JOURNAL OF THE TRANSPORTATION RESEARCH FORUM

Volume 34 Number 1 **1994**

TRANSPORTATION RESEARCH FORUM

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CHINA RAILWAY PERFORMANCE MODELLING

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ABSTRACT

Models of railway line performance were developed at a level of detail midway between what is needed for detailed simulation models and what is commonly used in network models. These models produced the performance parameters needed for a transportation network model that measures system-wide and corridor-level effects to support cost-benefit analysis of railway investments. The rail performance models estimated link capacity as well as cost and travel time for high density, tightly scheduled rail systems. The models were developed as a part of the Railway Investment Study (RIS), which was designed to assist the Ministry of Railways (MR) in developing a 10-year investment plan for China. The model was applied in two recent studies of potential transportation investments in China. To promote acceptance of the network model results, the performance model was structured to be consistent with methodologies used by MR, as well as with the network modelling approach.

INTRODUCTION

Network traffic assignment models are used by engineers and planners to investigate the effects of transportation investments on traffic flows and costs, which are key inputs to project benefit-cost analysis. Network models are most applicable for complex networks that provide many alternative paths over links for which performance is well understood. Therefore, link performance functions are incorporated within these models to provide limits for link capacity and to estimate travel time and total cost for each origin-to-destination movement included in the traffic flows. In many models, both cost and travel time increase with link volume as a result of congestion when traffic flows approach the capacity of a link. As more traffic is assigned to a particular link, performance eventually deteriorates or a capacity limit is reached, so that alternative routes may become more attractive. Network models have been used most extensively in urban networks, where travel time is the dominant concern.

In freight networks, network models have developed more slowly than passenger models for several reasons. Intercity freight networks tend to be much less complex than urban networks, while predicting the performance of a rail link or a waterway is more complex than predicting travel time on a city street. Also, freight routing decisions are often made by the carriers, rather than by the shippers or the owners of the transportation infrastructure, so that the carriers can develop operating plans based upon detailed assessment of impacts on cost and service. If the carriers do not own the infrastructure, then they may not need to (or be able to) assess the need for infrastructure investments.

China's rail system provides an interesting case where the system is relatively complex, numerous links are near capacity, and the Ministry of Railways (MR) operates the service, owns the infrastructure and determines investment priorities. In China, freight network models are being used to identify potential bottlenecks that might result from major changes in traffic flows or to demonstrate the effects of changes in capacity on flows. For either purpose, it is first necessary to specify link performance in a sufficiently detailed manner to reflect the types of changes that are under consideration. Railroad links are particularly difficult, because of the many technological details that might be important. If the emphasis is on multi-modal flows, then an abstract representation of rail cost and capacity may be adequate. If the emphasis is on the capacity and performance of the rail network, then the link performance functions must represent more of the special characteristics of rail technology. If the emphasis is on engineering design, then a very detailed performance function may be needed.

BACKGROUND ON FREIGHT NETWORK MODELLING

In general, freight network modelling has proceeded along three divergent paths:

detailed simulation modelling, system-level modelling of costs and service, and sophisticated network modelling. However, a few models have attempted the mid-level simulation approach described in this paper, which looks for the middle ground between data-hungry simulation and over-simplified aggregation approaches.

Detailed simulation models

Morlok (1969) was one of the first to consider the development of a multi-modal freight network model based on a detailed simulation approach. More intricate--and more specific--simulation models have been developed concerning train performance and meet/pass planning, culminating in such models as the Association of American Railroads Train Energy Model (Drish and Singh, 1985) and numerous meet/pass planners, the first of which was implemented by Southern Railway (Sauder and Westerman, 1985).

A recent study used a train performance model and a rail line simulation model to study line capacity on the Beijing-Shanghai corridor in China (Van Dyke and Davis, 1991). Using a line capacity model that employed techniques developed at CSX Transportation by Kraft, they examined the effects of changes in train speed, reductions in headway, and building additional track in key locations. They concluded that increasing freight train speed, by using more power or by changing the signal system and/or operating rules to increase the maximum braking distance from 800 to 1600 meters, provided the greatest capacity benefits. They did not attempt to develop travel time or line capacity relationships that could be used in a network model.

