 and extended the electrification to Harrisburg in 1938 as a spur to its New York-Washington corridor. This permitted operation of the 600-series trains, as the Harrisburg locals are designated, into Penn Center Station in central Philadelphia, as well as through service to New York. (The underground Penn Center Station, also known as Suburban Station, provides better access to the heart of the city's office employment than does 30th Street Station, which is located west of downtown.) Though SEPTA uses electric propulsion for all of its trains, Amtrak's use of electric power is declining. Amtrak ceased operating the Keystone trains into Penn Center in 1988, terminating instead at 30th Street Station, and now all but the New York-Harrisburg trains routinely use diesel locomotives for traction power. Electric locomotives are used only as backup power. There is some concern about Amtrak's long-term commitment to maintaining electrification.

Two other Amtrak trains also operate in the corridor: the Broadway Limited between New York and Chicago and the Keystone State Express between New York and Harrisburg. The first does not have traffic rights within the range of interest, and the second does not stop at 30th Street Station in Philadelphia. Neither will be considered further in this paper.

In addition to the Harrisburg and long-distance trains, the PRR also operated local suburban trains oriented toward Phil-

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Delaware Valley Regional Planning Commission, 21 South Fifth Street, Philadelphia, Pa. 19106.

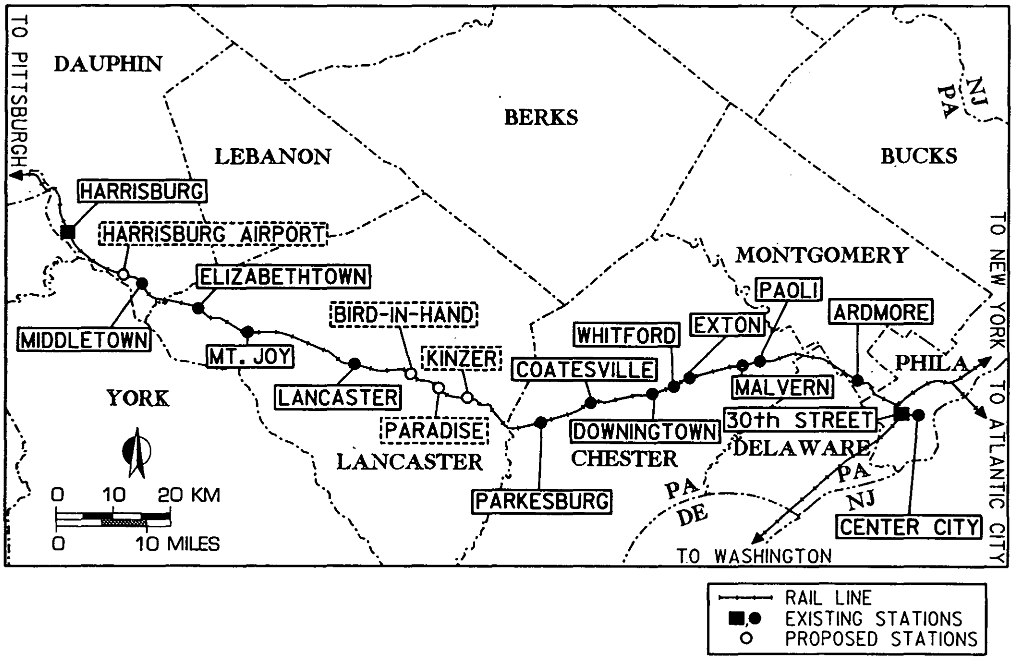

FIGURE 1 Philadelphia-Harrisburg rail line. Map shows stations and connecting lines served by Amtrak. Penn Center (Suburban Station) has not been served by Amtrak since 1988, though Amtrak tickets are honored on connecting SEPTA trains. Open circles indicate new stations proposed for eastern Lancaster County and Harrisburg Airport.

adelphia [milepost (MP) 0] at the eastern end of the line. Most of these trains used Paoli [MP 20 (32 km)] as their western terminus, though a few continued as far west as Downingtown [MP 32 (52 km)]. After SEPTA was formed in 1964, the PRR received a public subsidy to support operation of these trains. This arrangement continued under subsequent Penn Central and Conrail operation until SEPTA took over direct operation of the service at the beginning of 1983. SEPTA initially operated trains only as far as Paoli, but service to Downingtown was restored in 1985 and extended west to Parkesburg (MP 44) in 1990. Since 1984 SEPTA has designated this local service as Route R5.

Rail service in this corridor serves a number of travel markets. There are two separate commuter markets, one oriented eastward toward Philadelphia and the other westward toward Harrisburg. Since the line connects the state's largest city with its capital, a significant number of business trips are generated. Many members of the Amish community, who do not own automobiles and are centered in Lancaster County, rely on the train to meet their intercity travel needs. Several schools and universities are located within walking distance of stations, making rail travel easy for students and faculty. Discretionary markets include visitors to Philadelphia, Lancaster, and Harrisburg, as well as local residents needing access to the national Amtrak and airline networks.

AMTRAK SERVICE

Amtrak has published monthly reports of ridership by route since 1978. Ridership, service, and fare trends since 1980 for the corridor are given in Table 1. The years shown are fiscal years ending on September 30 of the indicated year. The values for service levels, average speed, and fares are those in effect on January 1 (winter timetable).

Frequency of service, travel time, and cost are important parameters affecting travel decisions, although other factors, such as service reliability and passenger comfort, are also clearly important. The ridership trend is shown in Figure 2. Generally the trend has been one of falling patronage, though ridership does appear to have bottomed in 1989. The first half of the decade showed an average annual loss of 6.2 percent, and in the second half the loss rate increased to 18.4 percent per year, notwithstanding the bounce back at the end. (These are statistical averages reflecting the slope of the best fit straight line drawn through the points and do not depend solely on the end points chosen.)

Changes in service levels since 1980 are shown in Figure 3. Longer-distance trains with traffic rights in this range were included, because they help attract riders to this market. The value given for daily round-trips represents a weighted average taken over 1 week and was obtained by counting the number of one-way trips (in both directions) made between Philadelphia and Harrisburg and dividing by 14. The largest single change occurred in January 1986, when Amtrak reduced the number of daily round-trips from 9.5 to 6.6 (from 11 to 7 weekday round-trips). This service reduction of 30.5 percent coincided with the steepest decline in ridership observed during the decade (45.3 percent from 1985 to 1987). At the same time, SEPTA reinstated commuter service to Downingtown at fares lower than those charged by Amtrak. This siphoned off some of the ridership to and from stations in Chester County west of Paoli.

TABLE 1 Amtrak Ridership and Service Trends

Fiscal Year	Ridership	Daily Round Trips	Avg. Speed (km/h)	Fare One-Way	Fare Round Trip
1980	1,024,700	9.7	92.7	$8.25	
1981	895,300	11.1	92.9	$10.00	
1982	815,600	11.1	91.2	$12.10	$20.30
1983	807,800	11.1	92.1	$13.75	$21.00
1984	741,747	9.4	93.2	$14.75	$22.50
1985	756,616	9.5	90.8	$14.75	$22.50
1986	578,595	9.5	89.0	$15.25	$23.00
1987	413,711	6.7	90.1	$16.00	$24.00
1988	349,806	6.6	89.8	$16.00	$24.00
1989	317,443	6.6	83.8	$16.50	$25.00
1990	334,963	6.6	83.7	$17.00	$25.50
1991	330,619	6.6	84.2	$17.00	$26.00
1992	305,222	6.6	85.8	$18.00	$27.00
Average Annual Change[a]					
1980-85	-6.15%	-1.69%	-0.24%	10.41%	
1985-90	-18.42%	-8.78%	-1.66%	2.69%	2.50%

[a]Average annual change was calculated by using trend analysis to determine the slope of the best fit straight line drawn through the relevant points. This was then converted to a percentage value by using the average of the annual values over the time span as a base.

Between 1980 and 1990, average speeds, as calculated from the scheduled time required to traverse the entire length of the line, declined by approximately 9 km/hr (5.6 mph). This reduction only adds about 10 min to the schedule, which by itself probably has an insignificant impact on ridership. However, average speed is also a measure of the condition of the track structure and the quality of the ride, and this affects the marketability of the service. Although Amtrak has upgraded some sections of track, in general, investment has not kept pace with depreciation.

Fares increased steadily during the same period, but the rate of increase slowed after 1984. Between 1980 and 1984 Amtrak raised one-way fares at an average rate of 15 percent per year, although the impact on ridership was moderated by the introduction of round-trip excursion fares (approximately 1.5 times the one-way fare) in 1982. Even so, ridership fell by 27.6 percent in the first 4 years of the decade. Since 1984, the rate of increase has fallen below the inflation rate, and at this point it probably has only slight effect on ridership.

Schedule reliability is shown in Figure 4. The graph is based on monthly averages of on-time performance for Keystone trains for the fiscal years 1985 through 1991. Though significant fluctuations from month to month are evident, the general trend indicates declining performance in the early years, reaching a nadir in November 1987. Performance improved markedly after schedule times were lengthened and has re-

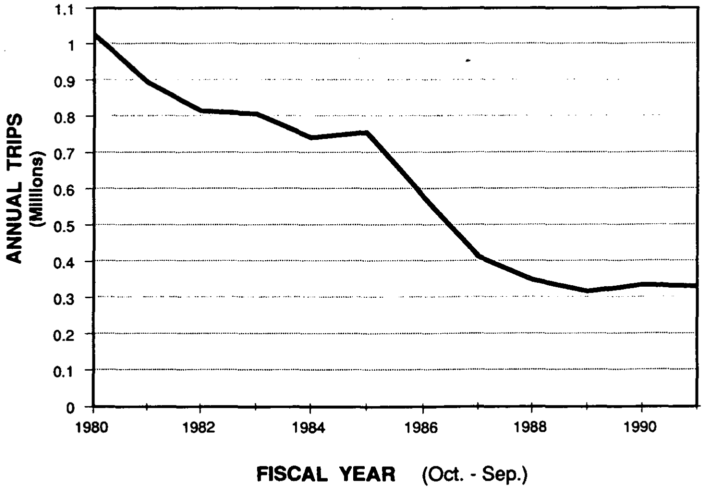

FIGURE 2 Annual Amtrak ridership reported for Keystone trains.

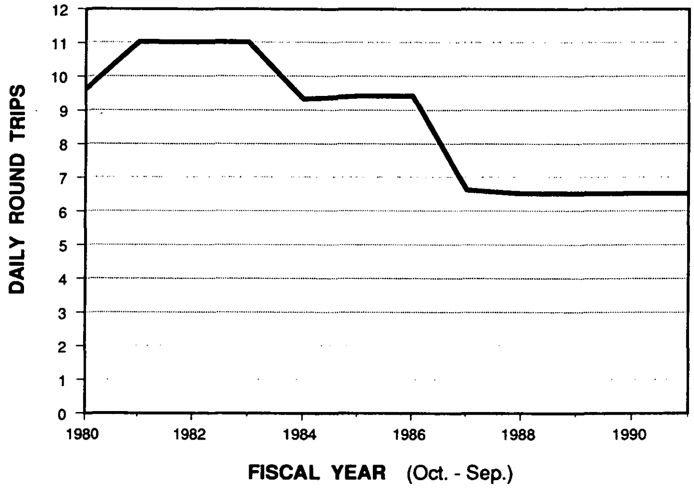

FIGURE 3 Average number of daily round-trips by all Amtrak trains operated on January 1 of indicated year. Trains without traffic rights in the corridor have been excluded.

mained on a relatively high plateau since. Consistency has also improved, with smaller fluctuations observed over the last 2 years. Currently, these trains rank among Amtrak's most reliable, achieving 95 percent on-time performance in most months.

LOCAL SERVICE

In 1980 Conrail operated a single weekday round-trip for commuters between Downingtown and Philadelphia under contract with SEPTA, which was discontinued when SEPTA took over direct operation of commuter trains in January 1983. For the next 2 years Amtrak was the only carrier providing passenger service west of Paoli. In March 1985 SEPTA reinstated service as far as Downingtown with two weekday round-trips. Service was subsequently expanded in stages, with midday and Saturday service added in 1988 and a route extension to Parkesburg introduced in April 1990. In spring 1992, SEPTA operated 13.5 round-trips beyond Paoli on weekdays. Most use Downingtown as their western terminus, with three trains traveling to/from Parkesburg. Figure 5 shows the trend for all trains combined. Only SEPTA trains running west of Paoli are included. Increases in SEPTA service have more than negated Amtrak's cuts for those traveling on the eastern half of the line on weekdays. However, SEPTA operates only as far as Downingtown on Saturdays, and there is no service west of Paoli on Sundays or holidays. For those traveling to Lancaster or Harrisburg or traveling on Sundays and holidays, the cut in Amtrak service is very real.

SEPTA's annual survey of regional rail riders provides data on station activity, which can be used to estimate ridership on specific line segments. Estimates of SEPTA ridership were obtained by totaling the passengers boarding or alighting at

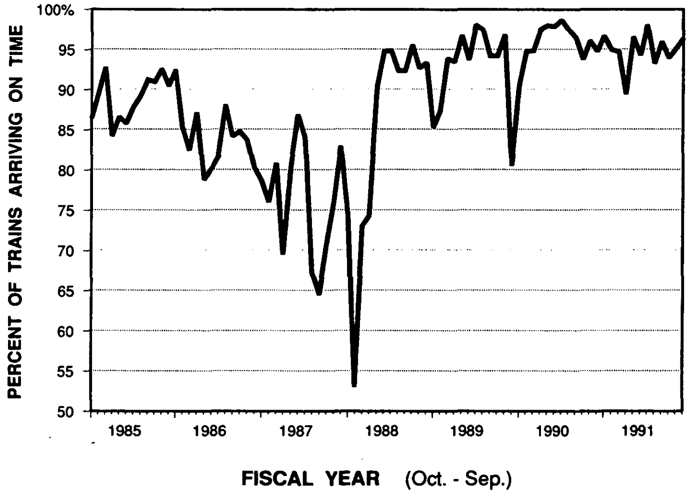

FIGURE 4 Schedule reliability—monthly percentage of trains arriving at their final destination within 15 min of scheduled time.

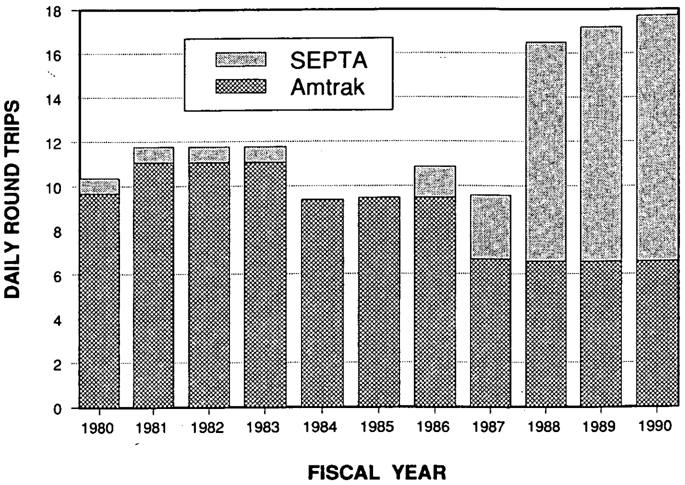

FIGURE 5 Total number of daily round-trips operated by Amtrak and SEPTA. Service is that in place on January 1 of indicated year and is averaged over the week. Only trains traveling west of Paoli are counted.

stations west of Paoli and using a factor of 254 to convert from average weekday to annual ridership. Figure 6 shows that though total ridership on the line has remained relatively constant, there has been a dramatic shift from Amtrak to SEPTA. Riders have responded positively to increases in service, and in 1990 SEPTA carried approximately 580,000 trips. This brings total line ridership to more than 900,000, the highest level since 1981. It appears that at least a portion of Amtrak's ridership decline can be attributed to passengers switching to a cheaper SEPTA service.

To test this conjecture, Amtrak's ridership was divided into ranges using origin/destination data available from the Amtrak Passenger Accounting System. Retrieving the data involved constructing a composite trip table from the microfiche records of three routes: Philadelphia-Harrisburg (Keystone), New York–Harrisburg, and New York–Philadelphia-Pittsburgh. Thus, the data include riders on long-distance trains, provided their trip is confined to the Philadelphia-Harrisburg segment, as well as those on the Keystone trains. To avoid the effort required to search 12 sets of monthly records for each year, September ridership was used to represent travel behavior for the year.

Results are given in Table 2. Range I comprises passengers whose entire trip lies within the Philadelphia-Paoli commuter territory. Range II counts riders who travel west of Paoli but who do not go beyond Parkesburg. Range III includes those on the western end of the line (Lancaster-Harrisburg), and Range IV encompasses passengers traveling between the eastern and western halves of the line (i.e., those traveling across the Chester-Lancaster county line). Riders whose entire trip lay east of Parkesburg constituted almost 48 percent of all Amtrak passengers on the line in 1983, but by 1990 their share

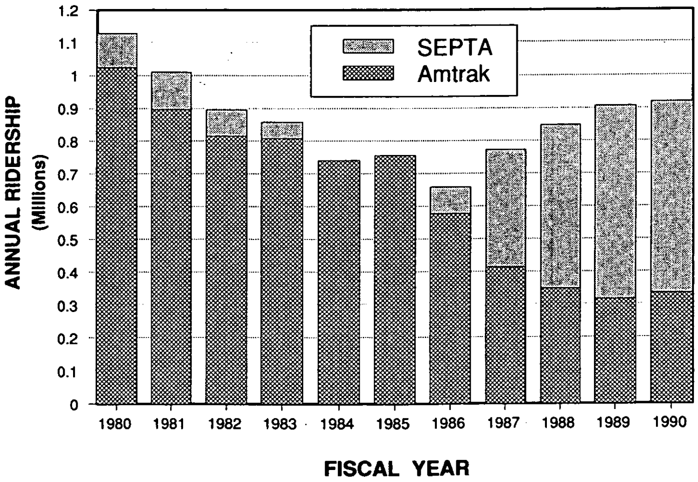

FIGURE 6 Total Amtrak and SEPTA ridership west of Paoli. Amtrak's fiscal year ends on September 30. SEPTA ridership was estimated from on-off station counts taken in October of the preceding year.

TABLE 2 Ridership Trends by Geographic Range

	Range Share[a]				
	I	II	III	IV	Total
Sep 1983	4.6%	43.2%	4.7%	47.6%	100.0%
Sep 1984	2.4%	27.7%	6.9%	63.0%	100.0%
Sep 1985	2.6%	29.6%	6.8%	61.0%	100.0%
Sep 1986	2.3%	28.4%	6.6%	62.8%	100.0%
Sep 1987	2.2%	19.4%	6.3%	72.0%	100.0%
Sep 1988	2.0%	16.4%	6.4%	75.1%	100.0%
Sep 1989	2.2%	14.3%	6.1%	77.4%	100.0%
Sep 1990	2.5%	13.5%	6.0%	78.0%	100.0%

[a] Ranges are defined as follows:
I - Philadelphia to Paoli
II - Philadelphia to Parkesburg, exclusive of Range I
III - Lancaster to Harrisburg
IV - Trips between Ranges II and III

had declined to 16 percent. In 1983, less than 48 percent of the line's business was for trips that crossed the Chester/Lancaster county line, but in 1990 these trips constituted 78 percent of the market. Local trips at the Harrisburg end (i.e., west of Lancaster) rose slightly, from 5 to 6 percent. It appears that Amtrak's market has indeed changed from one that handled significant number of local riders at the Philadelphia end to one that focuses on attracting through passengers traveling longer distances.

MARKET SEGMENTS

A detailed analysis of Amtrak ridership by train and by day gives some basis on which to segment the market, at least into broad categories such as commutation, weekday discretionary, and weekend trips, and by direction (whether oriented toward Philadelphia or Harrisburg). Amtrak's passenger accounting system provides detailed trip information for each train, though some assumptions must be made to account for passengers traveling on passes. A detailed analysis of ridership was made for the months of September 1983 and September 1990.

The Philadelphia commuter market is served by two weekday round-trips, which in September 1990 carried an average daily combined ridership of 257. The ridership never fell below 187 during the month. The latter number was used to estimate the size of the existing commuter market (round-trips) to Philadelphia, and anything above the minimum was assigned to the weekday discretionary market.

The commuter market to Harrisburg is served by two westbound trains in the morning, but only one eastbound in the afternoon. In 1990 these trains carried an average of 115 round-trips on weekdays. Following the same logic used for Philadelphia, the Harrisburg market was estimated at 81.

The discretionary market consists of the remaining riders during the rush hours plus those at midday and in the evening, properly sorted by direction. Trips destined to Philadelphia were assumed to be eastbound in the morning and westbound in late afternoon and evening, with the midday trips apportioned to provide balance. Trips in the reverse direction were assigned to Harrisburg and Lancaster. Lancaster is a significant travel destination, as well as an important origin, and now generates more Amtrak passenger activity than does Harrisburg. Average weekday discretionary round-trips were estimated at 152 toward Philadelphia and 138 toward Harrisburg.

For travel purposes the weekend starts at midday Friday and continues through Sunday evening. Since Friday is the heaviest travel day of the week, the excess above the weekday average was considered as part of the outbound segment for weekend trips. Trips taken on Sunday were assumed to be return legs, and Saturday trips were apportioned for balance. This methodology assigned 916 weekend round-trips to the market oriented toward Philadelphia and 1,064 toward Lancaster and Harrisburg.

The preceding analysis included neither one-way trips and trips with external origins or destinations nor round-trips that were not completed within 1 day or on a weekend. It did, however, provide a reasonable basis for a broad market segmentation and is supportable from the existing data base. It is also possible to analyze data from earlier periods to obtain information on market trends. Table 3 compares the 1990 markets with those found 7 years earlier in 1983. Since service and travel patterns repeat on a 7-day cycle, trips were tabulated on a weekly basis. Three trends are immediately noticeable. First, the market oriented toward Philadelphia declined from 73 to 57 percent of the total. Second, the commuter market declined from 42 to 35 percent. Third, weekend riders in 1990 made up 26 percent of the total, up from 15 percent 7 years earlier. These are all consistent with the conjecture that the expansion of local SEPTA service to Parkesburg has captured most of the short-haul market at the eastern end of the route.