Cost, Service and Capacity Models

Models developed by or for the rail industry have tended to take traffic flows as an input; the models focus on providing accurate predictions of costs and service rather than on forecasting traffic flows, since railroads already have good data on current traffic. The Operations Cost Model, developed by USRA for analyzing restructuring options in the northeastern US following the Penn Central bankruptcy, was subsequently used in many merger studies. The Service Planning Model (McCarren and Martland, 1980), developed by MIT for the Association of American Railroads, has been used by most of the major railroads to evaluate operating plans and develop service standards.

Roberts developed higher level performance models in his studies of freight modal choice (Roberts et al., 1976; Roberts et al., 1977). In these studies, Roberts considered specific corridors rather than networks and modelled logistics costs in great detail. Instead of trying to calculate fuel consumption and other detailed elements of costs, he estimated rail prices; instead of estimating meet/pass delays, he estimated trip time distributions based primarily upon the probability of missed connections at yards (Terziev and Roberts, 1976).

On the academic side, substantial efforts have been devoted to upgrading the capabilities of network models, taking advantage of the rapid growth in computer capabilities and development of faster algorithms. Harker (1987) reviewed the work on forecasting intercity freight flows. He identified three approaches: network models, spatial price equilibrium models, and econometric models. As is typically the case in the transportation economics literature, he made almost no mention of how costs and capacity ultimately relate to the characteristics of the route or of the technology that is used. His concern was to provide a consistent general equilibrium framework that encompasses producers, carriers, and consumers of freight.

Network models

Roberts and Kresge (1970) were the first to actually develop a large-scale, multi-modal network model (the so-called "Harvard Brookings Model"), which they applied to the overall transportation system in Colombia. In the network portion of the model, each link was first characterized in terms of waiting time, travel time, travel time variability, probability of loss or damage, and transportation charges; an "R-factor" (i.e. a "resistance factor") was calculated based upon shippers' or passengers' perception of the costs of each of the five link performance characteristics. Given the R-factors for each link, it was relatively easy to route traffic through the network using a linear program.

The link performance characteristics were based upon cost-performance models for each mode. The rail cost-performance model, developed by Soberman (Roberts and Kresge, Appendix B), took the following approach to estimating performance:

1. Calculate the gross capacity of a single train (tare weight plus shipment weight) and then the net capacity (shipment weight only)
2. Determine the required trains per day
3. Calculate the average running speed using equations for tractive effort and train resistance
4. Calculate delays based upon the number of trains, length of links and sidings, and type of signals
5. Calculate operating statistics (train-miles, train-hours, car-miles, etc.) that can be used to estimate costs

Though it took a mid-level simulation approach, this method required a great deal of data to describe link and operating characteristics, which ultimately limited its use on the computer hardware existing at that time. In the model, travel times increased with the number of daily trains, which will be the case if meets and passes are not carefully built into a train schedule. This model pioneered the way for later mid-level simulation approaches such as that presented in this paper.

Subsequent efforts to model railroad networks often sought more abstract representations of rail performance that included estimates of capacity. In response to the oil crises of the 1970s, two models were developed that looked at capacity relationships. List and Clausing (1983) used a mathematical programming approach in their Coal Transport Planning Model (CTPM). They considered three objectives: minimize fuel, minimize transport cost, and minimize cost per BTU. The transport cost objective minimized the costs associated with train-miles, car-miles, gallons of fuel, gross ton-miles, locomotive- and car-months, and the costs associated with rehabilitating links or adding capacity. Fuel costs were calculated using a simple equation based upon distance and grades (net rise and fall over the route). Each link was assigned a capacity constraint for coal trains that was ultimately based upon a line simulation model developed by Burlington Northern that estimated meet delays as a function of siding length and spacing. They defined line capacity as the number of trains that can be operated with at most 70 minutes of delay per 100 miles. They found that there was an almost linear relationship between line capacity and the miles of second track per hundred route-miles, and it was this relationship that they used in the math program. They used a constant cost per mile per month for adding one additional train per month. Increases in capacity could be achieved by adding sidings or by rehabilitating track to increase train speed.

Friesz et al. (1983) undertook another study of the effects of increased coal transport on freight transport capacity using a freight network equilibrium model (FNEM). FNEM used abstract functions for link delay, which were ultimately based upon average link characteristics and results of prior work by Bronzini (1979) and Morlok (1969). Link costs were based upon ICC costing techniques. FNEM did not directly include capacity constraints for the individual rail links. Instead, it included delay curves that had sharply increasing delays beyond a certain annual level of traffic. Including such curves facilitated equilibrium modelling and avoided the need for absolute capacity calculations in the model, but glossed over the underlying variables.

As Waters (1987) indicated in reviewing FNEM and similar models, "most of these nation-wide models do not have the level of specific details that individual railroads required to make specific capacity planning decisions". One exception is the work by Markow and Brademeyer, who used the Intercity Transportation Planning Model to determine traffic flows and the demand for track maintenance in both Egypt (Markow, Brademeyer et al., 1984) and in Spain (Moavenzadah et al., 1982); they used the network model to estimate traffic flows, then examined the impacts of track rehabilitation and track investment on capacity and service.

BACKGROUND ON THE CHINESE RAILWAYS

Chinese rail operations are extensive, ranking fifth in the world in terms of track and second in terms of traffic. The system handles roughly the same amount of freight as the US system, but on a network of only 57,400 route-km, which is less than a quarter the size of the US network. As a result, the density of freight operations is higher even than that in the USSR and much higher than that in the US. In addition, the system handles the highest density of intercity passenger traffic in the world, at 6 million passenger-km/route-km (World Bank, 1991).

Railway performance in China has become a major issue in the last decade due to the rapid growth of the economy and a general shortage of transport capacity to accommodate the growth in transport demand which, in some cases, has been even faster than economic growth. While the economy has grown at a rate of 9.5% per year since 1979, freight traffic has grown at 8% per year and passenger traffic at 12% per year on a national level, despite increasing constraints on the national transport network. Some provinces, such as Guangdong Province in the south of China have experienced traffic growth of over 20% per year for several years in this period.

The rapid traffic growth combined with underinvestment in transport facilities compared with other sectors of the economy has resulted in transport bottlenecks and rationing of transport capacity, especially in the railway system. The railway system, which handles most of the medium and long distance traffic in China, has not been able to expand fast enough to accommodate the increasing demand for rail transport services and 37% of the main railway system links currently carry traffic representing 95% or more of capacity. In addition, these bottlenecks caused a peak of unsatisfied demand in 1989 amounting to 7% of freight demand and up to 30% of certain passenger services.

THE RAILROAD INVESTMENT STUDY

In order to cope with the problems of expanding the railway system in the most cost-effective manner and with the maximum of economic benefits, the Chinese Ministry of Railways conducted the Railroad Investment Study (RIS) in 1989-1991 in collaboration with the World Bank (World Bank and Ministry of Railways, 1991). A major feature of the RIS was the development of a state-of-the-art, PC-based, decision support system to evaluate alternative investments in railway infrastructure. While the RIS focused on investments in the railway subsector only, it employed a multimodal transport network for traffic forecasting, in order to capture the effects of competition and cooperation among modes on railway transport demand. This transport network includes all trunk railways and waterways that provide significant feeder and linehaul services in the eastern half of China (Figure 1).

The first step in an RIS analysis is scenario definition, which specifies all the necessary data and assumptions. Once a scenario is defined, the analyst carries out a complete round of analysis by activating four modules in sequence (Figure 2):

1. Traffic Forecasting Module: forecast freight traffic within and between major national (O/D) traffic zones and between provinces (for each demand scenario)
2. Facility Performance Module: estimate the capacity, costs and transit times for existing and proposed railway links and yards, waterway links, and ports
3. Traffic Assignment Module: assign forecasted traffic to modes and routes within the transport network, using inputs from the previous two modules
4. Benefit-Cost Analysis Module: estimate the economic and financial benefits and costs of proposed railway investment alternatives under the current scenario

From the perspective of the RIS, it was necessary to create a sub-system for estimating costs, travel time, and line capacity. Unlike FNEM, RIS could not use delay curves based upon coarsely described line characteristics; RIS required its own sub-system, much as Soberman developed the rail performance system for use in the Colombian study. Ideally, the performance sub-system should have enough detail to describe the effects of the major options for expanding capacity, including adding tracks, increasing train length or weight, increasing horsepower, or reducing headways.