Not all of the decline in Amtrak ridership can be attributed to the expansion of local SEPTA service. Although most of the decline occurred on the eastern half of the line, ridership oriented toward Harrisburg, which is not served by SEPTA, went down by 24 percent between 1983 and 1990. Reduced service certainly accounts for some of the loss, and this poses the core problem. A competing service captures a portion of the market served by a route and this forces a reduction in

TABLE 3 Ridership Trends by Market Segment

		1983		1990		
Orientation	Market Segment	Weekly One-Ways	Market Share	Weekly One-Ways	Market Share	Change 1983-90
Philadelphia	Commuter	5,230	32.5%	1,870	24.7%	-64.2%
	Discretionary	5,460	33.9%	1,520	20.1%	-72.2%
	Weekend	1,124	7.0%	916	12.1%	-18.5%
	Subtotal	11,814	73.3%	4,306	57.0%	-63.6%
Harrisburg	Commuter	1,570	9.7%	810	10.7%	-48.4%
	Discretionary	1,500	9.3%	1,380	18.3%	-8.0%
	Weekend	1,228	7.6%	1,064	14.1%	-13.4%
	Subtotal	4,298	26.7%	3,254	43.0%	-24.3%
	Line Total	16,112	100.0%	7,560	100.0%	-53.1%

service, because there are no longer enough passengers to support the former level. This in turn reduces ridership in markets not served by the new operator.

DEMOGRAPHICS

Overall, the population along the Keystone Corridor did not grow rapidly, increasing by only 2 percent in the decade between 1980 and 1990. Indeed, Philadelphia and Delaware counties lost population, and Dauphin County at the western end only matched the overall nominal rate of 2 percent. Most of the growth is now occurring along the middle of the corridor, with Chester and Lancaster counties increasing by 19 and 17 percent, respectively. This is one reason why Lancaster now exceeds Harrisburg in station boardings, even though little white collar employment lies within easy reach of the station. The residential catchment area for Lancaster grew by 13 percent, in contrast to 4 percent for that surrounding Harrisburg. Another reason for Lancaster's higher ranking is its location a significant distance south of the Pennsylvania Turnpike, whereas Harrisburg is served directly by the turnpike. Thus, the competitiveness of the train vis-à-vis automobile and bus is improved at Lancaster for travel eastward. Similarly, Harrisburg is much better served by air than is Lancaster.

Much of Amtrak's market for work trips toward Philadelphia now comes from Lancaster County. Residents of Chester County can use a substantially cheaper SEPTA service, and Dauphin County is too far removed from Philadelphia to generate a significant number of work trips. Though Harrisburg comprises a smaller job market, the potential commuter market at the western end of the line is growing faster. The population with good access to stations at Middletown, Elizabethtown, Mount Joy, and Lancaster grew by 13 percent between 1980 and 1990, and downtown employment in Harrisburg is growing faster than that in Philadelphia.

Station spacing along the line is very uneven, varying from 1.3 to 38.3 km (0.8 to 23.8 mi). The largest gap is between Parkesburg and Lancaster, essentially leaving eastern Lancaster County, with its Amish community and tourist attractions, unserved. Several alternatives have been considered to fill the gap. The Strasburg Railroad, a steam-powered tourist railroad operating on a 6-km (4-mi) branch line, has indicated that it would like to participate in a joint station at Paradise. The location is convenient to US-30 and almost bisects the unserved gap. An alternative is to trisect the gap by adding two new stations, at Kinzer and at Bird in Hand. This would improve local coverage but would have reduced tourist potential. In any event, one or two new stations in this gap could strengthen the market for rail travel. A new station at Harrisburg International Airport, replacing the existing Middletown station, would provide both intermodal convenience and better access to rail from Hershey and other communities east of Harrisburg.

RESTRUCTURING SERVICE

Whereas Amtrak has reduced its Philadelphia-Harrisburg service, SEPTA has expanded its service in Chester County to meet a growing commuter market. This leaves open the question of whether other markets, such as work trips to Harrisburg, business travel, and trips originating from eastern Lancaster County, are adequately served. It also raises the question of what roles Amtrak and SEPTA should play in serving these markets.

Amtrak currently owns the Philadelphia-Harrisburg rail line, as well as the stations, and operates the Keystone trains, as well as other longer-distance trains, over it. There is no inherent reason why this has to remain the case. Amtrak's primary mission is to provide intercity rail passenger service nationwide, and the Keystone Service is not ranked very high on its scale of priorities. (Amtrak has traditionally viewed the service as primarily a commuter operation and therefore inconsistent with its basic mission.) Other institutional arrangements are possible that would increase the level of local control and provide the capital investment needed to improve service.

Three separate functions must be considered when looking at alternatives to Amtrak service: line ownership, policy management, and operations. If ownership of the line were to change, Amtrak would continue to operate its longer-distance trains (such as the Broadway Limited and Pennsylvanian) over the line, although it would then have to buy trackage rights from the new owner. Policy management refers to the power to set policy and make decisions at the broadest level.

The most likely alternative to Amtrak ownership is for control of the line to be transferred to the state of Pennsylvania, either PennDOT or an entity established for the purpose. The state would then be responsible for capital investment and maintenance, but it would have control of the level and timing of these investments, and it could ensure that the interests of corridor travelers were protected. If the state legislation that created SEPTA and that limited its service area to the Philadelphia area were amended, SEPTA could possibly acquire the line, though the resources for its acquisition and improvement would still have to come from the state and other sources. SEPTA has the capability in place to manage and maintain rail lines. Since in either case financial responsibility would reside largely with the state, state ownership should be seen as the principal alternative to Amtrak ownership.

If any changes in the institutional arrangements are made, they should include passing control of policy decision making to the state, since it is the people of Pennsylvania that have a primary interest in upgrading the service. Though day-today management would be provided by whoever operates the service, the state should retain the right to set general policy regarding service, fares, promotion, and capital investment. The state would also maintain oversight control over the operator.

Even if Amtrak does not own the line and control the Keystone Service, it could still contract to operate the trains. There is precedent for Amtrak operation of local trains under contract elsewhere in the Northeast Corridor. Another possibility is to have SEPTA operate the trains to Harrisburg as an extension of its local service to Chester County. SEPTA already operates more train-kilometers on the line than does Amtrak. The service could also be put out to bid for operation by an independent contractor, or the state could establish an agency to operate the trains, as was done in New Jersey. However, by operating only a single line, neither the state nor an independent contractor would be able to enjoy an economy of scale. It appears that Amtrak and SEPTA may be the only realistic option for operating a state-controlled Keystone Service.

SUMMARY

The Keystone Corridor serves several distinct markets, including commutation at each end, business and discretionary travel to Philadelphia and Harrisburg, and connections to points beyond. The corridor has experienced declines in ridership and service over the past decade, although a portion can be attributed to an expansion of SEPTA local service to Chester County. An analysis of origin-destination data shows that significant shifts in markets have indeed occurred. Most of the Philadelphia commuters have moved to SEPTA, with the result that through trips now constitute a larger share of Amtrak's market. Other trends are also apparent. The share of Amtrak trips oriented toward Lancaster and Harrisburg has increased from 27 percent in 1983 to 43 percent in 1990, and a larger share of Amtrak's passengers are now traveling on weekends, when SEPTA has less service.

Population growth is now occurring mainly in the middle of the corridor, namely in Chester and Lancaster counties. Partly because of this growth, Lancaster now boards more passengers than does Harrisburg, and additional ridership could be captured by adding one or two new stations in eastern Lancaster County.

Though rail markets at the western end of the corridor and for through trips could be stimulated with better service, Amtrak is constrained by limited resources and is unable to make the needed investment. Little improvement is likely under current institutional arrangements. A restructuring of these arrangements would provide greater local control and responsibility. A rationalization of service would increase the options available to travelers and avoid disruptive competition between local and through trains. Only through a new institutional arrangement, dedicated to planning, operating, and aggressively promoting a customer-oriented service, can the full potential of linking the state's largest city and its capital with a fast, reliable, comfortable, attractive, and affordable train service be realized.

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Assessing the Station and Access System Design Implications of a Small Magplane System for Intercity Travel

JERRY B. SCHNEIDER

It is assumed that a U.S.-designed second-generation maglev system will be developed that will feature many small magplanes operating at high speeds and short headways over a national system of magways. The station location, number, and intermodal connection needs of such a small magplane system are examined. The use of a small magplane means that a larger number of small stations can be provided than is possible for conventional high-speed, long train systems like the French TGV or German ICE. Urban development and other macroscale implications as well as specific station location and design issues are identified and discussed. A major trade-off between maglev switching speed and station cost is identified. Use of many small stations offers the possibility of providing travel times that are competitive with air travel by making deep cuts in ground access and airport terminal waiting times.

Interest in developing a maglev-based high-speed ground transportation system for use within the United States and for export to other nations has grown significantly in recent years. As this interest grows, more system design and impact questions are beginning to be asked (*1*). Of particular interest is the question of how such a system should be designed and operated to complement the many existing ground and air transportation systems now in operation.

Any large-scale transportation improvement proposal should be subjected to a macroscale systems analysis before significant commitments are made to develop and test the necessary technology. Figure 1 shows some of the factors and interrelationships that will influence decisions about the three system-level components considered in this paper. Only brief attention is given to Components 1 and 2 because they are covered well elsewhere (*2,3*). The focus of this paper is on Component 3—the high-speed system station. Four basic questions are examined: How many stations should be provided? Where should they be located? How large should they be? How should they be designed?

SYSTEMS ANALYSIS FRAMEWORK

Component 1—Vehicle Size and Magway Preferences

Component 1 in Figure 1 represents the process of assessing the many technical, service, and impact options and questions that must be considered before a useful maglev technology can be developed, tested, and put into operation. Answers are being sought from the research being conducted under the National Maglev Initiative (NMI). This initiative is conducted jointly by the Federal Railroad Administration, the U.S. Army Corps of Engineers, and the U.S. Department of Energy. Within the NMI program, four large system concept definition (SCD) studies were supported with funding of $8.7 million. The studies have been conducted by four groups of companies (consortia) and were designed to identify four system concepts that could be used in the United States. Even though both the Japanese and German maglev technologies have been undergoing development and testing for several years, many believe that they can be surpassed with a concerted U.S. effort.

From the NMI information available, it is fairly clear that there is agreement on one important characteristic of any transportation technology—the optimal vehicle size. Small maglev vehicles (hereafter called magplanes) are proposed that would be very similar to an aircraft fuselage, without wing or tail surfaces, flying through the air. In operating terms, this implies that many magplanes of small to moderate size (more like airplanes than trains) would be dispatched frequently from many stations to selected destinations. A single magplane might be about 30.5 m (100 ft) long. Figure 2 shows a baseline magplane configuration that was included in a recent research report (*3*).

Component 2—Control System Design

The control system and operations concept that is implied by the emerging SCD findings regarding the optimal (small) size and single-magplane operation represents a radical departure from conventional thinking and practice, especially in Europe. For example, the French TGV and German ICE high-speed rail systems are currently specifying that their stations have platform lengths of from 400 to 480 m (437 to 525 yards) to be able to accommodate two 10-car trainsets. Two French TGV-A trainsets coupled together can carry up to 1,044 passengers, and the French have recently ordered 45 new double-deck TGV trainsets to increase their passenger-carrying capacity (*4*).

In contrast, the U.S. maglev concepts being developed involve operating a large number of small magplanes, at much higher speeds, with all stations off line and served with skip-

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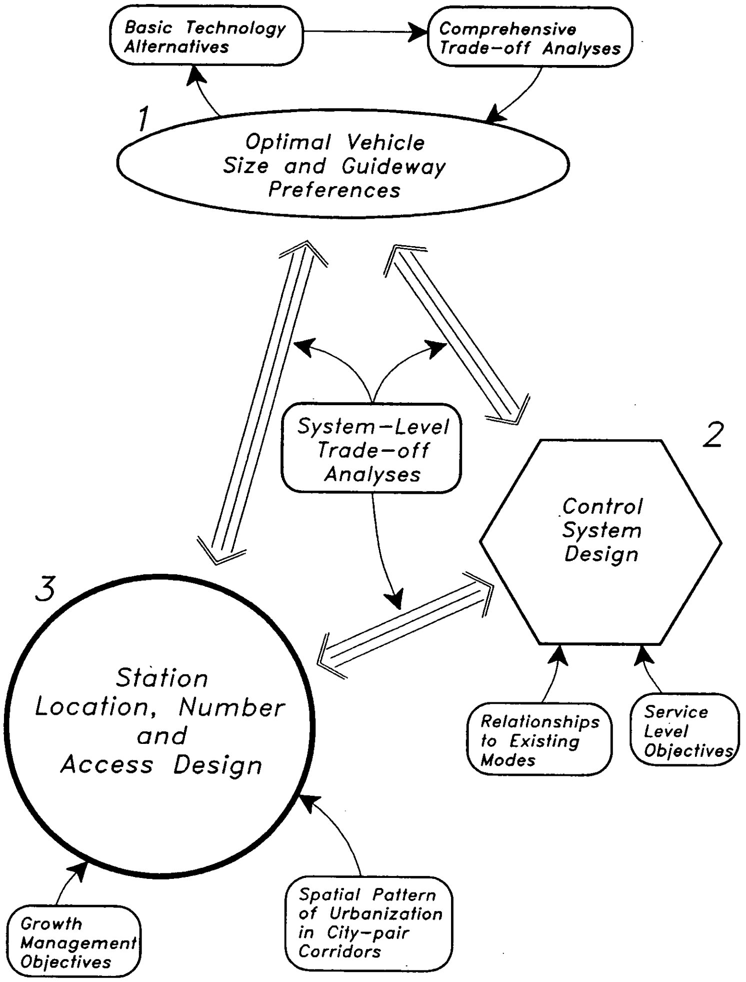


FIGURE 1 Components of a systems analysis of a high-speed ground transportation system.

stop (express) service. All magplanes would be under the control of a central computer system, and headways as short as 20 sec are thought to be feasible. Clearly, this type of operation is similar to an airport where one typically can see 50 or more operations per hour. Such a system will be referred to as a small magplane system (SMS).

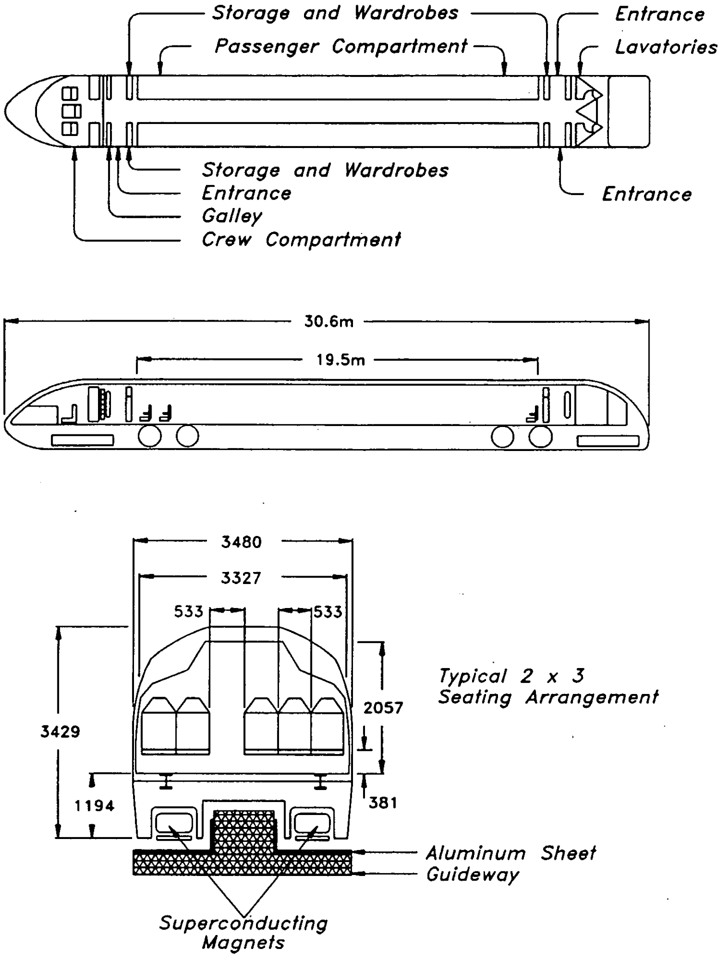
Component 3—Magstation Location, Number, and Access System Design

In the U.S. high-speed studies that have been conducted, the investigators have used the conventional assumption that the stations would be few and far between. As shown in Figure 3, the system's average speed will decline as the number of stations is increased, so there is a desire on the part of the system operator to keep the number of stations to a minimum. This is even more true for a maglev system, where cruise speeds of 483 kph (300 mph) are frequently cited as desirable. At these speeds, the minimum station spacing must be large if the train must stop at every station. For example, if one assumes a reasonably comfortable acceleration of 1.5 *g* (gravitational pull) and deceleration of 0.2 *g* and if the average speed is to be at least 90 percent of the cruise speed, then for a cruise speed of 100 m/sec (224 mph) the mean interstation distance should be at least 57 km (35 mi) (*2*). For the higher cruise speeds and the even lower *g* factors believed necessary by some, the mean interstation distance would have to be even greater.

Since high cruise speeds are often cited as being required to be competitive, the mean distance between stops might have to be at least 80 km (50 mi) or more for any maglev system. However, if all stations are off line, the station spacing can be less than 80 km (50 mi) if desired. This mode of operation would still allow high average system speeds even though the number of stops made by each magplane at the system's magstations would be limited.

GENERAL MAGSTATION LOCATION AND DESIGN ISSUES FOR EN ROUTE STATIONS

What are the implications of the SMS concept for the physical design and layout of the stations? First, assume that it will be



All dimensions are in millimeters, unless otherwise specified

FIGURE 2 Baseline magplane configuration—100 passengers (*2*).

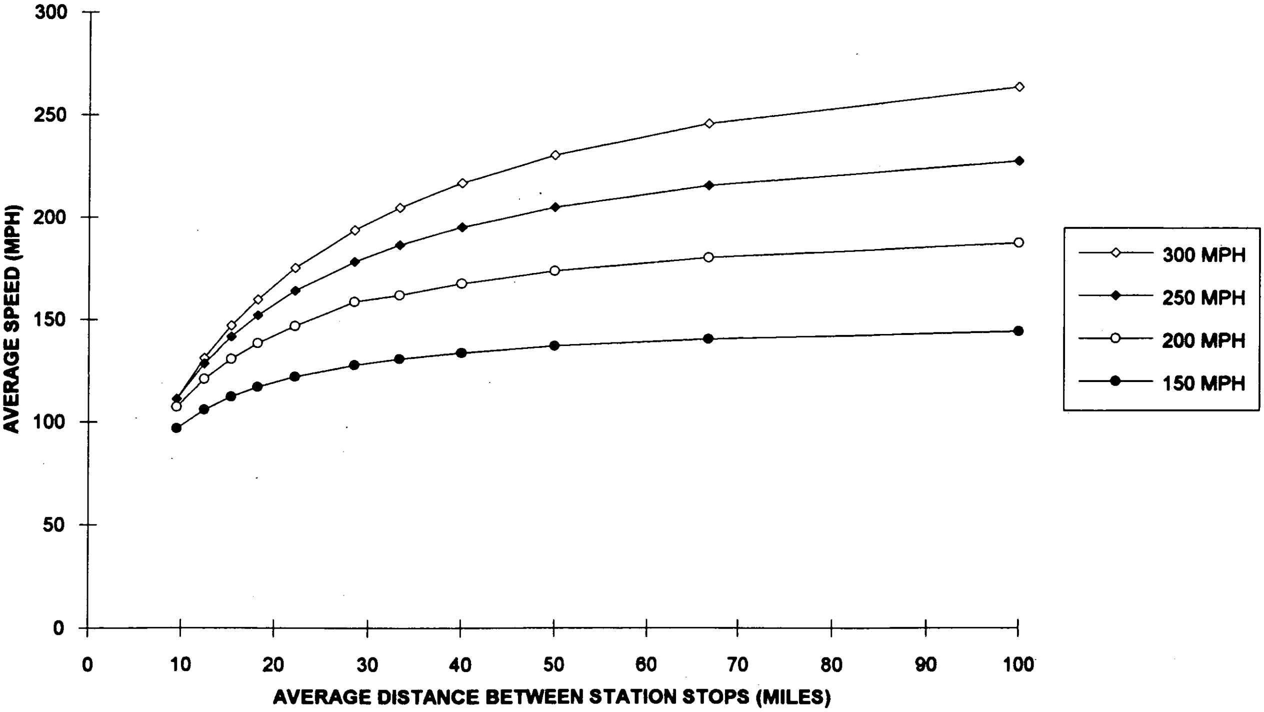


FIGURE 3 Average speed as a function of distance between stops for various values of cruise speed, 0.1 *g* acceleration.

possible and desirable to design all maglev stations as off line, so that magplanes can whoosh through (or by) them at high speed [402 to 483 kph (250 to 300 mph)]. A key technical issue is the type of switch used to allow the magplane to move from the mainline magway to the off-line magway. If a low-speed switch is used, the off-line stations could have a compact layout. High-speed switching would require a much longer off-line magway. Figure 4 shows these two possibilities for an en route magstation layout.

Most of the en route stations would not have to be very large, because there would be many of them and each would serve a relatively small geographic area. Figure 5 compares a conventional and a magplane route/station layout for a hypothetical corridor, initially and in the future. The high-speed line connects two major cities but also provides service to other cities in the corridor. Clearly, one needs to determine what access standards and urban growth policies are desired to guide the design of the system. Long-term issues are involved, as illustrated by the different patterns of growth that may evolve, influenced in part by the number and location of the stations that are provided. Magstation spacing decisions should be related to the present and desired future urban development pattern, and they will vary greatly in different regions of the United States.

It is, of course, very difficult to get a "region" to define "its" goals with respect to a regional growth pattern. Few regional groups in the United States are capable of accomplishing such a task. A forthcoming paper provides a more detailed discussion of the problems of selecting and evaluating the number and location of stations in an urban corridor (*5*).

Smaller stations would be easier to locate in highly urbanized regions, because they will be perceived to have a smaller negative impact on the surrounding community, especially in terms of the traffic congestion, noise, and air pollution. This is a factor of great importance to private developers, who need to minimize the delay that often precedes approval for development projects. However, if a large-scale development is planned around the magstation, this "rapid approval" benefit might not be realized. Several recent studies provide considerable evidence, from the United States and abroad, of the opportunities and pitfalls in this area (*6–9*).

Another factor (negative to some, positive to others) is that if many stations are built, some would probably be located in urban fringe or largely rural areas. Such locations might

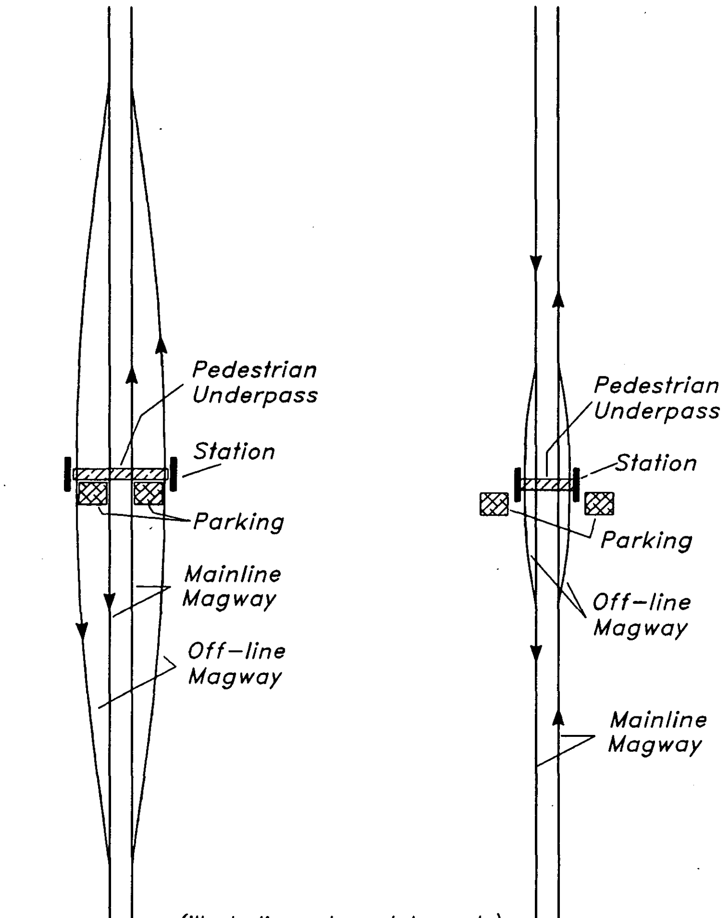


FIGURE 4 En route magstation layouts.

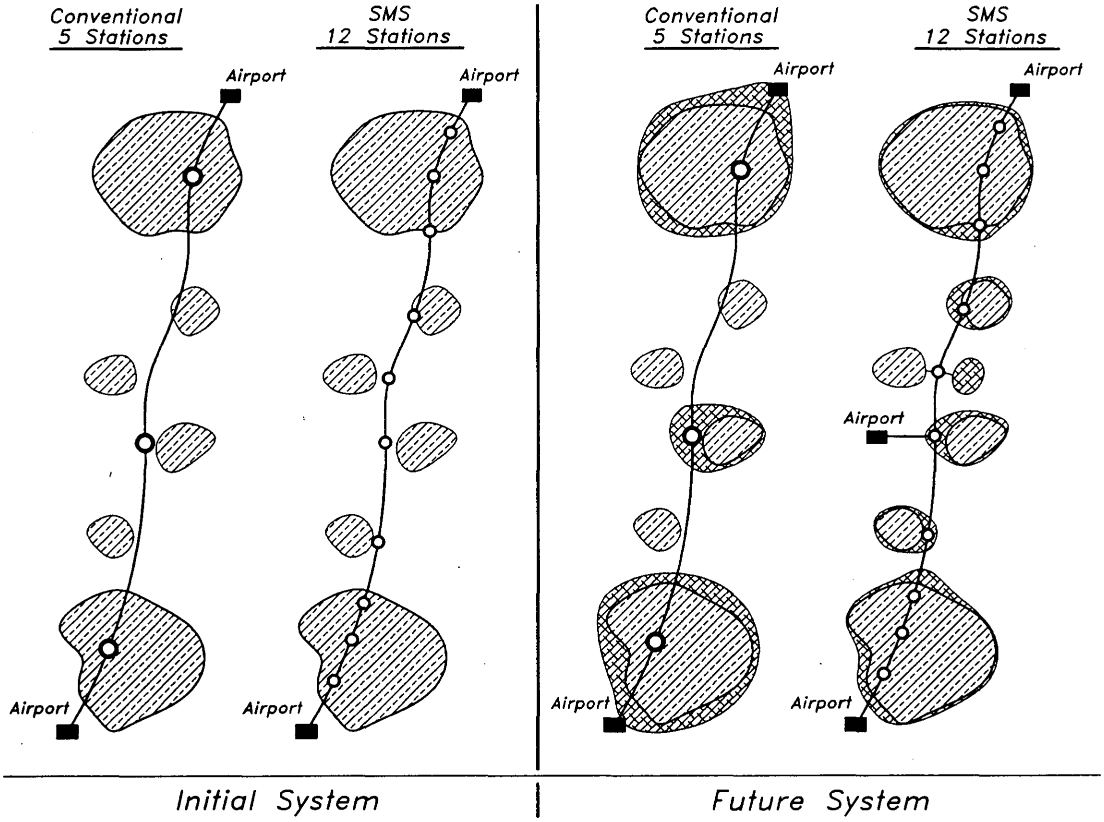


FIGURE 5 Access and growth effects of a conventional and a small magplane system in a regional corridor.

stimulate a more dispersed urban development pattern than might otherwise occur. To some this means more urban sprawl and its associated large infrastructure costs and environmental degradation (*10–12*). Others will think only of the likely increase in land prices that would occur.

Providing numerous stations would generate a higher level of conflict between those who favor compact urban development patterns and those who believe that affordable housing objectives and new compact communities (*13*) could be served by such stations. Providing parking spaces at these smaller stations would be easier, because fewer spaces would be required and the impact on the surrounding community would be less. But it would be more difficult to make these stations into full-fledged intermodal ground transportation hubs. This is because the volume of passengers needing such services would be too low in many cases to make the provision of conventional transit services economically feasible.

It is much more likely that vehicular connecting modes would be of a "dial-a-ride" type, or small buses, vans, and taxis. Such modes probably could provide a level of transit service that is appropriate to the relatively low demand at the magstation, assuming that several hundred parking spaces are provided adjacent to it. If parking is not provided, more extensive transit services might be possible and necessary.

The preceding discussion has considered only en route stations. An SMS would generate two other system design problems. One has to do with the design of a stub magstation—one that is at the end of a route, probably in a central city location. Typically, these stations have been designed to accommodate a few long trains, and they have a long and linear shape. This type of layout will not work well for a large number of small magplanes that arrive and depart at frequent intervals. It may not be feasible to remodel most of the old central city stub stations so that they could accommodate a large number of magplanes.

A physical layout more like that of an airline terminal would probably be needed (*14*). Figure 6 shows what such a stub terminal might look like. It was assumed in Figure 6 that the magplanes could negotiate a loop configuration to reverse their direction of travel. Figure 7 shows a similar loop-type layout for a magstation located adjacent to an urban rail station at a suburban intermodal hub. Figure 8 shows a similar layout except that a turntable is used to enable the magplanes to reverse direction. Figure 8 also shows four magways beyond the turntable that could be used to store reserve magplanes. This type of storage area would be needed at several locations to help deal with peak demand and directional imbalance problems as they arise.

SPECIFIC MAGSTATION DESIGN ISSUES

A major factor in the design of magstations would be to ensure that the high-speed magplanes could whoosh through or by the magstation at up to 483 kph (300 mph) safely and without causing discomfort to people waiting at the magstation. This might require that the magstation be located at some distance from the mainline magway or that special techniques be used

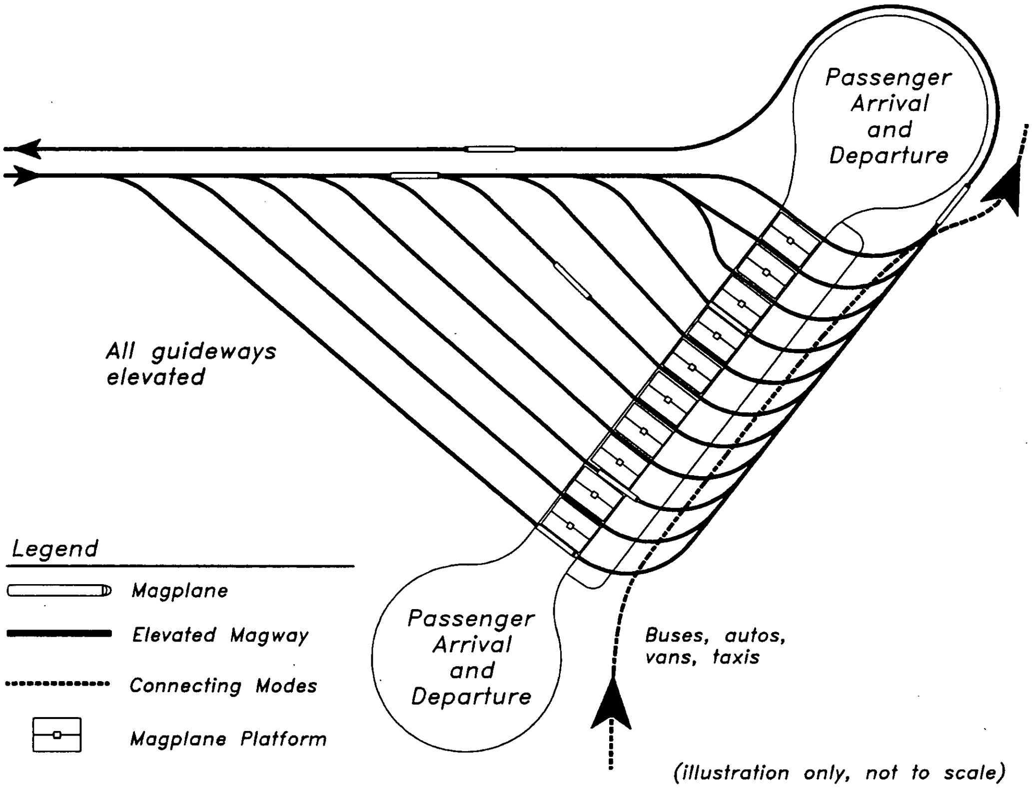


FIGURE 6 **Stub station for an SMS.**

to reduce the noise, vibration, and wind/pressure effects of a high-speed "flyby" to satisfactory levels. Considerable noise/vibration insulation treatment of the magstation buildings might be required. Special consideration would also have to be given to the situation where trains moving at high speed in opposite directions pass each other at or near the magstation. Some type of enclosure, like a tube, might be needed at the magstation to ensure that noise, vibration, and wind levels are maintained at satisfactory levels.

Clearly, a considerable length of off-line magway will be needed to provide for the deceleration and acceleration needs of a magplane. Many believe that a magplane probably cannot be switched to an off-line magway at speeds greater than 241 kph (150 mph). Using this assumption, a magplane would have to decelerate from about 241 kph (150 mph) at the off-line magway switch to a stop at the magstation. If the deceleration rate over the braking distance was 0.2 *g*, the deceleration segment of the off-line magway would have to be about 2 km (1.2 mi) in length. Adding an acceleration magway of the same length would make the length of one side of the off-line magway about 4 km (2.4 mi) or 8 km in total. If this magway is assumed to cost about $10.6 million per km ($17 million per mi) (*2*), the off-line magway for such a magstation would cost about $82 million. If the cost of buildings and associated facilities is added to this figure, an en route magstation cost of around $100 million might result. Of course, if the magplane speed were reduced significantly before switching to the off-line magway, the cost could be reduced significantly—but so would the average speed of the SMS.

Other options have been suggested that involve using the same section of magway for both deceleration and acceleration. William Aitkenhead of Magneplane, International, has devised several such concepts (see Figures 9 and 10). In Figure 9, the length of off-line magway needed could be reduced at the cost of some additional switches, overpass construction, and some additional control problems on the bidirectional magways. Aitkenhead has also suggested that the bidirectional magway concept be applied to the design of way-off-line magstations (see Figure 10). In Figures 9 and 10 it has been assumed that each magstation would have a turntable to reverse the direction of the magplane. If these way-off-line magstations were not served more than a few times each day, considerable savings in magway cost could be achieved by using a bidirectional magway. But some additional switches would be required and the control problem would become a little more complicated. In all cases, these trade-offs need further investigation.

COMPETITIVE POSITION CONSIDERATIONS

The preceding discussion highlights the significant trade-off between the maximum switching speed and the cost (and therefore feasible number) of the stations. The use of high-speed switching implies that a magstation might cost as much as $100 million. At such a price there would be a strong tendency to minimize the number of stations provided—and therefore the access ease. Ultimately, important trade-offs

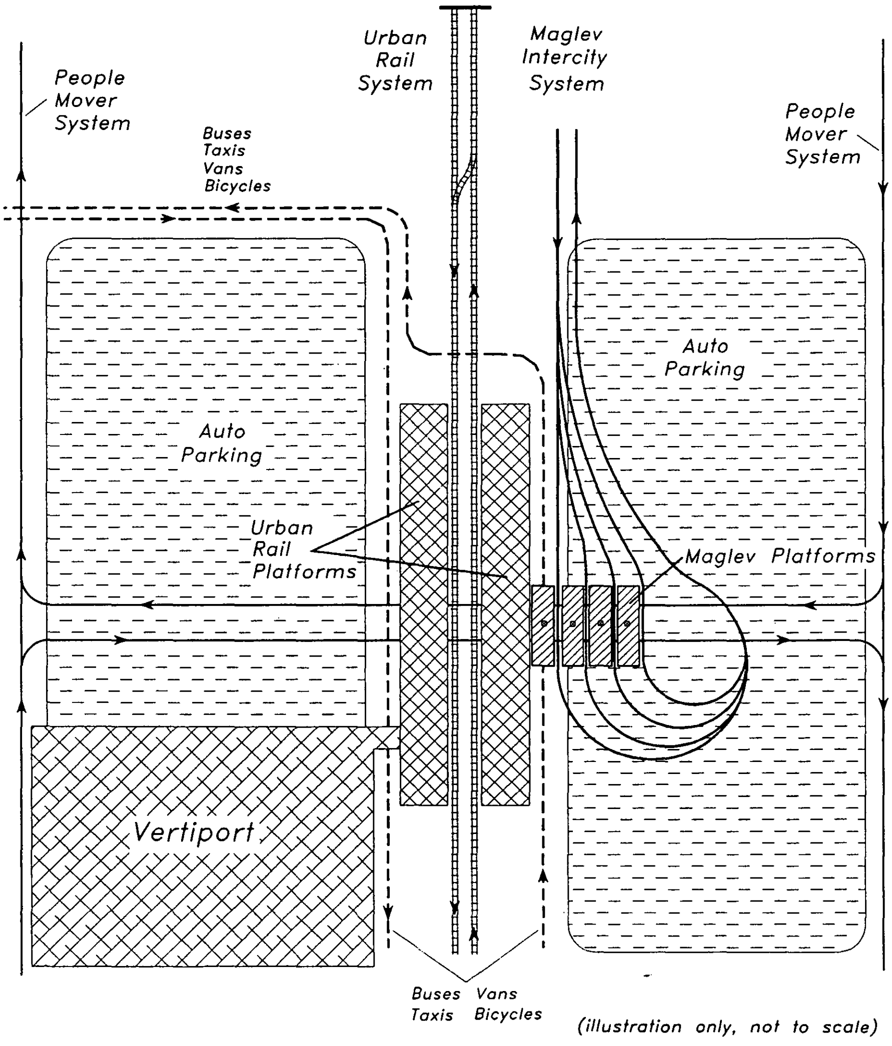


FIGURE 7 Suburban intermodal transportation hub—loop option.

will have to be made between the spatial extent of system access (and associated door-to-door travel times and costs), average system speeds, and total capital cost. This three-way trade-off is complex. Two essential questions are, How important is system access (i.e., door-to-door travel times and costs) relative to average system speed and capital/operating costs? How important is system access to the competitive position of the maglev mode?

For example, the mainline magway cost of a 300-mi maglev system would be about $5.1 billion, at $17 million per mi. If such a system had stations every 30 mi (a total of 11 stations, 2 stubs and 9 en route) and used a high-speed switch, the magstation cost (at $100 million per magstation) would be about $1.1 billion. This is a little more than 20 percent of the mainline magway cost. Use of a lower-speed switch would reduce the magstation cost substantially but might also reduce the average system speed considerably and complicate the operational control problem.

Clearly, the likely savings in door-to-door travel times and costs must be examined before any rational approach to dealing with these trade-offs can be defined. One such attempt was made recently in a study of the potential market for a civil tiltrotor system (*15*). In this study, comparative estimates of door-to-door travel times via conventional air and civil tiltrotor were developed for the Northeast Corridor of the United States. Twelve vertiport locations were assumed (6 in New York, 3 in Boston, 2 in Washington, and 1 in Philadelphia). Assumed schedules were then evaluated with the Boeing Market Share Model, a proprietary simulation model used for fleet planning.

The result was that an average trip via a conventional fixed-wing aircraft would take 3.2 hr, whereas a civil tiltrotor trip would require only 1.9 hr, a 1.3-hr savings (or a 41 percent reduction). The average flight times were almost identical, so all of the travel time savings were due to reductions in ground access, terminal waiting, and taxi out/in times. Figure 11 shows these results. These findings cannot be extended too far, but they suggest that an SMS with 12 or more stations in the Northeast Corridor could be competitive with conventional air travel because it would allow deep cuts in ground access

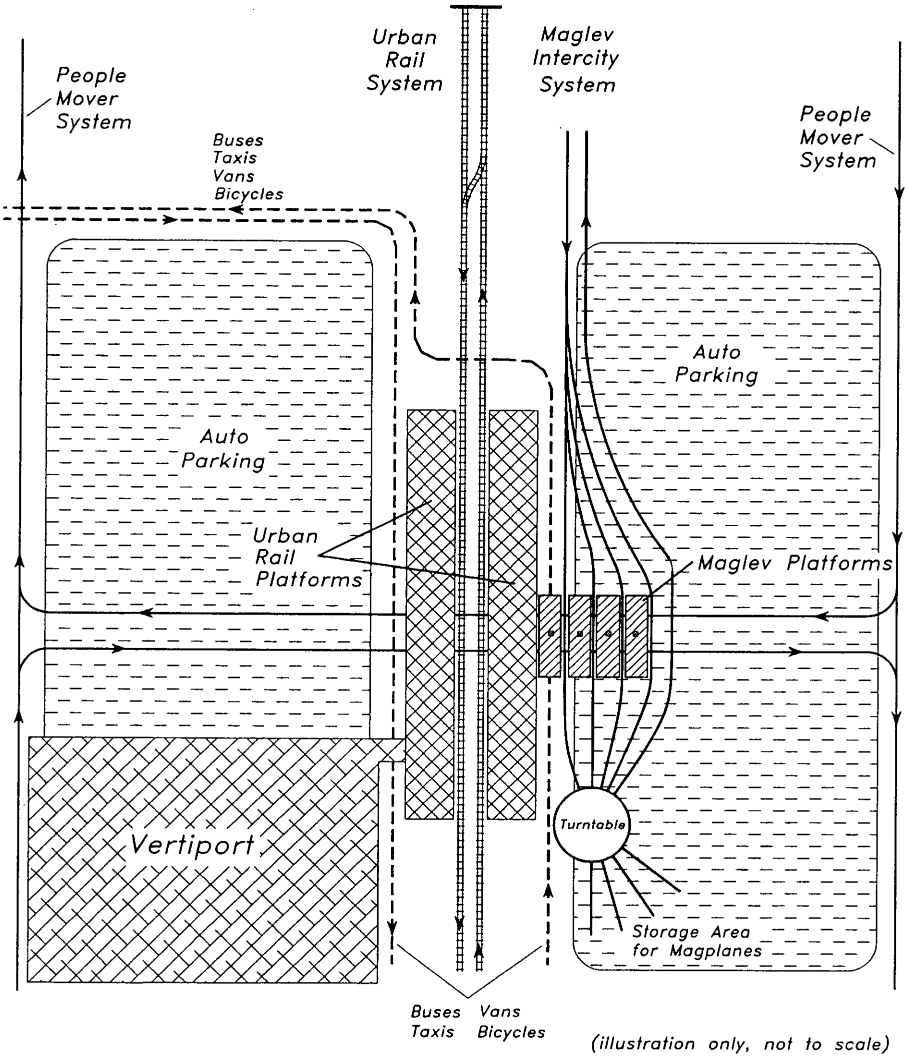


FIGURE 8 Suburban intermodal transportation hub—turntable option.

and terminal times. Together, these two times were estimated to require about 80 percent of a 3.2-hr door-to-door travel time by the Boeing Market Share Model.

Of course, 12 vertiports might be able to provide shorter average ground access times than could 12 maglev stations, because they would not have to conform to a linear configuration. Given the very dispersed urban form in most U.S. metropolitan areas, linear systems cannot provide access levels as good as those not so constrained. For example, conventional wisdom suggests that if a transportation system takes you directly to the downtown of the metropolitan area, it will serve most of the important destinations in the metropolitan area. This is a common misperception. Few U.S downtowns contain more than 20 percent of all the employed persons in a metropolitan area. The other 80 percent are spread widely in small- to medium-sized clusters or commercial strip developments, mostly in suburban areas. This means that a linear system that provides service to the downtown as a primary objective will neglect many important destinations, which require substantial time and effort to reach from a downtown location.

Finally, any assessment of the cost of the components of a maglev system and its competitive position must include how it is to be financed. If public funds were used to pay for all of the stations and private funds were used for all other components of the system, the type and number of stations provided would be determined by a political process conducted at a regional or multistate level with considerable input from the federal government. The physical design of such a system (routes and stations) will be strongly influenced by the way in which private and public funds are commingled to generate the large investments needed to build and operate the system.