To gain acceptance from railway officials, it was essential that the methodology be congruent with Chinese railway practices. Models calibrated to or designed for North American operating conditions would not work well in China, because of the high density of

FIGURE 1

RIS Multi-Modal Transport Network-Base Case

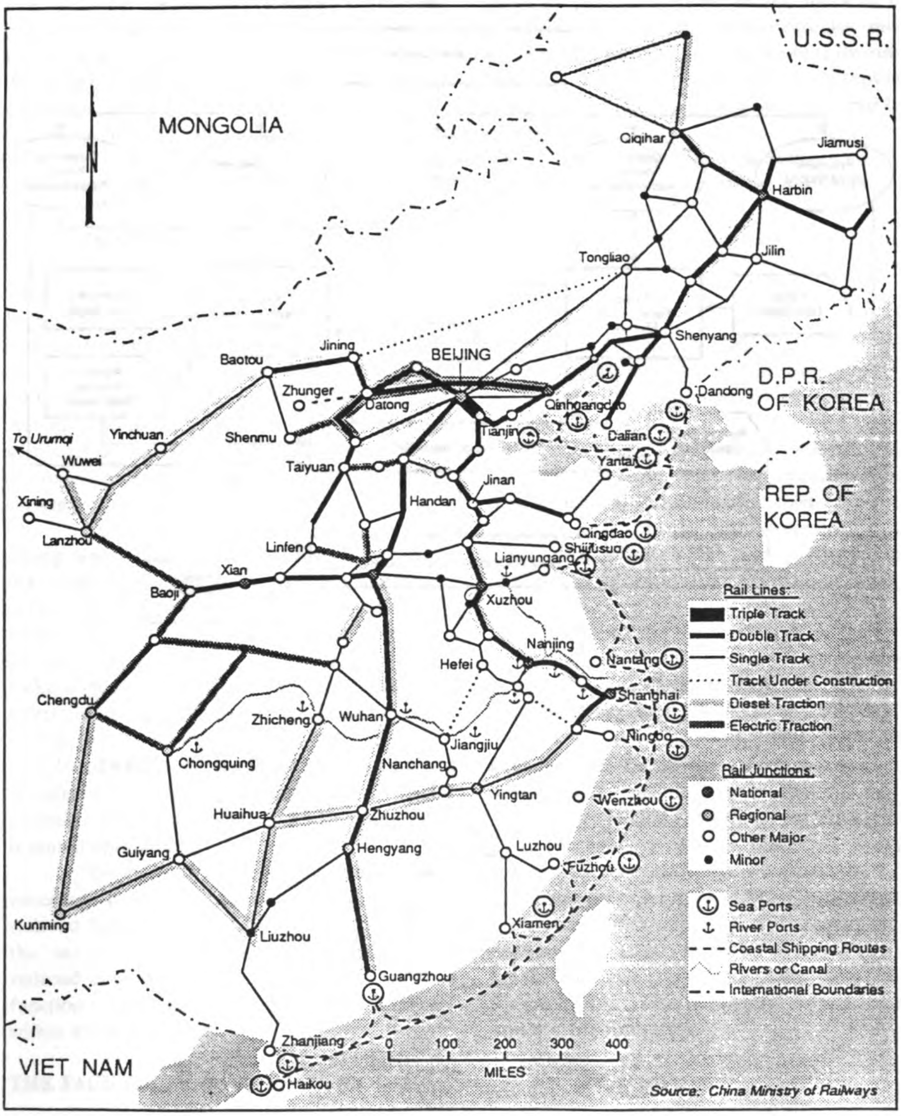
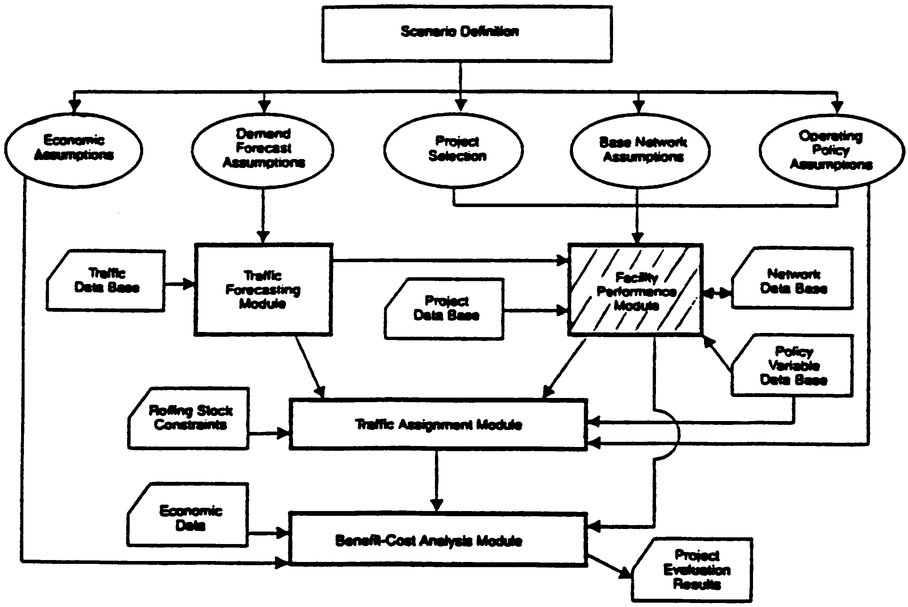
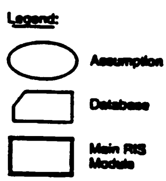