GROWTH CONTROL CONSIDERATIONS

If developers can be found that own or can acquire large parcels of land in locations suitable for stations and if they are willing and able to undertake large-scale development projects that include an integrated SMS magstation, both the developer and the SMS owner (and perhaps the public) could benefit. Such an arrangement generally falls under the head-

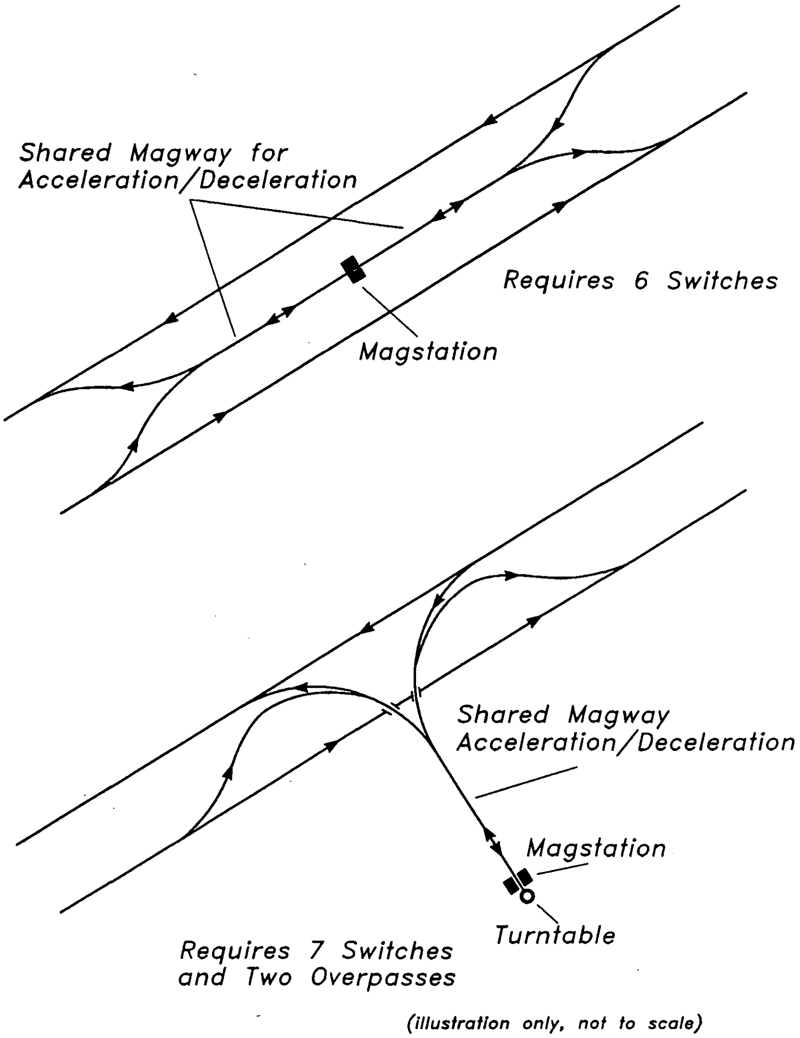


FIGURE 9 Two shared-magway concepts for magstations.

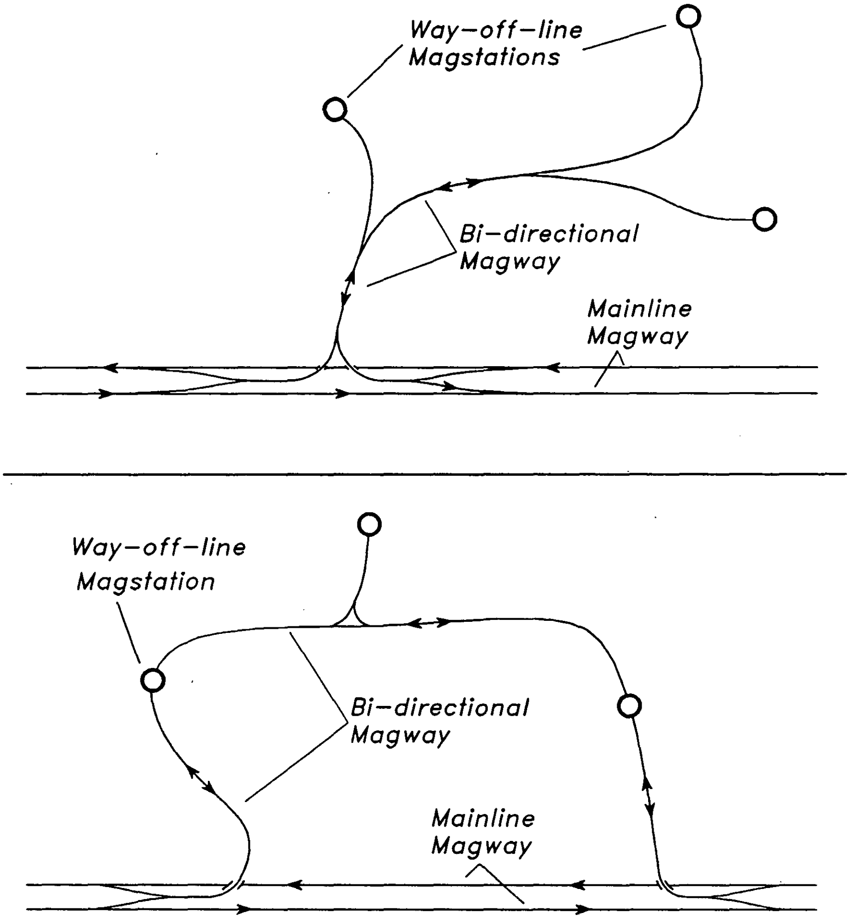
ing of joint development and is often cited as a synergistic opportunity that could arise from the deployment of a maglev system. Joint development offers a means of cost sharing and the possibility of a fairly large built-in clientele for the maglev system. The essential idea is that such megaprojects would be like "pearls on a string," with the maglev line the link that ties them together.

An adverse impact, in the minds of many persons, would be the tendency of an SMS to encourage a further rapid development of relatively inexpensive land in urban fringe and semirural areas. Whereas some such developments might be viewed as desirable by nearly everyone and permitted, others might be considered to be undesirable. They could only be prohibited by strong growth controls and regulations in those areas where they would generate major damage to the ecosystem or require large public expenditures for new infrastructure. At present, only a few states have reasonably strong growth management laws in place (e.g., Oregon, Washington, Florida, New Jersey, and Vermont).

It is not clear that the states that have enacted growth management laws could handle the land use impacts of an SMS without some amendments to their current growth management laws. SMS can provide major increases in accessibility in certain locations, and such a technology was not even contemplated at the time this legislation was formulated and passed. An important part of any national maglev program would be to encourage (or require) the affected states to enact appropriate land use legislation for dealing with the growth-inducing accessibility impacts of the new system.

CONCLUSIONS

Current thinking about a second-generation U.S. maglev technology suggests that it would use many small magplanes, skip-stop service to off-line and way-off-line stations, and very frequent service. This means that the design of its access facilities can be radically different from European practice and conventional thinking among U.S. practitioners. In short, a high-speed maglev system that uses small magplanes to serve many stations would provide access times far superior to those



(Illustration only, not to scale)

FIGURE 10 Two way-off-line magstation concepts.

provided by conventional airports, whose difficult access problems are likely to grow worse.

This might make an SMS competitive with air travel because its ground access and terminal times might (conservatively) be less than half those of congested airports. Access time savings could, in some cases, make door-to-door travel times equal to or less than those provided by the airlines. Moreover, if the maglev system had high reliability and delays were virtually nonexistent, further time savings over air travel could be realized. If the maglev fare were equal to or less than air fare and all other factors were comparable, SMS passenger volumes might be significantly higher than those currently forecast for conventional high-speed, long-train systems that provide only a few stations.

The system benefits derived from these SMS attributes are significant and should encourage those who hope to develop and deploy such systems. However, two major adverse effects could occur. A successful maglev system could divert many more persons from the air travel sector than is now thought to be likely (*16*), and the airlines might oppose the deployment of an SMS. Or they might decide to participate in the financing, ownership, and operation of the SMS. Companies, like Boeing, that manufacture aircraft could decide to manufacture magplanes, making use of their extensive aircraft fuselage design and manufacturing knowledge and experience.

The larger implications derived in this paper indicate the need to broaden the scope of future maglev studies. A systems analysis approach that includes system access as a major variable is needed to make any maglev system investment proposals credible. Before any maglev system can be justified, its proper role in relation to existing and expected intercity travel options must be defined. Our governments should not allow a "stand-alone" maglev system to be built. Analyses of future intercity options should also include tiltrotor-type aircraft and their associated vertiports as a possible competitive intercity mode (*17*). A high priority should be given to finding ways to integrate vertiports, urban rail transit, maglev systems, and connecting ground modes in the form of intermodal stations.

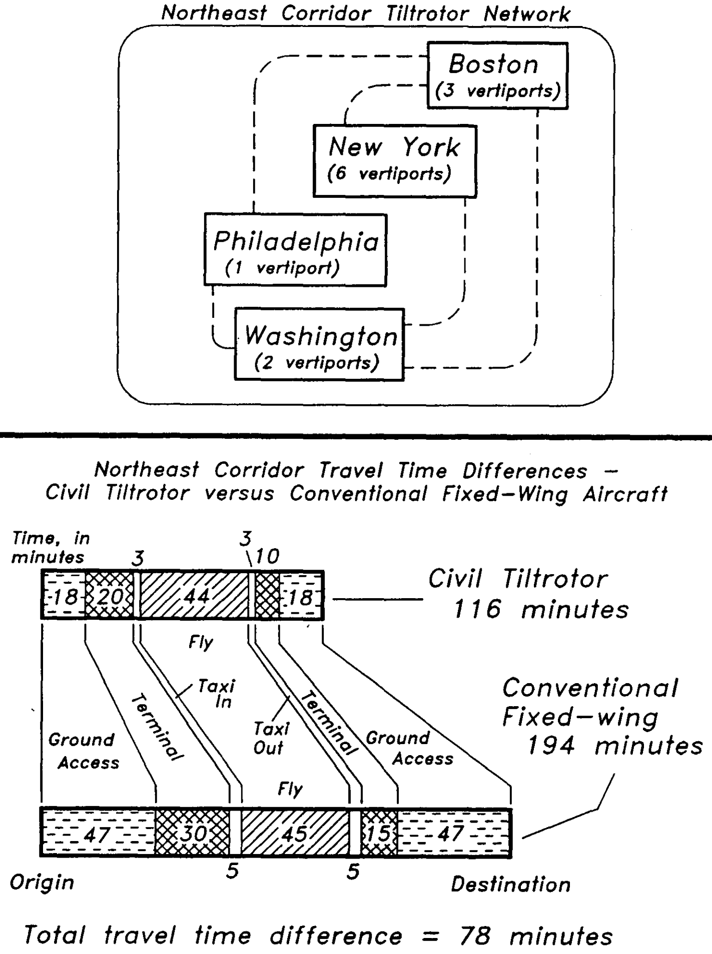


FIGURE 11 Comparison of door-to-door travel times via conventional air and civil tiltrotor in the Northeast Corridor (*15*).

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Midcontinent Railroad Network Trends

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The railroad network of the United States underwent vast changes during the decade of the 1980s, removing miles of excess capacity and responding to the pricing and service freedoms provided by the Staggers Act. The four-state area of Iowa, Kansas, Missouri, and Nebraska lost about 5,000 railway mi, ending the decade with about 20,000 mi. These system changes are described in detail. Changes in the agricultural industry, major railroad mergers, bankruptcies, and reorganizations are identified. Network rationalization, public assistance programs, and intermodal facilities developments are assessed for each state. The following trends are anticipated to continue for the rail system in the region during the 1990s: (*a*) concentration of grain-gathering rail lines, (*b*) growth in intermodal traffic (bridge traffic), and (*c*) the shifting of the predominant grain traffic pattern from long-haul movements to the Gulf of Mexico to short-haul movements of grain within the region.

The decade of the 1980s was a period of substantial change for the railroad industry. Much of the change resulted from the passage of the Staggers Act of 1980, an act that gave rail management pricing and service freedoms. The new market freedoms revised the business patterns in the railroad industry, which greatly affected the structure of the rail system in the midwest. In addition to or in association with regulatory reform, four other major developments affected the rail structure. These are (*a*) changes in the agricultural industry and the resulting changes in grain shipment patterns, (*b*) the bankruptcy and sale of the holdings of the Chicago, Rock Island and Pacific Railroad (the Rock Island) and of the Chicago, Milwaukee, St. Paul and Pacific Railroad (the Milwaukee Road), (*c*) the rationalization, sometimes with state assistance, of the rail systems by the remaining rail carriers, and (*d*) the growth of intermodal traffic.

This paper reports changes in the railroad routes, facilities, and services for the four states Federal Region VII. After reviewing the structural changes in the agricultural sector and changes experienced by the region's carriers, including their intermodal operations, the rail system changes in each of the four states are described. The impacts of these major actions on the size and nature of the railroad systems are discussed, from the perspective of changes in each state's rail networks, intermodal facilities, and rail finance programs. Conclusions are presented concerning likely trends in the 1990s.

STRUCTURAL CHANGES IN AGRICULTURAL SECTOR

Three major interrelated changes in the agricultural sector had impacts on the regional rail system or were affected by changes in rail services.

Diversification

The agribusiness industry has diversified in the four states, resulting in more processing of agricultural commodities rather than shipping the raw products out of the region in bulk. For example, a number of wet and dry milling facilities were built in Iowa, Kansas, and Nebraska during the 1980s to produce ethanol, sweeteners, starches, and other milling by-products. In Iowa alone, during the 1980s, milling plants were built that consumed nearly 90 million bushels of corn per year (*1*). During the late 1980s, income in the region derived from nondurable goods (mostly grain and meat processing) increased about 6 percent per year (*2*, p. 17).

The increase in processing facilities has been a major factor in diverting some of the flow of agricultural goods (primarily grains) to movements within the region, instead of shipping to facilities outside the region and to the Gulf of Mexico ports for export. The shift to short-haul grain movements during the 1980s has been striking. For example, in 1980, 19 and 12 percent of Iowa grain shipments by rail were destined to Iowa and Illinois, respectively, and 11 and 24 percent were destined to Louisiana and Texas, respectively, presumably for export. In 1987, 36 and 26 percent of Iowa grain shipments by rail were destined to Iowa and Illinois, respectively, and 6 and 3 percent were destined to Louisiana and Texas, respectively (*2*, p. 79). During the same period, Iowa rail grain shipment volume (measured in tons) increased by about 60 percent.

Another factor that partially contributed to the decline in rail shipments to Gulf of Mexico ports for export was the slump in exports of corn that occurred during the mid-1980s. The slump and temporary recovery (in 1988 and 1989) in U.S. corn exports can be seen in Figure 1. Total U.S. corn exports in 1990 and 1991 were 23 percent lower than 10 years earlier.

Rail Regulatory Reform in 1980

The shift from long-haul rail grain movements to short-haul movements is also influenced by economic regulatory reform. Under the Staggers Act of 1980, railroads were permitted to contract for service, allowing transportation customers to negotiate with one or more carriers and using more than one mode. As a result, increases in short-haul traffic are partially attributable to movements to river ports on the Missouri, Mississippi, and Illinois rivers and then down the Mississippi on barges to Gulf of Mexico ports.

In the regulated environment before the Staggers Act, this type of cooperation was impossible, and rail carriers had an incentive to promote long-haul rail shipment of grain from the midwest to Gulf of Mexico ports. Contracting allowed shippers to negotiate with rail and barge carriers to obtain the most efficient services. The chronically depressed barge

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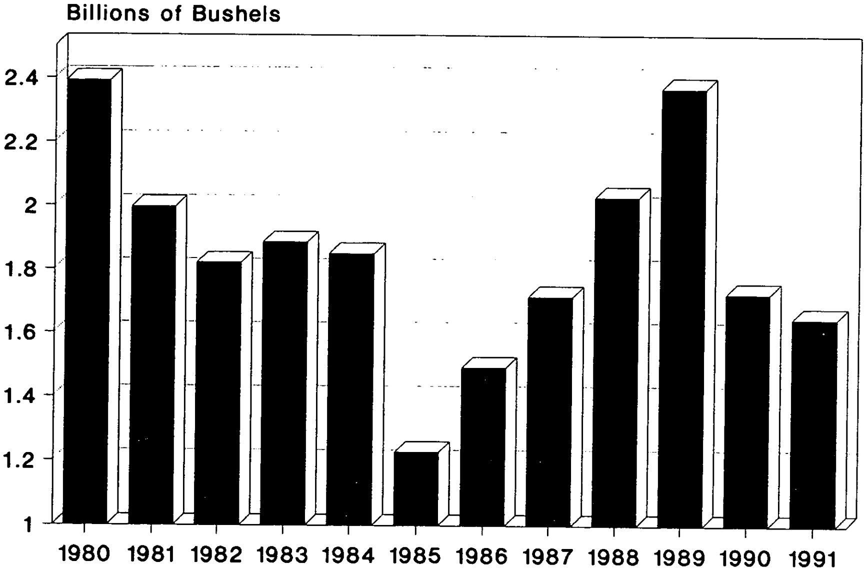

FIGURE 1 U.S. corn exports during the 1980s (U.S. Department of Agriculture).

rates also played a part, with railroads being forced by truck-barge competition to short-haul themselves to the river.

Concentration of Grain Shipping Points

The Staggers Act made it much easier for rail carriers to abandon unprofitable light-density lines and discontinue services. At the same time, grain movements from the farms were increasingly passing through large, more efficient, and more central grain terminals. These two forces have led to a concentration of services and grain shipments. For example, 50 percent of the rail tonnage in Iowa originated in 10 counties (from 99 total) in 1980. By 1987, the same counties originated 66 percent of the tonnage (*2*, p. 82).

In addition, the variability in export volumes, shown in Figure 1, had significant impacts on the traffic levels of grain-gathering lines. During poor export years, light-density agricultural lines, recently spun off to regional and short-line operators, may cease to carry any traffic. Where a large portion of the investment in rail lines is tied up in fixed assets, such fluctuations make the survival of these lines extremely tenuous. Their demise would further concentrate the rail network.

The concentration of grain origins, the shifting from long-haul grain transportation to short-hauls to river ports, and the diversification within agribusiness have all led to dramatic shifts in flows of grain movements. The shifts in transportation patterns along with changing regulatory requirements have helped to dramatically change the structure of the rail network in the Midwest.

RAILROAD INDUSTRY STRUCTURAL CHANGES AFFECTING REGION VII

Railroad Bankruptcies

The four midwestern states examined were highly affected by the bankruptcies of the Milwaukee Road and the Rock Island and the sale by the Illinois Central Gulf Railroad Company (ICG) of its lines. The Milwaukee Road and the Rock Island lines were largely reorganized and sold to other rail companies, and most of their lines remain in operation today. For example, the Rock Island operated nearly 3,200 mi of lines in the four states when it ceased service in 1980. At the end of the decade, roughly 2,400 mi of the Rock Island network was owned and operated by other carriers.

The changing of ownership of the Rock Island and Milwaukee Road lines was the result of Class I carriers becoming better aligned in existing service areas through acquisitions of entire railroads and of line segments to penetrate new markets. In addition, several parts of the rail system were spun off and are operated by new regional (railroads longer than 350 mi in length are considered regional railroads) and short-line railroads (*3*). For example, three new regional railroads, the Iowa Interstate Ltd. (IAIS), the Kyle Railroad Co., and the Oklahoma-Kansas-Texas Railroad Co. (a subsidiary of the Union Pacific System), were created in the region during the 1980s and operated on lines previously owned by the Rock Island.

The ICG sale was much like the reorganization of a bankrupt railroad because the ICG sold or abandoned about 820 mi of line in the four states during the 1980s. Similarly, most of the ICG lines were sold. ICG sold its lines only to regional and short-line railroads.

Line Spin-Offs

The strategies of spinning off unprofitable or marginally profitable lines by Class I carriers, instead of abandoning them, and actively recruiting local or regional operators, were popular in the 1980s, as over 190 new railroads began service in the United States (*4*, p. 144; *5*, p. 124). Class I carriers, with their high labor costs, could then concentrate their efforts in denser markets rather than serve thin, dispersed markets along branch and low-density lines. Often there was no loss of traffic for the Class I carrier because the local or regional railroad had no connection except to the line's original owner. In addition, the Interstate Commerce Commission's (ICC's) interpretation of the Staggers Act released the new non-Class I line owner from protective labor conditions imposed on the prior line owners. The new line operators functioned with lower wages and fewer labor rules, resulting in lower labor costs (*6*, pp. 93–94). Lower labor costs allow new short-line and regional railroads to remain profitable in markets where demand is too thin to support Class I carriers.

A 1989 Federal Railroad Administration (FRA) survey of 10 Class I railroads found 7 carriers (including 5 with Region VII operations) with plans to transfer 17,265 mi of track to non-Class I railroads over the next 5 years (*6*, pp. 93–94). An example of this form of transfer of service to short-line and regional railroads from Class I carriers and the symbiotic relationship between the original owner and new non-Class I operator is the Union Pacific's (UP's) offer to lease two lines and help the new operator develop cooperative agreements for marketing and equipment (*7*).

Intermodal Operations

National Perspective

Intermodal traffic in the form of piggyback or trailer-on-flatcar (TOFC) has been offered since 1926 (*8*, p. 8). By 1980, piggybacks accounted for about 13 percent of all rail loadings and were second to coal in frequency of loadings by commodity groups (*9*). More recently, double-stack technology and its efficiencies helped to increase container-on-flatcar (COFC) traffic volumes, with the number of double-stack container spaces increasing from 400 in 1983 to 24,000 in 1988 (*10*). During the period between 1980 and 1987, intermodal traffic originating or terminating in Region VII increased by 138 percent, compared with 41 percent for the entire country. In addition, the region was a major conduit for intermodal traffic moving between the east and west coasts, with roughly 25 percent of all U.S. rail intermodal movements passing through the four-state region [compiled from the ICC confidential waybill sample (*2*, p. 111)].

Double-stack container shipping showed the most growth in the intermodal area following the 1984 introduction of "Linertrain" service by American President Lines. Double-stack service was attractive because it offered piggyback flexibility, a smoother and less damaging ride as a result of modern articulated equipment designs, and 20 to 25 percent lower cost than conventional piggyback service (*11*). Cost savings came from the greatly reduced tare weights of the double-stack platforms (*9*), better aerodynamics (*12*), and better equipment utilization (*13*).

Containers accounted for 40 percent of the intermodal freight in 1989; 20 percent of all rail traffic was intermodal (*11,14*). Whereas double-stack trains originally hauled containers inland from ports, expedited domestic service also grew. As double-stack equipment became more available in domestic corridors, there was potential for the railroads to divert more traffic from motor carriers.

Facilities

While intermodal traffic volumes increased, the number of intermodal terminals dropped dramatically, as simple piggyback ramps were closed and mechanized container loading hubs, each requiring sizable investment and serving a wider area, were located in major traffic centers. The Region VII facilities became concentrated mostly in larger cities, such as Kansas City, St. Louis, and Omaha.

STATE RAIL STRUCTURES AND PROGRAMS

Iowa Rail System

Rationalization

Within the four-state region, changes in the Iowa rail physical plant were the most dramatic. A comparison of Iowa's rail carriers and roadway miles in 1980 with those in 1987 [compiled from Iowa (*15*) and given in Table 1] identified a reduction of more than 2,000 roadway mi, a loss of 35 percent. Before their liquidation and reorganization, the Rock Island and the Milwaukee Road operated the second- and third-largest networks of track miles in Iowa. The 7,000 mi of Rock Island lines that were liquidated created the nation's largest sale of lines to other rail companies and rail line abandonment (*16*, p. 29; *17*, p. 33). The Milwaukee Road was reorganized, and the core of its system was sold to the Soo Line (*18*). Iowa's fifth-largest (pre-1980) rail carrier, ICG, sold or abandoned all of its Iowa lines as part of a corporate strategy to reduce its system from 9,600 to 3,000 mi (*19*).

Rock Island The largest portions of the liquidated Rock Island lines were taken by regional and local railroads, with the IAIS operating on the Rock Island's Chicago to Omaha line and the Iowa Northern Railway operating on the Rock Island line between Cedar Rapids and Manly, and connecting with the Chicago and North Western (C&NW) main lines. Other major portions of Rock Island lines were purchased by the C&NW to augment its own network. Of particular importance to the C&NW was its purchase, for $93 million, of 720 mi of Rock Island main line—the "Spine Line"—between Minneapolis–St. Paul and Kansas City, a transaction highly contested by the Soo Line (*15*, p. 87; *20*). Other smaller portions of the Rock Island were purchased by the Milwaukee Road, the Cedar Rapids and Iowa City Railroad (CR&IC), which is owned by the Iowa Electric Light and Power Co., and the 9.5-mi Appanoose County Community Railroad. Almost 1,100 of the 1,500 mi of Rock Island's Iowa system were still in use at the decade's close (*15*, p. 87).

Milwaukee Road The Milwaukee Road reorganization resulted in the Soo Line's operating about half of its original Iowa system. The major portions were across the northern third of the state and along the Mississippi River, cutting across to Kansas City at Muscatine. About 66 mi between Davenport and Washington, Iowa, was abandoned in favor of parallel track purchased from the Rock Island. The Soo Line's purchase of the Milwaukee Road was met with strong bidding competition from the C&NW and from the Grand Trunk Lines (*21*). Ultimately, the ICC approved the purchase proposals of the C&NW and the Soo Line; the trustee then accepted the Soo's proposal (*18*). Other minor portions of the

TABLE 1 Iowa Railway Miles—Changes from 1980 to 1990

Railroad	1980 Roadway Miles	1990 Roadway Miles
Class I		
Chicago and North Western Transportation Co.	2,093	1,724
Rock Island	1,575	Bankrupt
Milwaukee Road	1,341	Bankrupt
Burlington Northern	729	646
Soo Line Railroad Co.	0	620
Illinois Central Gulf	669	0
Norfolk and Western RR	168	85
Atchison, Topeka and Santa Fe Railway Co.	20	20
Union Pacific	2	2
Class II		
Chicago, Central, & Pacific RR Co.	Not Est.	553
Iowa Interstate Railroad Ltd.	Not Est.	355
Dakota, Minnesota & Eastern RR Co.	Not Est.	Track. Rights
Class III		
Iowa Northern Railway Co.	Not Est.	134
Cedar Valley RR Co.	Not Est.	90
Iowa Southern RR Co.	Not Est.	5
Cedar Rapids and Iowa City Railway Co.	20	56
D & I RR Co.	Not Est.	Track. Rights
Davenport, Rock Island and NW Railway Co.	Not Est.	35
Iowa Terminal Railroad Co.	25	0
Des Moines Union Railway Co.	Not Est.	
Waterloo Railroad Co.	14	
Appanoose County Community RR Co.	Not Est.	10
Iowa Traction RR Co.	Not Est.	13
Ottumwa Terminal RR Co.	Not Est.	4
Keokuk Junction Railway Co.	1	5
Burlington Junction Railway Co.	Not Est.	2
Des Moines Terminal Co.	< 1	
Iowa Transfer	< 1	
TOTAL	6,659	4,359

Compiled from: Iowa, *1980 Iowa Railroad Analysis Update* (Ames: Iowa Department of Transportation, 1980); Iowa Department of Transportation (unpublished data), Dec. 1990.

Milwaukee Road were purchased by the CR&IC, the Burlington Northern Railroad (BN), C&NW, and the D&I Railroad.

ICG The ICG's network concentration resulted in the sale of all its Iowa holdings. A regional railroad, the Chicago, Central and Pacific Railroad (CC&P), and a local railroad, the Cedar Valley Railway (CVR), were spun off. The CC&P operated the former ICG Omaha to Chicago main line, with branches to Sioux City and Cedar Rapids. The CVR operated between Waterloo and north of the Minnesota border, connecting with C&NW's line from Minneapolis-St. Paul to Kansas City.

A central issue in the evolution of Iowa's rail network was the Chicago-to-Omaha corridor. All five of Iowa's major Class I railroad companies served this corridor in 1980. Whereas the Milwaukee Road's line through Iowa had been largely abandoned (except for 100 mi) 10 years later, two Class I's and two regionals still provided Chicago-to-Omaha service.

State Financial Assistance Programs

The first of Iowa's two financial assistance programs partially sponsored by state funds was the Iowa Rail Assistance Program (IRAP), which is administered through the Iowa Department of Transportation. The Iowa General Assembly appropriated $3 million in 1974 for IRAP and has provided a total of $20 million in state funds since the beginning of the program. No state funds have been approved for the past 5 years. Additional funding sources included the FRA's Local Rail Assistance Program (until October 1988) and repayments of loans by shippers and railroads. IRAP awarded funds for line rehabilitation through a mixture of grants and no-interest loans. The mix of grant versus loan in each project depended on an assessment of the recipient of the funds and the individual project.

IRAP-allocated assistance funds were limited to a maximum of 80 percent of the cost of a project. The levels of funding varied, depending on the priority of the project. Priorities were assigned on the basis of financial participation in the project by nongovernmental organizations, the ability of the line to be financially viable, the project's benefit to cost ratio, and the potential for economic development benefits. The IRAP revolving fund supported 44 projects costing $125 million. With the ending of tax support, the funding pool was kept liquid through repayment of loans.

The second rail assistance program, the Iowa Railway Finance Authority (IRFA), was created by the Iowa General Assembly in 1980. Its purpose was to take an active role in the restructuring of the state's rail network in the face of the Rock Island bankruptcy and the Milwaukee Road reorganization. Initially, IRFA was given the power to enter into partnerships with the private sector to purchase, improve, or operate a rail facility. IRFA also made loans available for rehabilitation projects at interest rates below commercial rates. An interest-free loan was provided in 1983 from the highway use tax, and $2.2 million in delinquent property taxes from bankrupt Iowa railroads was deposited in IRFA's fund. With the loss of the fuel tax, the only revenue source for IRFA was the repayment of loans.

Intermodal

The number of TOFC and COFC loading sites in Iowa has declined since 1980, from 37 sites in 23 cities to 18 sites in 14 cities by 1988 (*22,23*). Competition to provide service also declined. Nine locations were served by two or more carriers in 1980; Des Moines was served by three, and Sioux City and Council Bluffs were served by four carriers each. By 1988, three cities (Cedar Rapids, Council Bluffs, and Des Moines) were served by two carriers. Ten cities lost intermodal terminal sites entirely (although not necessarily all intermodal service that could still be provided by drayage); most notably, the BN closed all of its TOFC ramps in Iowa. Newton was the one city added to the facilities listing.

Kansas Rail System

Rationalization

The Kansas rail network remained relatively intact through the 1980s. There were 7,368 mi of track in 1980 and 6,491 mi in 1991. The total route miles are given in Table 2. The Kansas rail system was dominated during this period by two carriers with about 90 percent of the traffic originating or terminating in Kansas. The UP, including its Missouri-Kansas-Texas and Oklahoma-Kansas-Texas (OKT) subsidiaries, had 44 percent of the total track miles; the Santa Fe accounted for 37 percent.

Rock Island Before the liquidation of the Rock Island, Kansas had nearly 1,000 mi of its track. Afterwards, about 85 percent of this mileage in Kansas was being operated by three railroads: the Kyle (a regional operator), the OKT (part of the UP), and the St. Louis Southwestern [SLSW, a subsidiary of the Southern Pacific Railroad (SP)]. Roughly 150 mi of additional Rock Island track, including the line from Topeka northwest to Missouri, was abandoned.

The 320-mi portion across northern Kansas to Colorado operated by the Kyle (under a lease-purchase arrangement) is owned by the Mid-States Port Authority, which had been created by the Kansas legislature to restore the line and operate rail service. The authority acquired a loan, 50 percent guaranteed by the state, from FRA for the line's purchase.

TABLE 2 Kansas Railway Miles—Changes from 1979 to 1991

Railroad	1979 Roadway Miles	1991 Roadway Miles
Class I		
Atchison, Topeka and Santa Fe Railway Co.	2,553	2,026
Burlington Northern	208	576
Chicago and North Western Transportation Co.	1	0
Chicago, Rock Island and Pacific	984	Bankrupt
Kansas City Southern Industries	26	28
Missouri-Kansas-Texas	220	Merged with UP
Missouri Pacific	1,821	Merged with UP
Oklahoma-Kansas-Texas	Not Est.	Merged with UP
Southern Pacific (includes St. Louis Southern)		348
St. Louis-San Francisco	527	Merged with BN
St. Louis Southwestern	0	Merged with SP
Union Pacific	991	2,636
Class III		
Dodge City, Ford and Bucklin	Not Est.	25
Garden City Western	14	45
Hutchison and Northern Railway	5	3
Johnson County Industrial Airport Railway	4	4
Kansas and Missouri Railway and Terminal Co.	2	2
Kansas City Terminal	10	11
Kyle	0	336
Midland Railway (tourist train)	Not Est.	11
Northeast Kansas and Missouri Railroad		107
South Kansas and Oklahoma		219
Southeast Kansas	Not Est.	71
T & P		41
Wichita Union Terminal	2	2
TOTAL	7,368	6,491

Compiled from: Kansas, *1982 Kansas State Rail Plan* (Topeka: Department of Transportation, 1982); Kansas, *Kansas Rail Plan, 1991 Update* (Topeka: Department of Transportation, 1991).

The SP's SLSW subsidiary purchased the Golden State Route running from New Mexico to Topeka, Kansas, and linking the state with the SP's line between the West Coast and El Paso, Texas. This route provided the SP with its deepest penetration into the Upper Midwest (prior to an operating linkage into Chicago). The SLSW had trackage rights on the UP line from Topeka to Kansas City. The SLSW's purchase of the Rock Island's line from Kansas City to St. Louis completed a large circle of SP-operated main lines, with the track from El Paso through Kansas on the top and the original lines running south from St. Louis through San Antonio to El Paso on the bottom.

The third Kansas portion of Rock Island track salvaged was the line running from Abilene through Wichita and south to Fort Worth and Dallas (*24*). The OKT Users Association purchased about 150 mi of the line in Kansas and about 110 mi in Texas. Financing was through an FRA loan partially guaranteed by the state of Kansas. In Oklahoma, 351 mi of the line was purchased by the state. The OKT (now part of the UP) operates the line under a lease-purchase agreement.

Other Line Changes BN tripled its Kansas track miles in the 1980s with its acquisition of the St. Louis-San Francisco. Another major spin-off was the Southeast Kansas Railroad, which purchased the former Missouri Pacific Railroad (MoPac) line running from Coffeyville to Nevada, Missouri, and connecting with five Class I carriers. A railcar repair company in Pittsburgh, near the center of the line, owns and operates the railroad.

Three Class I railroads had trackage rights in Kansas but owned no track in 1991. The Norfolk and Western (N&W) and Soo Line operated over a few miles in the Kansas City area. The Denver, Rio Grande and Western purchased trackage rights over a MoPac line (with 445 mi in Kansas) running from Colorado to Kansas City.

Although Kansas lost only 12 percent of its rail system miles after 1980, it very likely could lose another 500 mi. Most lines that are likely to be abandoned are segments of less than 70 mi each and are paralleled by financially stable lines.

State Financial Assistance Program

Before 1980, Kansas was prohibited from participating in the improvement of facilities other than those dealing with highways and water resources. The state constitution was amended by a public vote in 1980 to allow direct involvement in the subsidizing, operations, construction, or maintenance of railroads or their facilities (*25*). However, the policy limited state financial support to the amount of federal matching funds received (*26*). Thus, when the FRA local assistance program was phased out of existence, rail assistance funds from Kansas were also curtailed.

Intermodal

The number of intermodal loading and unloading facilities in Kansas declined from 38 in 1980 to 11 in 1988. The number of cities having terminals or facilities likewise fell, from 26 to 7. Kansas City and Wichita maintained service by three railroads, while Topeka fell, in terms of intermodal terminal availability, from four railroads to one. Others retaining facilities were Emporia, Newton, and Parsons (*23*,*24*).

Missouri Rail System

Rationalization

Missouri, more than any of the other states in the region, was affected by changes in rail line ownership. For example, two Missouri main lines were purchased by their third owner in 5 years.

Rock Island The Rock Island operated two main lines in Missouri: (*a*) the southern portion of the Spine Line (from Minneapolis–St. Paul to Kansas City), later rehabilitated and part of the C&NW, and (*b*) the eastern portion of the Golden State Route, purchased by the SLSW, but with only local service along the Kansas City-to-St. Louis line.

Milwaukee Road The main line from Kansas City to Chicago was part of the reorganized Milwaukee Road system sold to the Soo Line.

ICG The ICG lines from Kansas City east to Chicago and Chicago to East St. Louis were purchased by the Chicago South Shore and South Bend Railroad in 1986 (*27*). Renamed the Chicago, Missouri and Western, it started operation in 1987 but filed for bankruptcy less than 1 year later (*5*).

Other Rationalization As indicated in Table 3, Missouri lost about one-fourth of its rail mileage in the 1980s (*28*). The reduction was mainly from the sale or abandonment of light-density lines and branch lines by the BN, the UP, and the N&W. In the early 1980s, the N&W (a subsidiary of Norfolk Southern) operated on a line, owned by the Wabash Railroad, that ran 156 mi northwest from Brunswick to the Iowa border, continuing north to Council Bluffs (*29*). ICC authorized the abandonment of the line in 1984. The Northern Missouri Railroad and Iowa Southern Railroad began operation on portions of this line under lease-purchase agreements. Financial difficulties, partially due to the loss of two bridges to floods, caused the Northern Missouri to cease operations in 1987. The N&W 22-mi branch line to Columbia was spun off into a short line, the Columbia Terminal.

The BN abandoned 579 mi of track in Missouri and was able to spin off 32 mi. Combined with the N&W and C&NW abandonments during the 1980s, the northwestern portion of Missouri was left without rail service. Within the UP system, 476 mi was abandoned and 61 mi was spun off, creating the Jackson and Southern (18 mi), the Golden Cat (11 mi), and the Southeastern Kansas Railroads (32 mi in Missouri, 72 in Kansas) (*30*,*31*).

State Financial Assistance Program

The Missouri State Rail Preservation Act specifically prohibited the use of state funds, property, or credit to assist in the

TABLE 3 Missouri Railway Miles—Changes from 1979 to 1989

Railroad	1979 Roadway Miles	1989 Roadway Miles
Class I		
Atchison, Topeka and Santa Fe Railway Co.	220	220
Burlington Northern	1,054	1,587
Milwaukee Road	135	Bankrupt
Chicago and North Western Transportation Co.	82	122
Denver and Rio Grande Western	0	20
Rock Island	509	Bankrupt
Illinois Central Gulf	231	0
Kansas City Southern Industries	195	195
Missouri-Kansas-Texas	340	Merged with UP
Missouri Pacific	1,352	Merged with UP
Norfolk and Western RR	613	443
St. Louis-San Francisco	1,144	Merged with BN
St. Louis Southwestern	193	384
Soo Line Railroad Co.	0	135
Union Pacific	1	1,155
Class II		
Chicago, Missouri & Western	Not Est.	231
Class III		
Arkansas and Missouri	Not Est.	32
Beiver and Southern	10	0
Columbia Terminal	Not Est.	22
Golden Cat	Not Est.	11
Green Hills	Not Est.	37
Jackson Industrial	Not Est.	18
Illinois Terminal	2	0
Kansas Public Service	9	0
Kansas City Terminal	7	7
Manufacturer's Railway	2	25
St. Joseph Belt	5	0
St. Joseph Terminal	< 1	< 1
Southern Kansas	Not Est.	32
Terminal Railroad of St. Louis	Not Est.	17
Terminal Railroad Association	23	0
Union Terminal	4	0
TOTAL	6,132	4,694

Compiled from: Missouri, *Missouri Rail Plan: 1980 Update* (Jefferson City: Missouri Highway and Transportation Department, 1980); Rail Planning, Missouri Highway and Transportation Department (unpublished data), 1989.

funding of rail assistance programs. However, a public referendum authorized the issuance of $600 million of state bonds as a "Third State Building Fund" to assist projects that would encourage economic development. This fund supported three rail-related projects administered through the Missouri Rail Facility Improvement Authority. The city of West Plains built an industrial spur, the Jackson and Southern short line rehabilitated its line, and Green Hills Development, Inc., received funds to buy the former Wabash track. With the depletion of the Third State Building Fund, Missouri has no mechanism in force to provide further financial assistance.

Intermodal

Like Iowa and Kansas, Missouri lost more than 50 percent of its intermodal facilities after 1980. Its 35 loading and unloading facilities in 18 cities dropped to 16 facilities in the St. Louis area (including Illinois), Kansas City, Parsons, and Springfield (*23,24*).

Nebraska Rail System

Rationalization

The Nebraska rail network was dominated by two railroads, the BN and the UP. In 1980 these two rail carriers owned 86 percent of the track miles in the state (*32*). A third Class I carrier, the C&NW, had 441 miles across Nebraska. As indicated in Table 4, several regional and local lines were established in the 1980s. The net track loss was 742 mi over the 10-year period. Nebraska's rail system provided mostly east-west rail service with about 75 percent through traffic. The only highly utilized north-south route was the BN line from Montana to eastern Colorado, passing through the western quarter of Nebraska.

Rock Island The Rock Island formerly had 130 mi in Nebraska; 51 mi was acquired by the Mid-States Port Authority (see Kansas, above). Service in Nebraska was operated by the UP. The remaining Rock Island track was abandoned.

TABLE 4 Nebraska Railway Miles—Changes from 1979 to 1989

Railroad	1979 Roadway Miles	1989 Roadway Miles
Class I		
Atchison, Topeka, and Santa Fe Railway Co.	1	1
Burlington Northern	2,590	2,274
Chicago and North Western Transportation Co.	514	441
Chicago, Rock Island, and Pacific	130	Bankrupt
Missouri Pacific	314	Merged with UP
Union Pacific	1,297	1,307
Class II		
Chicago, Central, & Pacific RR Co.	Not Est.	3
Class III		
Brandon Corporation	17	17
Omaha, Lincoln, and Beatrice	4	5
Sidney and Lowe	Not Est.	10
Non-Operating Rail Line Owners		
Ideal Cement (operated by BN)	Not Est.	2
Mid-States Port Authority (operated by UP)	Not Est.	51
Nebraska Public Power District (operated by BN)	Not Est.	20
Western Railroad Properties (subsidiary of and operated by C&NW)	Not Est	14
TOTAL	4,867	4,145

Compiled from: Nebraska, *Nebraska Rail Plan: 1980* (Lincoln: Department of Economic Development, 1980); Nebraska, *Map of Nebraska Railroads* (Lincoln: Department of Roads, 1989).

Other Rationalization Nebraska remained relatively untouched by other reorganizations and liquidations. The Milwaukee Road leased trackage rights in Nebraska but owned no right-of-way. The ICG also had trackage rights (and 3 mi of rail) in state, so the effects of its emerging as the CC&P were minimal.

In addition to the already existing terminal switching railroads, the 10-mi Sidney and Lowe was established to serve a freight car repair facility in western Nebraska. In addition, the Ideal Cement and Nebraska Public Power District owned short lines, operated by the UP and the BN, respectively.

Western Railroad Properties, a subsidiary of the C&NW, was the originating line for coal trains from eastern Wyoming, and stemmed from a 1976 ICC authorization for the C&NW and BN to jointly serve this area. The C&NW transfers its coal traffic to the UP at Joyce for the haul east and switched back to its own tracks at Freemont.

Financial Assistance

Using federal or local public funds for rail revitalization was permitted by the Agricultural and Industrial Branch Rail Revitalization Act of 1980, which established a seven-member council to oversee state railroad revitalization activities. The council could issue bonds but had no taxing authority. Local entities were permitted to form regional rail councils and to be responsible for each line revitalization project (*33*). About one-half of Nebraska's system was light-density and branch lines, carrying about 95 percent agricultural traffic, and potential candidates for abandonment. A follow-up study of 2,000 mi of low-density lines and branch lines divided them into four categories: (*a*) those generating enough traffic to be profitable, (*b*) those of borderline profitability but not in jeopardy, (*c*) those that could qualify for assistance based on analysis of benefit-to-cost ratios (including social costs of abandonment), and (*d*) lines that did not warrant financial assistance (*34*). On the basis of the analysis, 412 mi fell in the third category and 621 mi fell in the fourth category. Because there were no federal funds for the state to administer, Nebraska effectively has no state rail assistance program, and a majority of this mileage will likely be abandoned.

The C&NW has one line that is an abandonment or spinoff possibility. It runs north from Norfolk to South Dakota and on to Wyoming, with most traffic concentrated near Norfolk and north of Rapid City (and negligible amounts between).

Intermodal

The switch from TOFC to COFC meant that all 19 ramps in Nebraska, except for three in Omaha, were closed by 1988. Three of the four railroads serving Omaha have container-handling capabilities. Eleven cities lost intermodal loading ramps during the 1980s.

SUMMARY AND CONCLUSIONS

In the region, impacts on the rail system were most severe in Iowa, which lost about one-third of its roadway miles during the 1980s, and in Missouri. The rail systems of Kansas and Nebraska were comparatively unchanged. However, it is likely that the western half of the region will experience structural change in the 1990s that is similar to that already observed in Iowa. The insight provided by past experiences should help to promote better policy concerning the restructuring of railroads in Kansas and Nebraska. On the basis of research of past trends presented in this paper, it is surmised that the three following trends will continue into the future.

Networks

The rail system in the Midwest has gone through significant structural change in the 1980s and will continue to change. Clearly, much of the change is a result of the new pricing and service design freedoms that carriers were granted by the Staggers Act and that have allowed the carriers to develop a more efficient and compact rail transportation system. The rail system in Region VII is tightly linked to the structural and business pattern changes in the agricultural industry. The survival of short line and regional railroads operating on light-density grain gathering lines is uncertain, because many are precariously dependent on the stability of agricultural traffic.