FIGURE 2

RIS Analysis System Flow Chart



Source: World Bank and Ministry of Railways, 1991.



both passenger and freight operations and the tightly scheduled nature of the system. As pointed out by Van Dyke and Davis, Chinese passenger trains "adhered very closely to their schedules", while freight trains operated close to schedule. In a well-disciplined, scheduled operation, lines can operate close to capacity without delay; hence the notion of travel time increasing with congestion is not directly applicable, and it is necessary (and possible) to determine line capacity more directly.

RAILWAY CAPACITY

In general, problems arise if there is too much or too little capacity. With too much capacity, high fixed costs sap profits. With too little capacity, congestion hampers operations and hurts both costs and service. In most developed countries, the rise of superior modes attracted most of the traffic from the rail systems, and led to serious problems in dealing with excess capacity. In China, however, the dominant problem is too little, not too much capacity.

There are several broad strategies for easing capacity problems. Strategies to improve the supply of transportation include investment in current technology, development of new transportation technology, increased resources for planning and control, and development of technology for planning and control. Strategies to reduce the peak demands for transportation include pricing, flow control, and rationing. The Rail Investment Study concentrated on facility investments, including investments in both existing and new technologies for line-haul and terminal operations.

To evaluate these investments, it was necessary to create performance models for railroad lines that could be used to represent the various options available for increasing railroad capacity. This paper focuses on the function of the Facility Performance Module within the RIS system.

THE FACILITY PERFORMANCE MODEL

Overview

The Facility Performance Module (FPM) estimates the performance of individual links in the transportation system in terms of travel times, capacity, and operating cost (Figure 3). The FPM is designed to produce performance information for each element of the RIS network, including railway line segments, classification yards, waterway links, coastal shipping links, and transshipment links (such as ports). Because of the focus of the RIS, the performance calculations are much more detailed for the railroad than for the other modes, and for line than for terminal operations. This paper only addresses rail line performance.