The dramatic structural changes in Iowa's and Missouri's rail systems during the 1980s are likely to be paralleled by changes in Kansas and Nebraska in the 1990s. The rail plans of each state identified up to 1,000 mi as abandonment candidates. The major question will be which lines will actually be abandoned and which ones will become local railroads, still providing service at costs more in line with low levels of traffic. Neither Kansas nor Nebraska has financial assistance programs, a factor that will inhibit the states' abilities to promote efficient restructuring of their rail systems.

Intermodal

Intermodal movements have experienced extensive growth, with intermodal activity being highly concentrated at large city hub facilities. These facilities will largely continue to be located in urban areas that have high levels of demand to support the costs involved in a mechanized facility. The facilities will provide regional service through cooperation with drayage firms and trucking firms. Nevertheless, because of the significant capital investment involved, the core of intermodal activities, supported by TOFC or double-stack unit trains, with only a few notable exceptions, is likely to expand only in the densest traffic markets. The Midwest states playing the role of conduit for intermodal traffic but not participating in the expansion of intermodal traffic may present an ironic circumstance, but one likely to continue.

Agricultural Traffic

The large-scale deviations in the annual volumes of agricultural exports and fluctuations in traffic volumes make it very difficult for railroads, with high fixed investments, to remain profitable in light-density markets. On the other hand, marginal increases in regional processing capacity will provide more stable points of demand and consistent traffic. Barring a reduction in capacity of the major river traffic lanes (related to drought or lock and dam closures) or a major expansion of exports, the trend toward more short-haul movements and concentration of shipping points should continue.

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Development of Condition Indexes for Low-Volume Railroad Trackage

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Track managers of military, local, and industrial railroads as well as low-volume branch lines and yards of larger railroads need an objective and repeatable method to assess track that can be used as a basis to evaluate current conditions, predict future conditions, establish deterioration rates, formulate long-range budgets, and determine and prioritize renewal projects. In response to this need, the U.S. Army Construction Engineering Research Laboratories in conjunction with the University of Illinois developed condition indexes for rail, joint, and fastenings; ties; and ballast, subgrade, and roadway component groups. An overall composite condition index for railroad track, as a whole, was also developed. The indexes are based on data obtained from a panel of track experts assessing a variety of track conditions through the use of numerical ratings. A weighted deduct-density model is used to translate the panel ratings into meaningful indexes that are computed from routinely collected visual and rail flaw inspection information. The development of those indexes is described.

The U.S. Navy and the U.S. Army together own more than 5,700 mi of railroad track (*1*,*2*) that are vital to the mobilization and operational needs of the Department of Defense. Civilian local (switching, terminal, and line-haul) railroad companies control another 19,000 mi of track (approximately 10 percent of the entire commercial sector) (*3*). That predominantly low-volume ($< \approx 5$ MGT/year) track serves a transportation niche essential to the economic well being of the United States.

Whether the primary motive is mission readiness (military) or profit (commercial), there is a need for a simple and practical condition assessment method that can help maintenance managers perform the following tasks:

- Assess current track conditions,
- Predict future track conditions,
- Establish track deterioration rates,
- Determine and prioritize current and long-range maintenance and repair (M&R) needs,
- Formulate budgets, and
- Measure the effectiveness of M&R.

The method must also be objective and repeatable so that similar results are obtainable by different people. Such a procedure does not currently exist for low-volume track.

NEED FOR CONDITION INDEXES

In an attempt to improve the maintenance management process of military track networks (with a spin-off application to local railroads), the U.S. Army Construction Engineering Research Laboratories (USACERL) has developed and is enhancing a computer-based decision support system called the RAILER Engineered Management System (EMS) (*4*). A condition assessment method was needed in RAILER to support the needs addressed above. The method chosen took the form of unbiased and repeatable condition indexes for rail, joints, and fastenings (RJCI); cross ties and switch ties (TCI); and ballast, subgrade, and roadway (BSCI) component groups as well as an overall Track Structure Condition Index (TSCI). The indexes are able to objectively and quantitatively measure the overall condition of track segments.

Track management using RAILER is performed at two levels: network and project (*4*). These condition indexes are intended to play a key role at the network level, where roadmasters and others make large-scale decisions focusing on the "where," "when," and "how much" aspects of track management. Current condition assessments and deterioration modeling (prediction models are under development) are the heart of the management process. Deterioration modeling has been recognized as an important element in track maintenance planning (*5*–*8*). Critical index values can be determined whereby track segments that are below an established critical value are candidates for M&R. The candidate track segments can then be prioritized for actual work accomplishment, and long-range (2 to 10 years) work plans can result. Budgets can be developed on the basis of anticipated needs by correlating costs with projected future year index values.

Network level management using these indexes coupled to prediction models will also permit "what if" analyses to be made. For example, the costs (budgets) associated with establishing a minimum acceptable condition index at various target levels could be computed. Also, the effects of deferred maintenance or budget cuts, in terms of index value reduction, could be determined.

CONDITION ASSESSMENT METHODS

Different methods for assessing railroad track conditions have been or are being used to meet various management objectives. These include track standards and track quality indexes.

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Track Standards

Track standards are widely used in both the commercial and military sectors for condition assessment. Various standards have been developed by different federal agencies for the primary purpose of ensuring track safety (*9*) and safety combined with specific maintenance levels (*10,11*). Commercial railroads (large and small) may also have developed standards for their internal use.

Unfortunately, the various standards do not provide for an overall rating reflective of the overall condition of a track network, specific tracks, track portions, or components. Condition can only be classified generally in terms of meeting or not meeting the discrete requirements of a standard. Although current M&R needs can be determined with respect to an appropriate standard, condition prediction is not possible, nor can future work needs or budgets be determined. This is because deterioration rates cannot be determined or modeled for predicted performance.

Track Quality Indexes

Automated track geometry–based condition indexes have been developed that are commonly known as track quality indexes (TQIs) (*5,12–16*). The various TQIs generally measure different statistically based parameters (e.g., standard deviation) derived from alignment, profile, cross-level, warp, and gage measurements. Because of the expense associated with the data collection, TQIs are generally used only on important high-speed or high-tonnage lines. However, low speeds, certain track conditions, and car harmonics also can lead to derailments, and certain indexes have been developed to measure that potential (*17*). TQIs have been shown to be useful for M&R planning (*6,18–21*).

Since the military and most local railroad companies do not routinely collect automated track geometry information, these indexes are not applicable or useful (*22*). No TQIs, based primarily on routine visual inspections, have been developed for low-volume track, which is typically found on military and local railroads.

INDEX REPRESENTATION

Index Definition

Each component condition group index reflects (*a*) the current physical ability to support typical military, short-line, or industrial traffic and (*b*) the maintenance, repair, or rehabilitation needs to sustain that traffic. The TSCI is intended to do the same, but for the track structure as a whole.

Condition Category Guidelines

Condition and M&R guidelines were established for the seven categories that make up the index scale. These were needed to ensure that the computed indexes would meet the intended definition given above. Table 1 gives the seven categories and guidelines. As will be discussed later, the guidelines were essential to developing meaningful indexes.

APPLICATION CRITERIA

The indexes are intended to be used on military trackage, local track networks, some yards, sidings, branch lines, and other tracks of larger railroads that meet the following criteria:

- Track structure: Wood ties were assumed in the development of the TCI because of their preponderance in track. Also, all of the indexes were developed on the assumption that the rail weight was neither very light [less than about 35 kg/m (70 lb/yd)] nor very heavy [greater than about 59 kg/m (118 lb/yd)].
- Traffic density and speed: The indexes were developed on the assumption that traffic is generally light [less than about 5.5 million metric gross tons/year (5 MGT/year)] and that speeds are limited to about 67 km/hr (40 mph).

CONDITION SURVEY CRITERIA

The intended purposes of these indexes require neither very detailed nor extensive condition information. Thus, a research objective was to design a condition survey inspection procedure that collected just the right amount and type of information with a minimum level of effort. The survey is intended to be accomplished primarily through visual means during one or more periodic track safety inspections. Internal rail flaw surveys can be used to supplement the visual surveys. Annual, biannual, or less frequent condition surveys are envisioned depending on several variables, especially the rate of track deterioration.

To further minimize the level of effort associated with the condition surveys, sampling methods may be used. Since the intent is to quantify a generalized condition for the purposes cited above, the entire track segment length need not be surveyed. Rather, surveying a reasonable number of representative sample units for each track segment will suffice. The sample units were defined in the development process to be nominally 30 m (100 ft) in length.

The condition survey process is described elsewhere (*23*).

RATING SCALE DEVELOPMENT CONCEPTS

Rating Panel

Rating scales can be developed in various ways depending on the intent and parameter being scaled. One approach uses rating panels for the collection of rating information. With this approach, raters are presented with a physical stimulus, and a rating is provided in response (*24*). A rating panel approach proved to be an ideal method for developing these indexes.

The panel consisted of 27 track experts from commercial railroad companies, military installations, a research laboratory, a university, and a consulting business. Their experience averaged 22.5 years.

TABLE 1 Condition Category Guidelines

Index	Category	Condition Description
86-100	**Excellent**	Very few defects. Track function is not impaired. No immediate work action is required, but routine or preventive maintenance or minor repair could be scheduled for accomplishment.
71-85	**Very Good**	Minor deterioration. Track function may be slightly impaired. No immediate work action is required, but routine or preventive maintenance or minor repair could be scheduled for accomplishment.
56-70	**Good**	Moderate deterioration. Track function is somewhat impaired. Routine maintenance or minor repair may be required.
41-55	**Fair**	Significant deterioration. Track function is impaired, but not severely. Significant maintenance or minor repair is required.
26-40	**Poor**	Severe deterioration over a small percentage of the track. Less severe deterioration may be present in other portions of the track. Track function is seriously impaired. Major repair is required.
11-25	**Very Poor**	Severe deterioration has occurred over a large percentage or portion of the track. Less severe deterioration may be present in other portions of the track. Track is barely functional. Major repair or less than total reconstruction is required.
0-10	**Failed**	Severe deterioration has occurred throughout nearly all or the entire track. Track is no longer functional. Major repair, complete restoration, or total reconstruction is required.

Scale Classification and Method

The scale given in Table 1 is an interval scale (*25*). An interval scale lends meaning to number size and the differences between pairs of numbers. Ordering is possible, and mean and standard deviation have meaning. However, values are not proportional.

Interval scale ratings can be obtained directly or indirectly (*26,27*). The direct approach was used, which means that a rater can quantify his or her judgment directly on the scale.

Instruction

The development of an interval rating scale using the direct approach in compliance with established principles requires that the rating panel members be thoroughly instructed in their task (*25*). The instructions provide guidance and direction on specifically what raters are to do and how they are to do it. This process includes a definition of what the rating scale represents and an explanation of specific anchors and cues on the scale (*24,26*). For this development the primary anchor for that scale is 100, meaning that the track is free of observable distress. Each interval boundary (see Table 1) also serves as an anchor.

Cues lead to rater understanding of what the different portions of a rating scale represent (*24,26*). The condition descriptions in Table 1 provided the cues for the ratings. Two sets of cues were superimposed in the descriptions: operational and M&R considerations. The raters were advised to consider both in their ratings.

WEIGHTED DEDUCT-DENSITY MODEL

The collection of rating panel information, in itself, did not result in the desired condition indexes. A model was needed to translate inspection information into condition indexes based on the ratings. In fact, the condition indexes are mathematical models for estimating the average subjective ratings of an experienced rating panel. The weighted deduct-density model proved to be ideal for computing the component indexes.

Model Concepts and Theory

The degree of deterioration of a track component group is a function of three characteristics:

- Type of distress (e.g., rail defects);
- Severity of distress [e.g., bolt hole crack ≤ 12.7 mm (0.5 in.)]; and
- Amount of distress, commonly expressed as a percentage to indicate density [e.g., 10 percent of rails have bolt hole cracks ≤ 12.7 mm (0.5 in.)].

Each of these will have a profound effect on the determination and quantification of track component group condition. Thus, each must be included in a condition index mathematical model.

Within a given track component group, a multitude of distresses can occur. Different types, severities, and densities can all be present in the same track segment sample unit. The model must consider each type, severity, and density separately and in combination to derive a meaningful index. Since each of these potentially affects the derivation in an unequal fashion, weighting factors are needed. The model assumes that a track component group condition index can be estimated by summing the appropriate individual component group distress types over their applicable severity and density levels through the use of appropriate weighting factors. The basic weighted deduct-density model is

$$\text{RJCI, TCI, or BSCI} = C - \sum_{i=1}^{p} \sum_{j=1}^{m_i} a(T_i, S_j, D_{ij})F(t, d) \qquad (1)$$

where

RJCI = rail and joints condition index;
TCI = tie condition index;
BSCI = ballast and subgrade condition index;
C = constant, equal to 100 for this application;
$a(\ )$ = deduct weighting value depending on distress type T_i, severity level S_j, and distress density D_{ij};
i = counter for distress types;
j = counter for severity levels;
p = total number of distress types for component group under consideration;
m_i = number of severity levels for the ith distress type; and
$F(t, d)$ = adjustment factor for multiple distresses that vary with total summed deduct value, t, and number of individual deducts over an established minimum value, d.

Distress Types and Severity Levels

The various distress types and severity levels for each component group were defined in a manner that makes them easily identifiable during the condition survey. The defining process is described later.

Deduct Weighting Values

The deduct weighting values resulted from the panel's subjective condition ratings of individual distress type and severity level combinations. The panel provided the "weighting" through their ratings. The panel averages lead to the creation of deduct curves, which are graphical representations of deduct value versus density for each distress type and severity level combination. This is discussed further later.

Adjustment Factor for Multiple Distresses

Mathematically, nonlinearity is a requirement for the model. Otherwise, negative condition indexes could occur. From a rating perspective, it was found that as additional distress types and severity levels occurred in the same track segment sample unit, the impact of any given distress on the condition rating became less. To account for this in the model, an adjustment factor must be applied to the sum of the individual deducts. The panel ratings were used to determine these factors.

DISTRESS DEFINITIONS

Distress Types

Many distress types within a given component group were defined by combining a variety of possible defects for each different component within the group. An example using rail illustrates the approach. Within the RAILER EMS, 33 rail defects are identified (*28*). These defects include bolt hole cracks, broken bases, vertical split heads, corroded bases, crushed heads, detail fractures, and end batter. All 33 possible rail defects were combined into one distress type called "rail defects."

Still other distress types within a given component group were defined from the differing defects that are component specific. As an example, two different ballast defects include erosion and settlement. In this example, both of those defects were defined as separate distresses.

In all, 25 different distress types were defined. These include 6 for the rail, joints, and fastenings component group, 8 for the tie component group, and 11 for the ballast, subgrade, and roadway component group. They are given in Table 2. Complete definitions are found elsewhere (*23,29*).

TABLE 2 Distress Type Listing

Rail, Joints, and Fastenings
R1. Rail Defects
R2. Joint Defects
R3. Hold-Down Device Defects
R4. Tie Plate Defects
R5. Gauge Rod Defects
R6. Rail Anchor Defects
Ties
T1. Single Defective Tie
T2. Isolated Defective Tie Cluster
T3. Isolated Defective Tie Cluster that Includes One Joint Tie
T4. Adjacent Defective Tie Cluster
T5. All Joint Ties Defective
T6. Missing Tie
T7. All Joint Ties Missing
T8. Improperly Positioned Tie
Ballast, Subgrade, and Roadway
B1. Dirty (Fouled) Ballast
B2. Vegetation Growth
B3. Settlement of Ballast and/or Subgrade
B4. Hanging Ties at Bridge Approach
B5. Center Bound Track
B6. Pumping Ties
B7. Alignment Deviation
B8. Insufficient Crib/Shoulder Ballast
B9. Erosion of Ballast
B10. Inadequate Trackside Drainage
B11. Inadequate Water Flow Through Drainage Structures

As a matter of developmental philosophy, design deficiencies or current inadequacies, such as rail that is too light or tight curves (not caused by alignment deviations) that restrict speed or are derailment prone, were *not* considered as distresses. If present, those deficiencies will be reflected through relatively fast track deterioration, which will be measured over time by the appropriate condition index.

Severity Levels

Simply having distress types defined was not enough for a complete condition evaluation. A single distress type can have differing degrees of impact on a track's ability to perform as intended. The degrees of impact are reflected as severity levels. However, before specific distress severity levels could be defined, a general description of how severity levels would relate to the degree of impact on track performance was needed. Raters desired descriptions that relate to track operational criteria as specified in various track standards. Four severity levels resulted. Table 3 describes these levels and their meaning.

In the final outcome, not every distress type required all four severity levels. Some distress types simply cannot become so critical that they restrict or halt train operations. Also, for a few distress types, no severity levels were required because there are no discernible levels that would affect operations or M&R actions differently.

Definition Evolution

The final distress definitions evolved through an iterative process. First, review of the Federal Railroad Administration, Navy, and Army track standards led to an initial listing. Then discussions with track experts for feedback and revisions fol-

TABLE 3 Severity Level Descriptions

Severity Level	Description
Low (L)	Minor distresses that do not affect train operations. Routine M&R can be scheduled for accomplishment.
Medium (M)	Distresses that may or may not cause an operating restriction on the track. M&R should be scheduled for accomplishment.
High (H)	Distresses that generally would cause an operating restriction on the track. M&R must be accomplished to remove the restriction.
Very High (VH)	Distresses that prevent train operations or place a very severe operating restriction on the track. M&R must be accomplished to restore train operations.

lowed. This two-step process resulted in preliminary definitions that formed the basis for collecting an initial set of rating data. Discussions held with the raters during the collection process led to further definition revisions. Data analysis and the graphing of the deduct curves resulted in still further modifications. For example, Table 2 gives different tie distresses called, in part, "isolated" or "adjacent." The difference is the number of good ties between the clusters. That number (two or more) was derived from the rating data. A compilation of all of the final definitions is published elsewhere (*23,29*), and an example is given in Table 4.

DATA COLLECTION

Each distress type and severity level combination required the collection of rating data over a range of densities so that the deduct curves could be determined. Ideally, the rating panel would assess these different distress types, severity levels, and densities in the field. However, sufficient locations were not known that would result in the collection of all of the needed rating data, project funding did not permit sufficient travel for a rating panel to visit widespread locations even if they were known, and getting an entire group of experts to-

TABLE 4 Distress Definition for Joint Defects

R2. Joint Defects

Description: Joint defects include all items that reduce the strength or functionality of joints. Fifteen joint defects are possible. They are listed below within specific severity levels.

Severity Levels:

L - The following defects are low severity:

Broken or Cracked Bar (not through center)
Defective or Missing Bolt
Improper Size or Type of Bar
Improper Size or Type of Bolt
Loose Bolt
Torch Cut or Altered Bar

M - The following defects are medium severity:

All Bolts at Joint Loose
One Bar Center Broken or Missing
One Bar Center Cracked
One Bar Corroded
Only One Bolt per Rail End
Rail End Gap > 25.4 mm (1.0 in) and ≤ 50.8 mm (2.0 in)
Rail End Mismatch > 4.8 mm (0.1875 in) and ≤ 6.4 mm (0.25 in)

H - The following defect is high severity:

Both bars center cracked

VH - The following defects are very high severity:

All Bolts on a Rail End Broken or Missing
Both Bars Broken or Missing
Rail End Gap > 50.8 mm (2.0 in)
Rail End Mismatch > 6.4 mm (0.25 in)

Measurement: Each loose bolt, etc. is considered a separate defect occurrence at a given joint. However, as applicable, only the highest severity level shall be recorded for a specific component (i.e. if the VH severity defect of all bolts on a rail end are broken or missing is present, the L severity defect of individual defective or missing bolts is not counted at the same joint). Defects are summed on a per joint basis. Rails longer than 12 m (39 ft) in length shall be divided into the largest number of equivalent rail lengths of 12 m (39 ft) or less. Assume that imaginary joints exist linking those rails and that those joints are defect free.

Density: Number of Affected Joints / Total Number of Joints in Sample Unit gether at one time to do the ratings proved impossible. Thus, that approach for data collection was not feasible.

The answer to how to collect the necessary data was to develop coded schematic rating sheets to display different "track problems" that would be rated. The track problem displayed on each sheet represented a certain distress type and severity level at a density that could be found on a track segment sample unit. Figure 1 shows a situation where a single joint has two loose bolts [shown encoded as LBT(2)]. A series of sheets was developed for each component group to cover the range of distress types and severity levels at varying densities germane to that group. For some, particularly ties where the interactions of clusters would surely drive the defining process, various relationships were presented for rating.

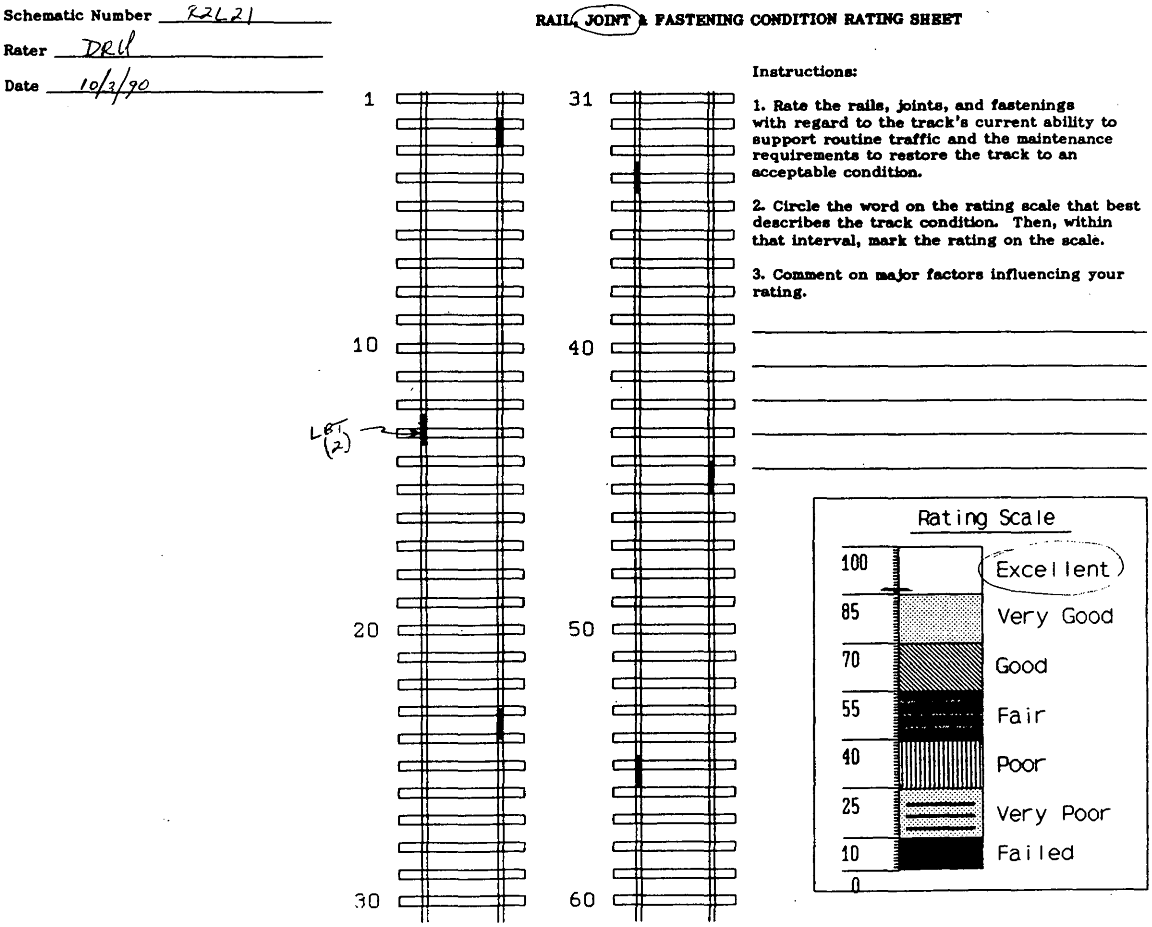
All of the sheets were sorted randomly before being given to each member of the panel. Also, the raters were not told of the distress types and severity levels that they were rating. Rather, the track problems were simply presented. Presenting the sheets in a logical sequence or providing descriptions with words like "very high severity" could have influenced the ratings and, thus, introduced undesirable error.

The rating sessions took place over a period of several months. Generally, the sessions occurred in small groups and at the normal work locations of the raters. Thus, the entire group never assembled concurrently, but most raters were involved in several sessions.

At each session, the raters were given general instructions by a facilitator, a copy of the rating guidelines to use as rating cues, Table 1, and a set of the rating sheets. As each rater completed a given sheet, it was collected by the facilitator. Raters were not permitted to review completed sheets while rating new sheets, nor were they permitted to see the ratings given by other raters. While each sheet was being rated, the facilitator described the track problem, encouraged the raters to discuss the track problem, and answered questions to help ensure understanding of what was to be rated.

After a given set of sheets was completed, either the facilitator reviewed the data during the session or a research assistant reviewed the data later. Any rating that was more than 15 points or two standard deviations (whichever was less) from the panel average was flagged for a rerate. This was done to allow raters the opportunity to correct certain ratings that may have been marked by mistake because of misunderstanding, misinterpretation, distraction, or some other reason.

To rerate, the appropriate sheets were given back to the raters to be rated again. Generally, a short discussion about the distress ensued. The raters were never told whether they were above or below the panel average, and they were under no obligation to change their marks. To reinforce the "no obligation to change" idea, typically the panel members present were all given the same sheets to rerate. Raters were



Schematic Number R2L21

Rater DRU

Date 10/3/90

RAIL, [✓ JOINT] & FASTENING CONDITION RATING SHEET

Instructions:

1. Rate the rails, joints, and fastenings with regard to the track's current ability to support routine traffic and the maintenance requirements to restore the track to an acceptable condition.

2. Circle the word on the rating scale that best describes the track condition. Then, within that interval, mark the rating on the scale.

3. Comment on major factors influencing your rating.

Rating Scale

100	[✓ Excellent]
85	Very Good
70	Good
55	Fair
40	Poor
25	Very Poor
10	Failed
0	

FIGURE 1 Example schematic rating sheet.

always advised to rate their convictions, not to be concerned about what others rated, and that differences in opinion were expected.

The development of the deduct curves required establishing a certain degree of accuracy for those curves. A reasonable goal was to have, on the average, the deduct value associated with a given density on the deduct curve with the highest variation be within five points of the true average deduct value at a 95 percent confidence interval. This goal was met through the large number of raters employed and amount of data collected (more than 13,000 data points). This is discussed in greater detail elsewhere (*29,30*).

DEVELOPMENT OF THE DEDUCT AND CORRECTION CURVES

A nonlinear regression analysis was used for initial deduct curve determination. Variances and the required rating panel size needed for the desired accuracy were computed from this. In the final form, some smoothing of the curves was performed, because pure reliance on mathematics ignores certain engineering logic. The deduct curves for each severity level within a given distress type form a family, and as such, certain consistent trends for that family are expected. A best smooth curve fit of the final curves ensures that the trends are correct and consistent with the physical happenings. Figure 2 shows the deduct curves for Distress Type R1—rail defects at low severity. The numbers near the curves indicate the number of defects per rail.

As part of the rating sessions, the facilitator gave each rater sets of coded schematic rating sheets that illustrated various combinations of distress within the same component group. For example, a defective rail and a defective joint might occur together on the same sheet. These average rating values were compared with values obtained from summing the deduct points obtained from the deduct curves for all of the distresses present. A family of correction curves resulted. An example set is shown as Figure 3. Note in Figure 3 that there is a numerical cutoff "q" for applying the correction. This cutoff was determined from a best fit analysis and varies for each component group.

FIELD VERIFICATION

The field verification procedure was simple. A group of raters would together survey a selected track segment sample unit so that all agreed on the distresses found. Each rater would rate the rail, joints, and fastenings; tie; and ballast, subgrade, and roadway component groups. Each rater was also asked to provide an overall composite track structure condition rating. Upon completion, the facilitator led a group discussion with each member explaining his rating to the other members of the group. The ratings were then averaged for use in the verification.

After the rating panel surveyed and rated the sample units, the condition indexes were computed from the survey data using the appropriate deduct and correction curves. The computed index values were then compared with the average ratings of the panel. The correlations were excellent. Table 5 gives the correlations.

The field work led to minor distress definition revisions, as appropriate, and to slight adjustments to a few deduct and

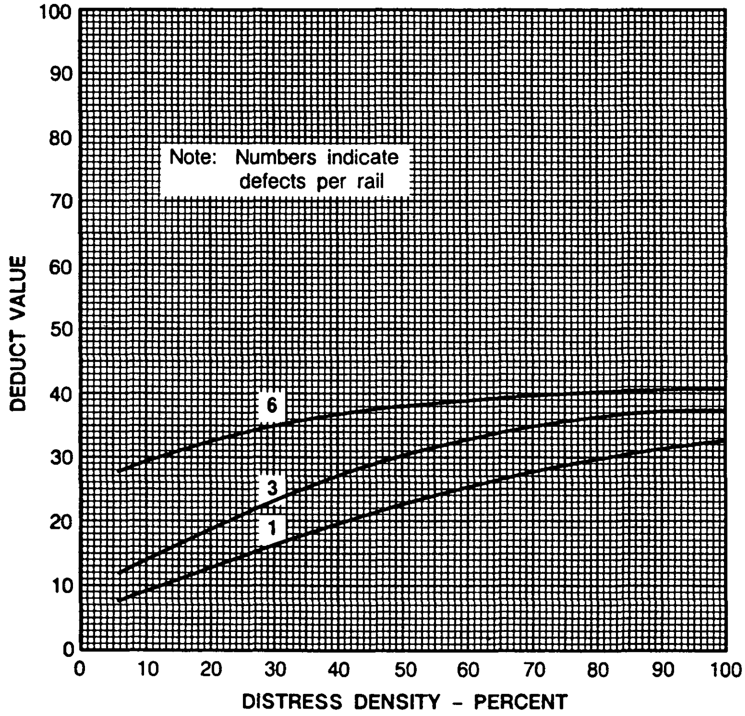


FIGURE 2 Deduct curves for Distress R1L—low severity rail defects.

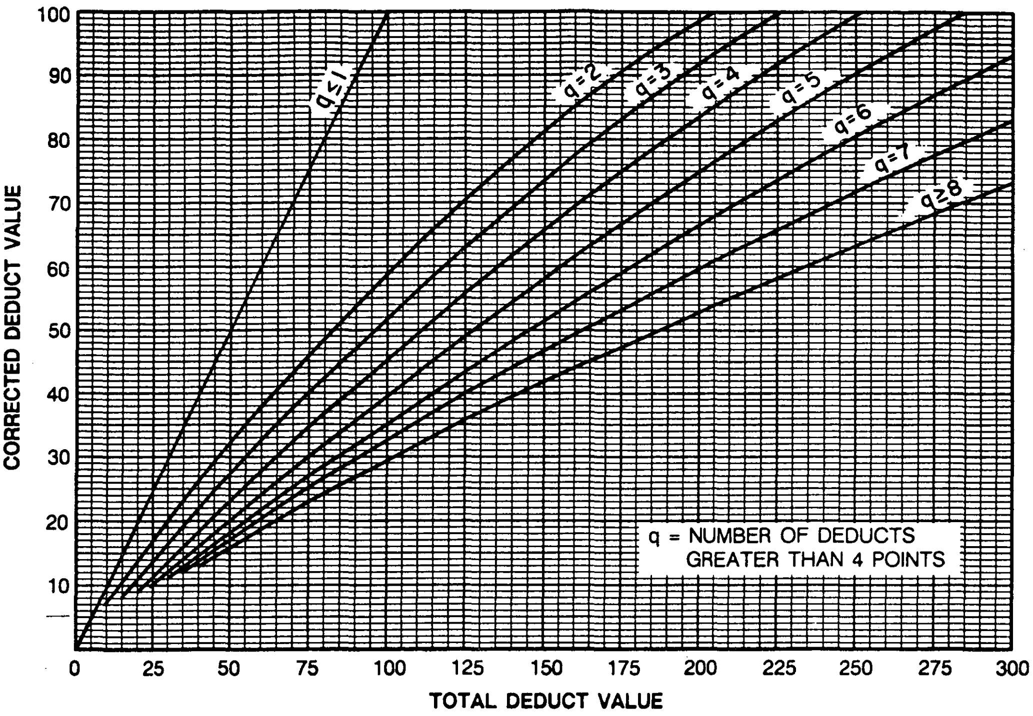


FIGURE 3 Rail, joints, and fastenings component group correction curves.

correction curves. The numerical cutoffs for the correction curves were also altered by a point or two, depending on the component group. An improved match between the computed condition indexes and the average panel ratings resulted.

TSCI DEVELOPMENT

Different approaches were investigated for aggregating the RJCI, TCI, and BSCI into the TSCI (*29,30*). The goal was to select the approach that led to the best correlation of predicted TSCI with the rating panel's average rating (TSCR) collected during the field validation stage described above.

A basic three-term linear equation was desired. Recognizing that the lowest component group index influenced the TSCI the most and that the highest component group index influenced the TSCI the least, the task was to determine the term coefficients. Each term coefficient, to be weighted properly, is a value less than 1.0, and the sum of the coefficients equals 1.0. The following equation resulted:

$$\mathrm{TSCI} = 0.50\mathrm{LOW} + 0.35\mathrm{MID} + 0.15\mathrm{HIGH} \quad (2)$$

The values used in Equation 2 are the computed RJCI, TCI, and BSCI, ranked low to high. The correlation between the panel ratings and the computed indexes is shown in Table 5.

CONDITION INDEX DETERMINATION PROCEDURE

Table 6 gives an example of how to compute an RJCI for a sample unit. The same process applies to the TCI and BSCI. A TSCI computation is also given. The indexes for a track segment, as a whole, are averaged from the sample unit indexes.

TABLE 5 Condition Rating/Condition Index Correlations

	Statistic	
Index	Mean Difference between Computed Index and Panel Ratings, (Δ pts)	Correlation Coefficient (r^2)
RJCI	-1.2	0.91
TCI	-0.4	0.76
BSCI	-0.5	0.94
TSCI	0.0	0.86

TABLE 6 Example RJCI and TSCI Computation

Step 1: Inspect Rail, Joints, and Fastenings Component Group in Selected Sample Units

Summary:

1 Rail, Single Occurrence of a Low Severity Defect
2 Joints, Single Occurrence of a Low Severity Defect
1 Joint, Single Occurrence of a Medium Severity Defect
24 Occurrences of Improper Spiking Pattern
9 Occurrences of Improperly Positioned Rail Anchors

Step 2: Compute Densities

60 Ties and 6 Rails in Sample Unit

R1L(1): Density = 1/6 = 16.7%
R2L(1): Density = 2/6 = 33.3%
R2M(1): Density = 1/6 = 16.7%
R3: Density = 24/(60*4) = 10.0%
R6: Density = 9/60*4) = 3.75%

Step 3: Compute Deduct Values (DV)

R1L(1): DV = 11 (from Figure 2)
R2L(1): DV = 22 (given)
R2M(1): DV = 35 (given)
R3: DV = 14 (given)
T6: DV = 10 (given)

Step 4: Compute Total Deduct Value (TDV): TDV = 92

Step 5: Determine "q"

q = 5 (total number of deducts greater than 4 pts)

Step 6: Determine Corrected Deduct Value (CDV)

CDV = 36 (from Figure 3)

Step 7: Compute RJCI and Determine Condition Category

RJCI = 100 - CDV = 64 --> Good (from Table 1)

Step 8: Compute TCI and BSCI for Sample Unit (as above); RJCI, TCI, and BSCI for all Other Selected Sample Units; and Average Results

Step 9: Rank Track Segment Average Component Group Indexes

Low = RJCI = 55 (given)
Mid = TCI = 58 (given)
High = BSCI = 67 (given)

Step 10: Substitute into Equation 2 and Compute TSCI

TSCI = 0.50(55) + 0.35(58) + 0.15(67)
TSCI = 58 --> Good (from Table 1)

CONCLUSIONS

This work was initiated to develop condition indexes for railroad track, and that development was accomplished. Specifically, indexes were developed for the rail, joints, and fastenings component group (RJCI); tie component group (TCI); ballast, subgrade, and roadway component group (BSCI); and the track structure in general (TSCI). The indexes represent the average subjective judgment of a panel of experienced track experts. The use of an interval rating scale using the direct approach proved workable for this application. The use of schematic rating sheets was shown to be a practical method of data collection as the results were field validated. The weighted deduct-density model was an excellent application for index development and use.

The indexes are intended primarily to help track managers perform a variety of network-level management tasks. These include assessing current condition, predicting future condition, determining deterioration rates, developing and prioritizing long-range work plans and budgets, and measuring the effectiveness of M&R work.

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Dynamic Track Support Loading from Heavier and Faster Train Sets

G. P. RAYMOND AND Z. CAI

The growing use of heavier axle loads and faster speeds in railway train operations increases the likelihood of a track support overloading. Using an analytical dynamic wheel/rail and track interaction model, the effects of heavier axle loads and faster speeds on the increase of wheel/rail forces, rail seat loads, and ballast/subgrade pressures are investigated. The axle loads input include those of typical 50-, 70-, 100-, and 125-ton cars complete with unsprung masses. Also included is a projection of what might be expected in the future should 150-ton cars become acceptable. The dynamic loads estimated are for a track composed of RE 136 rail (having a mass of 68.7 kg/m) supported by CN 55A concrete ties at 610 mm center to center and insulated with EVA tie pads and traversed by a truck with the front wheel having a rounded flat (50-mm length × 0.4-mm depth) and a perfectly shaped rear wheel. The theory and concepts are easily extended to dipped rail joints, rail corrugations, random worn wheels of any profile, and other rail or wheel irregularities traversing wood or concrete tie track.

One of the principal functions of the wheelset is to transfer train loads to the rail track, which in turn transmits and attenuates the loads from the wheels to the ballast and subgrade. With the growing use of heavier train loads and faster speeds, the dynamic wheel/rail forces and track responses associated with wheel, rail, and track irregularities, on present-day (1992) main line tracks, are mostly of high frequency and high magnitude. This will inevitably bring increased deterioration of the track support including the ballast layer and subgrade. Costly damages inflicted on the track components and the wheelset have led to widespread interest in investigating the wheel/rail impact forces. Representative studies included research carried out by Battelle Columbus Laboratories (*1–5*), British Rail Research Division (*6–9*), Track Laboratory of Japan National Railways (*10–12*), and Cambridge University Engineering Department in collaboration with British Rail (*13–15*). All these studies included both analytical and experimental techniques. Most of the studies limit consideration of rail seat and ballast loadings, and the effects on the rail seat loads and ballast pressures resulting from increased axle loads and faster speeds are rarely a subject of focus.

The work reported here is from continuing research on rail vehicle and track dynamics (*16–18*). The primary objective of this research has been the establishment of an improved theoretical model for investigating wheel/rail impact forces and track responses due to wheel and rail irregularities. The effects of a rounded wheel flat loading on typical North American infrastructure are investigated using the model. Rail support loadings from freight cars of different capacity are given particular attention.

WHEELSET MODEL

The wheelset is a four-degree-of-freedom lumped mass model as shown in Figure 1. The track model was initially developed for transversely symmetric vibration (*16*). This limits the wheelset model to include only the two unsprung masses (m_u) and the side frame (m_s, I_s) pertaining to one rail. The side frame mass is connected to the unsprung masses through the primary suspension springs at each end (k_1, c_1). The vehicle components above the truck body will not contribute much to high frequency wheel/rail impact because of the low resonant frequencies (below 5 Hz) involved. For this reason, they are ignored here. Only the static car body weight (P_s) is included. The wheel/rail reaction forces on the two wheels are $f_1(t)$ and $f_2(t)$. The equations of motion of the wheelset system are as follows:

$$[M]\{\ddot{Y}\} + [C]\{\dot{Y}\} + [K]\{Y\} = \{f\} \tag{1}$$

where

$$[M] = \begin{bmatrix} m_u & 0 & 0 & 0 \\ 0 & m_u & 0 & 0 \\ 0 & 0 & \dfrac{m_s}{2} & \dfrac{m_s}{2} \\ 0 & 0 & \dfrac{I_s}{l_w} & \dfrac{-I_s}{l_w} \end{bmatrix} \tag{1a}$$

and

$$[C] = \begin{bmatrix} c_1 & 0 & -c_1 & 0 \\ 0 & c_1 & 0 & -c_1 \\ -c_1 & -c_1 & c_1 & c_1 \\ \dfrac{-c_1 l_w}{2} & \dfrac{c_1 l_w}{2} & \dfrac{c_1 l_w}{2} & \dfrac{-c_1 l_w}{2} \end{bmatrix} \tag{1b}$$

in which the symbols are as shown in Figure 1. $[K]$ bears the same form as $[C]$ with c_1 in Equation 1b replaced by k_1. The displacement vector $\{Y\} = \{y_1, y_2, y_3, y_4\}^T$ and the force vector $\{f(t)\} = [-f_1(t), -f_2(t), P_s, 0]^T$.

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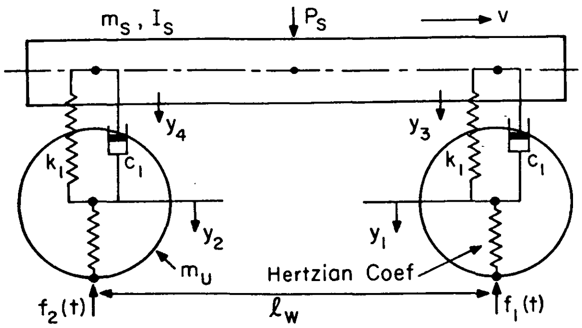

FIGURE 1 Wheelset model.

TRACK MODEL

By a procedure similar to but modified from that developed elsewhere (*7–9*), the track model was formulated by representing the rail and the ties as elastic beams, the rail pads (for a concrete-tie track) as linear springs with viscous damping, and the stiffness and vibration absorbing effect of the underlying track bed as a continuous array of linear springs and viscous dashpots. This is shown in Figure 2. The rail is assumed to have a finite length with the ends clamped and to be supported discretely on the tie beams at the rail seats. The effects resulting from the assumption of a finite length on the wheelset and track responses will be minimal at the midregion away from the ends when the rail length is taken long enough. The current model takes a track length of 40 tie spacings with a single two-axle truck transversing on the rails. Since the behavior and characteristics of the track structure has a great influence on the dynamic interaction between the wheel and the rail and the track support responses, the rail and the ties are described by the more complex and more realistic Timoshenko beam theory. In addition to the flexure and mass inertia considered in the commonly used simple beam theory, the Timoshenko theory takes into account the shear distortion (SD) and the rotatory inertia (RI) effects of the beam. The SD and RI are significant factors in governing high-frequency vibrations of beams.

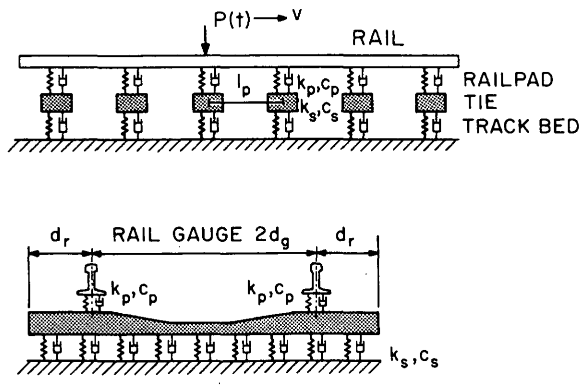

FIGURE 2 Railway track model: *top,* longitudinal track model; *bottom,* cross-tie model.

The equations of the track are obtained by first solving the free vibration of the track and then by applying the method of modal analysis (*16*). The resulting set of equations are

$$\ddot{Q}_n(t) + \sum_{k=1}^{N} 2\xi_{nk}\,\Omega_n\,\dot{Q}_k(t) + \Omega_n^2\,Q_n(t) = f_n(t) \qquad (n = 1, 2, \ldots, N) \qquad (2)$$

where

$Q_n(t)$ = modal time coefficient;
N = number of modes considered;
Ω_n = angular frequency of the track;
ξ_{nk} = coupled modal damping ratio; and
$f_n(t)$ = generalized modal force, expressed by

$$f_n(t) = \frac{1}{M_n}\left[W_n(vt)f_1(t) + W_n(vt - l_w)f_2(t)\right] \qquad (3)$$

where

W_n = *n*th mode shape function of the rail,
M_n = corresponding generalized track mass,
v = train speed, and
l_w = axle spacing.