To avoid undue complications, the RIS uses a linear approximation for link costs:

(1) $\text{Cost} = a + b^*(f)$

where

a = fixed cost for this link
b = variable cost per unit of flow
f = traffic flow over this link at capacity

In China, the dominant problem is that many lines operate at or near capacity. Hence it is reasonable to assume that traffic flows will be at or near capacity when computing costs. With this formulation, the average cost per unit of flow will be

(2) $\text{Average Cost} = (a + b^*(f))/f = (a/f) + b$

In general, the average cost per unit of flow therefore depends upon the amount of flow; as the flow increases, the average costs decline and, for large flows, approach b, i.e. the unit variable cost.

While this simplified cost equation is ideal for network flow assignments, a more complex formulation is needed within the FPM to capture the richness of railroad operating and investment opportunities. It must be possible to represent the effects of each investment option on the cost and capacity variables (a,b, and f) for each link. This is possible with a service unit costing formulation:

(3) $a = \Sigma(Ciw^*Siw)$

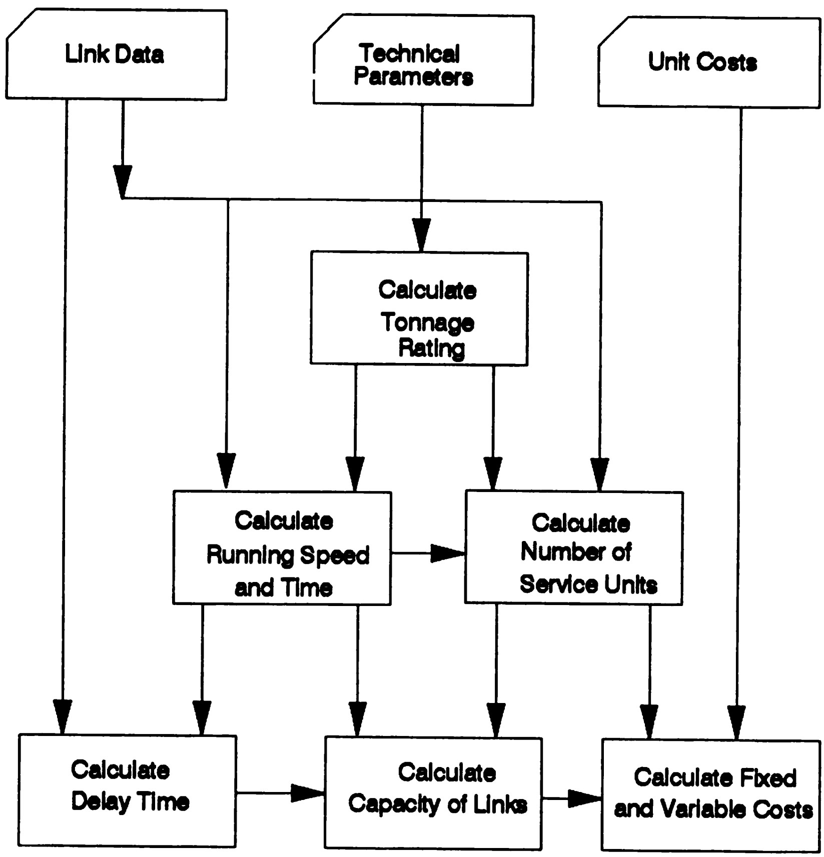
(4) $b = \Sigma(Cif^*Sif)$

where

Civ = the unit variable cost per service unit type i

FIGURE 3

Rail Line Analysis Portion of FPM



Cif = the unit fixed cost per service unit type i
Siv = the number of service units of type i associated with variable costs
Sif = the number of service units of type i associated with fixed costs

The service unit costing approach makes it possible to use engineering relationships to estimate such measures as locomotive-hours, wagon-hours, and fuel consumption, any of which could vary with track and signalling capabilities, traffic and operating characteristics, or the terrain. The variable costs for each service unit, as well as the variable cost per unit of traffic flow, can then be calculated for each link. With this approach, it is possible to translate investments in track, signals or equipment into changes in variable costs for a particular link.

Data Requirements

Three sets of data are required to run the link performance part of the FPM:

a. Rail link data, including physical characteristics, local and passenger train data, and policy variables related to local and passenger traffic
b. Technical parameters, including data matrices that describe train performance and fuel consumption under various link conditions and parameters used in capacity calculations
c. Service unit cost data, including cost per crew-hour, cost per train-hour, and cost per gross ton-km

A rail link will typically be 100 or more kilometers of track carrying similar traffic over reasonably homogeneous terrain. It may therefore include many intermediate stations and passing sidings. For the RIS study, nearly 400 unidirectional links were used to represent the 36,000 kilometer core portion of the Chinese Railways.