Equation 2 is a set of *N* coupled equations. The deflection of the rail is obtained using mode summation:

$$w(x, t) = \sum_{n=1}^{N} W_n(x)\,Q_n(t) \qquad (4)$$

HERTZIAN WHEEL/RAIL INTERACTION

The wheel/rail interaction is obtained from the Hertzian contact theory commonly used in wheel/rail contact mechanics and is expressed in the following form:

$$f(t) = G_H[y_W - w(x,t) - \delta(x)]^{\alpha} \qquad (5)$$

where

$f(t)$ = wheel/rail contact force,
y_w = wheel displacement,
$w(x, t)$ = rail deflection at the wheel/rail contact point,
$\delta(x)$ = wheel or rail profile change,
G_H = Hertzian contact coefficient, and
α = constant (1.5 is used here).

By coupling Equations 1 to 5, the wheel/rail interaction forces $f_1(t)$ and $f_2(t)$ and the modal time coefficients $Q_n(t)$ are solved by using the fourth-order Runge-Kutta method with adaptive time stepsize control. The track support responses are then obtained by using the principles of structural dynamics.

VALIDATION OF TRACK MODEL

To illustrate the applicability of the finite length track model in studying field rail track vibration problems, the dynamic receptance characteristics of a typical British Rail field track resulting from an earlier study (*16*) is shown in Figure 3.

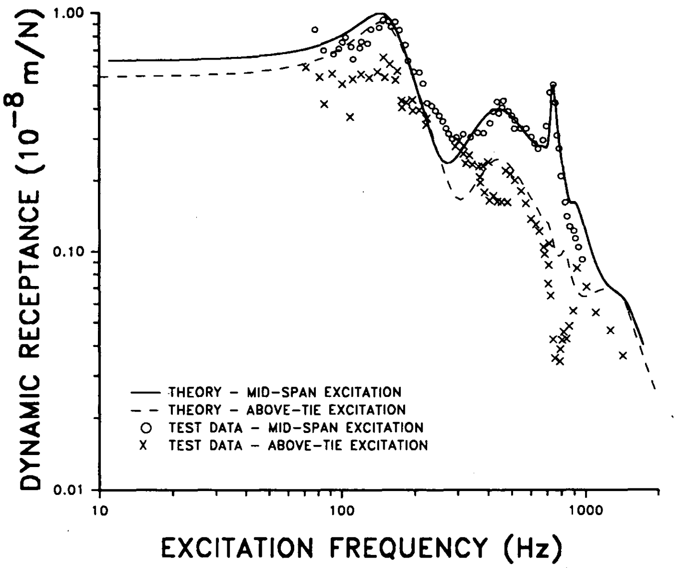

FIGURE 3 Comparison of dynamic receptance of model and field data.

Modal analysis and Fourier transform were used to formulate the theoretical solutions shown in Figure 3. Details of the solution procedure are published elsewhere (*18*). The theoretical results using the Timoshenko beam theory for the rail and the nonuniform tie are compared with field experimental data obtained by Grassie (*15*) for the same track, under both midspan and above-tie excitations. For the midspan excitation, the model gives close agreement to the field measurement data at frequencies below approximately 250 Hz (no data are available below approximately 70 Hz). Above this frequency, the difference between the model and the field data is practically negligible. When the excitation is above a tie, the model solution and field data also compare reasonably well. The response of the track is dominated more by the rail span as a deep beam spanning between two ties when the excitation is at the midspan, and it is dominated more by the rail-pad-tie and ballast system when the excitation is above a tie. The good comparison between the theoretical dynamic receptance results obtained using the finite length track model and the field experiment data indicates that the use of the finite length model is a reasonable representation of the field track under vibration. Further work is under way to validate the model solutions under wheel/rail dynamic interactions. Preliminary results have shown favorable comparison between the theoretical predictions and field measurement data (*19*).

EXAMPLE OF WHEEL/RAIL IMPACT FORCES DUE TO WHEEL FLAT

A typical wheelset with the front wheel having a rounded flat 50 mm long × 0.4 mm deep that is shown in Figure 4 and the rear wheel intact was run across a 40-tie track with concrete ties at various speeds up to 162 km/hr (track and wheel parameters are given in Tables 1 and 2, respectively). The predicted peak impact loads from the wheel flat are shown in Figure 5 for five freight cars of different capacity. The 150-ton car response is a projection of what might be expected should 150 tons become acceptable. The impact load depends highly on the speed. This is particularly so when the train speed is greater than approximately 90 km/hr. The peak load depends to a smaller extent (not shown here) on where the wheel flat strikes the rail, either directly above a tie (above-tie) or between two adjacent ties (midspan). The results presented here are from a wheel flat impact directly above a tie.

The effect of heavier-capacity cars on the peak dynamic wheel/rail loads are clearly seen in Figure 5 over the entire speed range considered. At speeds below approximately 30 km/hr, the increases in the wheel/rail loads from 50- to 150-ton cars are primarily due to the net increase in the static wheel loads. At a higher speed, the dynamic effects of the

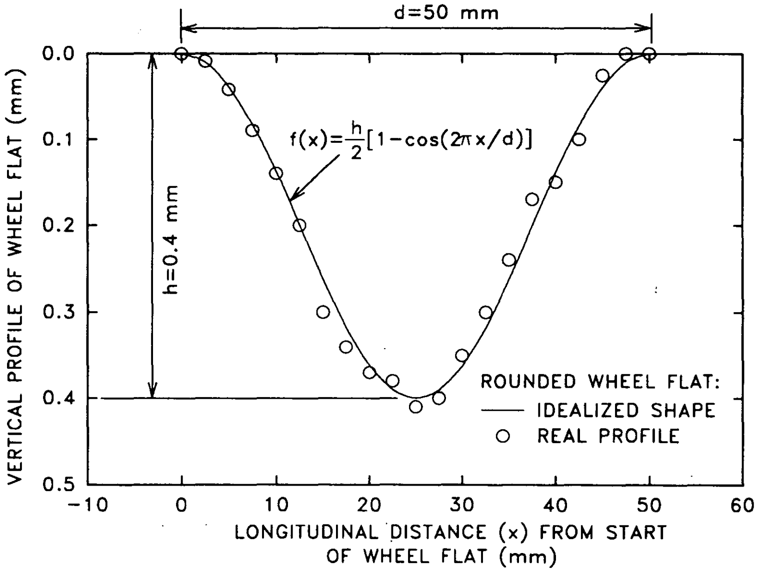

FIGURE 4 Radial wheel flat profile.

TABLE 1 Track Parameters

Tie Parameters (CN 55A Type)		Rail Parameters (RE 136 Type)	
Elastic modulus	E_t= 50 GN/m^2	Elastic modulus	E_r= 207 GN/m^2
Poisson's ratio	= 0.30	Poisson's ratio	= 0.28
Timoshenko shear coeft.	= 0.833	Timoshenko shear coeft.	= 0.34
Tie spacing	= 0.61 m	Cross-sectional area	= 8610 cm^2
Tie length	= 2.50 m	Second moment of area	= 3950 cm^4
Tie width (average)	= 0.25 m	Radius of gyration	= 67.7 mm
Non-uniform section		Bending rigidity	EI_r= 8.18 MN.m^2
Mid-segment length	= 0.90 m	Shear rigidity	κAG_r= 239.3 MN
Mid-segment depth	= 0.14 m	Unit mass	m_r= 68.7 kg/m
End-segment length	= 0.80 m	Rail pad stiffness	k_p= 850 MN/m
End-segment depth	= 0.21 m	Rail pad damping	c_p= 26 kN.s/m
Rail gauge length	= 1.50 m	Track bed stiffness*	k_s= 50 MN/m/m
Tie end to rail seat	= 0.50 m	Track bed damping*	c_s= 34 kN.s/m^2

* These values are assumed to be uniform across the length of the tie.

wheelset and truck side frame masses coupled with the vertical vibration of the track become more prominent. As a result, higher dynamic load increments are induced. A peak wheel/rail load is reached at about 60 km/hr for all the cars, which is followed by a gradual drop in the peak load until 90 km/hr. Above this speed, the wheel/rail impact loads begin to undergo considerable increases with a small increase in the speed. This is more profound for heavier-capacity cars than for lower-capacity ones. For example, the increment between the peak wheel/rail loads of the 125-ton car over the 100-ton car running at 160 km/hr is 3.6 times that between their static wheel loads (or zero speed). This clearly demonstrates that if there exists any irregularity on the wheel (or the rail), which is almost always the case, the use of heavier-capacity cars will certainly engage the rail and the wheelsets to endure dynamic load increments that may be largely in excess of the net increase in the static axle loads.

EXAMPLE OF PEAK RAIL SEAT LOAD AND BALLAST PRESSURE

The corresponding peak dynamic rail seat loads and the peak ballast pressures directly below the rail seat are presented in Figures 6 and 7, respectively, in relation to the speed. The tie for which the rail seat load and the ballast pressure are obtained is the 18th tie of the 40-tie track, above which the wheel flat impact is assumed to occur. Similar to the wheel/rail load shown in Figure 5, the increases in the rail seat loads shown in Figure 6 caused by the net increases in the static wheel loads of the various capacity freight cars are reflected by the initial portions of the curves below 30 km/hr. The sudden increase in the peak rail seat load for all the cars between 30 and 90 km/hr is a direct result of the development of intense dynamic interactions between the wheel and the rail atop the tie, as is indicated in Figure 5 by the quick growth

TABLE 2 Wheel Parameters

Car name (net US ton) Net car weight (MN)	50 0.50	70 0.70	100 1.00	125 1.25	150* 1.50*
Unsprung mass of wheelset (Mg)	1.02	1.10	1.42	1.59	1.79
Mass of side frames (kg)	0.74	0.88	1.13	1.21	1.40
Mass moment of inertia-side frames (kg.m^2)	202	260	363	542	622
Stiffness of primary suspension (MN/m)**	1.50	1.79	2.14	2.80	3.10
Wheel diameter (mm)	762	762	762	965	965
Axle spacing (m)	1.67	1.72	1.78	1.83	1.83
Hertzian coefficient (GN.m$^{-3/2}$)	81.9	81.9	81.9	86.8	86.8
Static wheel load (kN)	94	122	146	178	203

* 150 Ton car data is projected from data on other four cars.

** Damping of primary suspension is assumed to be the same for all the cars at: 9.9 kN.s/m

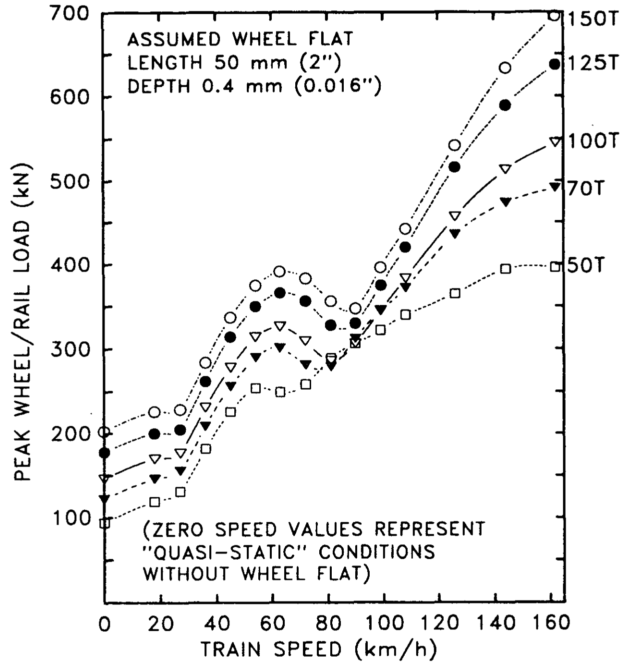

FIGURE 5 Peak wheel impact load due to wheel flat for freight cars of various capacities.

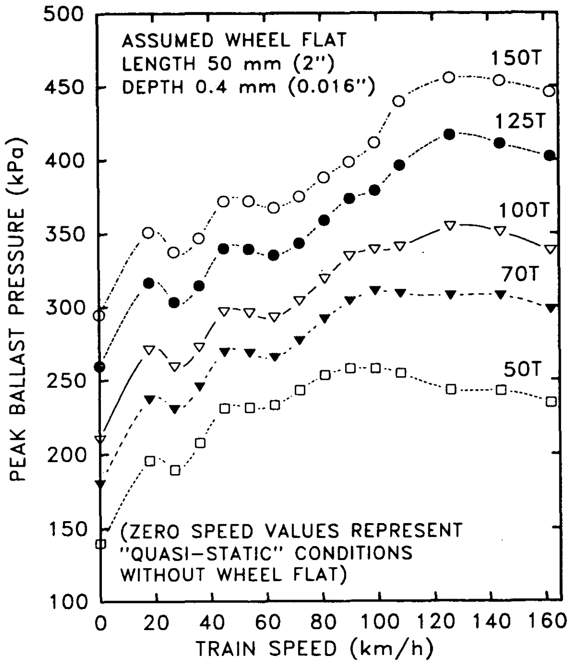

FIGURE 7 Peak ballast pressures for freight cars of various capacities.

of the dynamic peak load within that speed range. Above 90 km/hr, the increase in the peak rail seat load is moderate and begins to flatten for the 125- and 150-ton cars and to gradually decrease for the 100-, 70-, and 50-ton cars.

This leveling off or drop of the rail seat load at higher speeds, despite the marked increase in the wheel/rail impact load shown in Figure 5, is believed to be primarily due to two reasons. One is the shorter duration and thus higher frequency of the wheel/rail impact forces at a faster speed. The other is the increased damping effect of the rail pad, which more effectively attenuates high-speed (or high-frequency) vibrations (*18*). The effect of heavier-capacity cars on the increase of the peak rail seat load is again illustrated by the curves at speeds over approximately 100 km/hr.

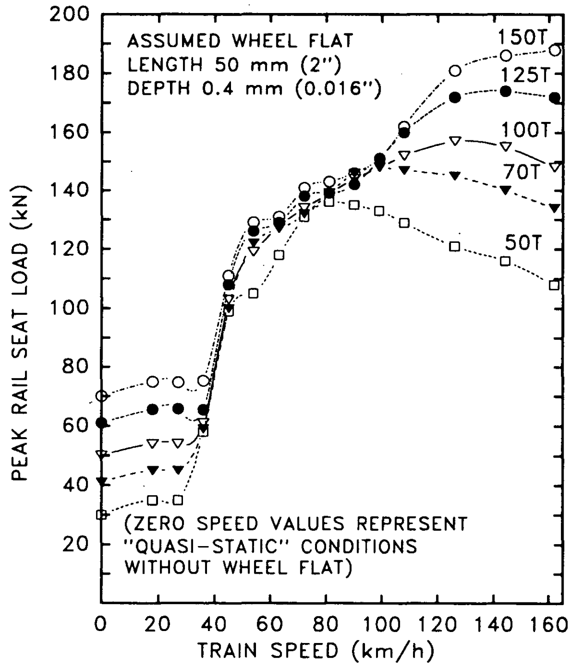

FIGURE 6 Peak rail seat load for freight cars of various capacities.

The effect of an increase in freight car capacity on the increase in the ballast pressure is distinctly evident from Figure 7. The relationship between peak dynamic ballast pressure and speed for different capacity cars, however, is modest compared with the wheel/rail impact forces (Figure 5) and the rail seat loads (Figure 6). For example, the peak ballast pressure under the 125-ton car at 160 km/hr is about 1.5 times its static value, whereas the peak rail seat load is 2.7 times its static value, and the peak wheel/rail load is 3.6 times its static value. Thus, the increase in the ballast pressure due to heavier-capacity cars is to a larger extent attributable to the net increase in the static wheel load than the increase in the wheel/rail load and the rail seat load. This is indicated by the relatively parallel ballast pressure versus speed curves shown in Figure 7. For example, the increment in the peak ballast pressure produced by the 125-ton car over the 100-ton car at 120 km/hr is only 1.3 times the static increment resulting from the net increase in the car weight, whereas the increment gained in the peak wheel/rail load (Figure 5) is close to 2.5 times the net static increment. The relatively moderate relationship between the peak ballast pressure and the speed results from the vibration-attenuating effects of the track structural components, namely the bending rigidity of the rail, the resilience and damping effects of the rail pad, the bending effect of the tie as an elastic beam, and the resilience and damping effects of the ballast itself.

However, below 20 km/hr, the ballast pressure undergoes a higher percentage of increase with the speed than the wheel/

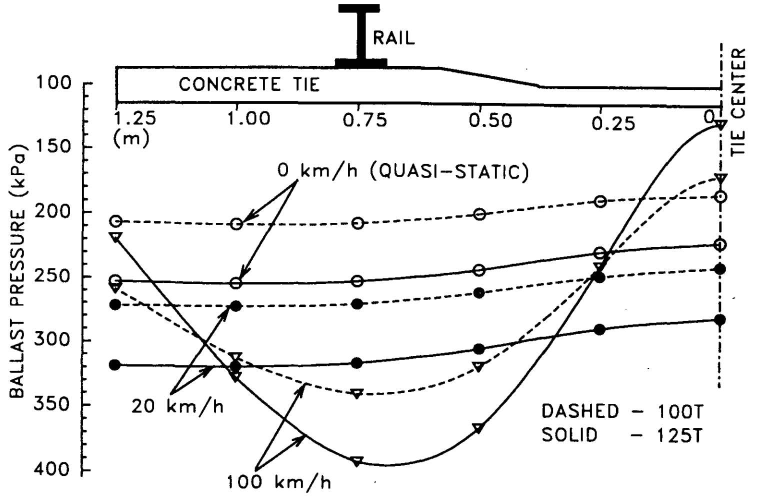

FIGURE 8 Typical distribution of ballast pressures along track tie.

rail load or the rail seat load within the same speed range. The extra increase in the ballast pressure is believed to be introduced by the vertical inertia effects of the concrete tie as a rigid mass on the wheel flat impact. At low speeds, the vertical vibration of the tie is dominated by its rigid mode (75 Hz) as a mass resting on the ballast spring stiffness and damper. At high speeds, the bending mode (155 Hz) of the tie as an elastic beam is more prominent than the rigid mode. This is shown in Figure 8, where the distribution of the ballast pressure along the 18th tie is shown for the 100- and 125-ton cars running at two different speeds as well as under the "quasi-static" condition. These pressure profiles are obtained at the moment when the ballast pressure underneath the rail seat area reaches its peak (the ballast pressure at other points along the tie may be higher than at this moment). The rigid mode and bending mode effects on the ballast pressure distribution are clearly demonstrated by these pressure profiles.

As mentioned earlier, the track structural components, namely the rail, the rail pad, and the tie, absorb a large portion of the dynamic forces generated at the wheel/rail interface. The dynamic impulses created by the wheel flat impact, however, still propagate through the track structures to the ballast/subgrade. Figure 9 shows a typical predicted time history of the ballast pressure under the 18th tie's rail seat area in relation to the front wheel (with flat) travel distance (approximately the middle 10 ties of the 40-tie track) and travel time. When the front wheel flat strikes the rail atop the tie, the ballast pressure oscillates significantly about its quasi-static value as the wheels travel along the rail. Such oscillations in the ballast pressure are harmful to the integrity of the ballast and the subgrade. When the rear intact wheel approaches, the ballast experiences only the quasi-static pressure produced by the static wheel load. The elevation of the ballast pressure due to the increase in the car weight is also evident in the time history traces of the ballast pressure.

CONCLUSIONS

An analytical dynamic wheel/rail and track interaction model and its application in predicting the track support loading

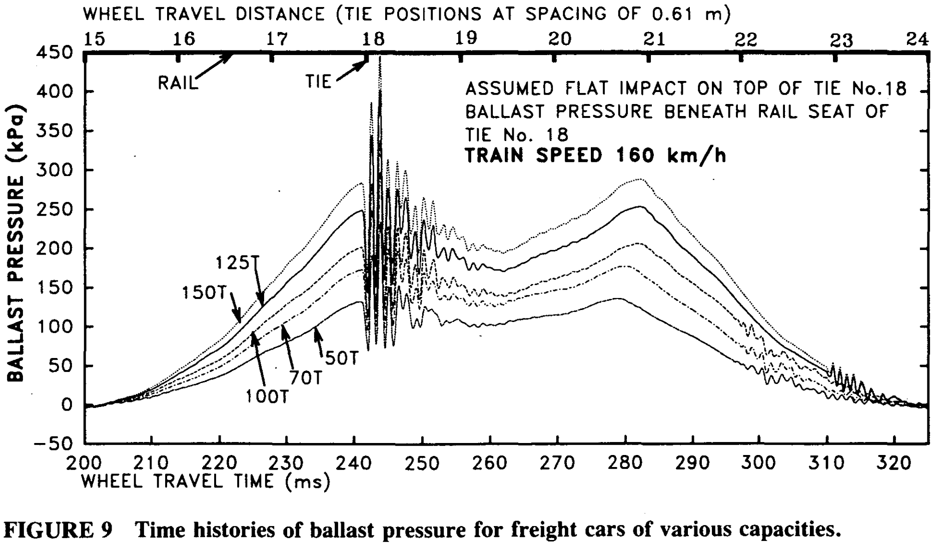

FIGURE 9 Time histories of ballast pressure for freight cars of various capacities.

environment are presented. The dynamic responses of the wheel/rail impact loads, rail seat loads, and ballast pressures produced by a wheel flat on different capacity freight cars commonly in use in North American railway industry are investigated. The theoretical results lead to the following conclusions:

1. For all the freight cars considered, the wheel/rail impact load, the rail seat load, and the ballast pressure depend on the train speed. The effect is largest for the wheel/rail impact load and least for the ballast pressure.
2. The increase in the freight car capacity increases the track support loading. At low speeds, the loading increment is primarily due to the net increase in the car weight. At high speeds, the dynamic interaction between the vehicle masses, mainly those of the truck side frames and the wheelsets, and the track vertical vibration become significant. This causes a loading increment in excess of that gained by the net increase in the static car weight. This effect increases with the speed as well as the capacity of the freight car.
3. The extent to which the loading increment, due to the increase in the car capacity, depends on the speed and car parameters is greatest for the wheel/rail impact load and least for the ballast pressure. For the particular track and train parameters considered, for example, the increment in the wheel/rail impact load from the 100- to the 125-ton car at 100 km/hr is 2.5 times its quasi-static value, whereas the increment in the ballast pressure is 1.3 times its quasi-static value.
4. High-frequency dynamic wheel/rail impact forces propagate into the ballast and subgrade. Thus, the ballast experiences high frequency pressure oscillations, which are adverse to the ballast/subgrade integrity. The ballast pressure distribution across the tie is primarily uniform at low speeds, with the rigid mode of the tie as a mass dominant, and is highly nonuniform at high speeds, with the bending mode of the tie as an elastic beam dominant.

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