Train Performance Calculations

The train performance calculations are based upon standard concepts of railroad engineering. MR has developed various engineering relationships concerning locomotive performance and train speed over various kinds of gradients (Northern Jiaotong University, 1982; Third Survey Design Institute, 1988). These relationships are used to estimate tonnage constraints, running times, and energy consumption for each type of locomotive, given the grades and curvatures as defined by the category.

Tonnage Constraints - The tractive effort of the locomotive must be sufficient to pull the train up the ruling grade (generally the maximum gradient on the link). Also, the train must fit within the passing sidings.

Minimum Running Time - The minimum running time required for a train to move over the link is based upon the characteristics of the route and the train. MR categorizes each link on the railroad into one of 10 terrain categories, where each category shows the percentages of the line with each of a discrete set of gradients. MR has developed relationships that show the maximum force available for ascending grades for each type of locomotive. Given the weight of a train, these relationships give either the maximum grade that can be ascended at a particular speed or the speed that can be sustained on a particular grade. On descending grades, braking capabilities and MR safety requirements are also taken into consideration. An important constraint on descending speeds is that MR requires all trains to be able to stop within 800m (which is an important constraint, as shown by Van Dyke and Davis (1991)). Given the average speed on each gradient for a particular terrain type, it is a short step to estimate the minimum running time over the link. A similar approach is used to estimate energy requirements by type of locomotive, train weight and speed, and type of terrain.

Total Link Time - The time required for stopping at stations is added to the minimum running time. An input to the FPM gives the train delay caused by a typical stop at a station, includes deceleration, train interference delay, and acceleration.

Link Capacity

The method adopted for initial RIS analysis closely followed the general methods presently used in China. A basic assumption is that trains alternate, one in the "up" direction followed by one in the "down" direction. Hence it is natural to consider the "cycle" time for a pair of trains to operate over a link, including the time required for the trains to meet at a station at one end of the single track sections. The number of cycles per day will therefore equal the maximum link capacity (measured as trains per day) in either the up or the down direction. To obtain the capacity available for through freight trains, MR subtracts the capacity required for passenger and local freight operations, and makes adjustments for track maintenance and seasonality of demand. Finally, capacity is converted from trains per day to units of 10,000 net tons per day.

Cycle time for a single track section - For a rail link that has several sidings, the cycle time is calculated for the most restrictive single track section, i.e. for the section with the longest running time. The inputs to the cycle time calculation are as follows:

- Vt Average running speed
- Ss Maximum siding spacing for this link
- td Train delay caused by a typical stop at a station

For single track, the cycle time is constrained by the maximum siding spacing:

(5) $tc = 2(Ss)(60 \text{ minutes/hour})/Vt + td$

where Vt is given in km/hour and time is given in minutes.

Cycle time for a double track section - For double track with unidirectional travel, the cycle time is simply the headway between trains and there is no station delay.

(6) $tc = 60\,(dh)/Vt$

where dh = Headway (distance between trains on double track)

The headway is a function of the signalling characteristics, which reflect the braking capabilities of the trains.

Link capacity - For the purposes of the RIS, link capacity must be given in terms of the net through freight tonnage per year that can be handled on a link. To go from cycle times to link capacity for through freight trains, the following variables are also needed for each link:

- N Number of tracks
- tm Maintenance window (the average time per day required for track maintenance on each track)
- RC Coefficient of reserve capacity (a percentage of the track capacity is left unscheduled as a reserve for either unforeseen delays or for special train operations)
- SC Coefficient of seasonal fluctuation (if the track is fully utilized only part of the year, as in a harvest season, then the average annual capacity must be reduced)
- Qp Number of passenger trains
- PC Coefficient of removal for a passenger train (the reduction in daily through freight train capacity resulting from scheduling one passenger train)
- Ql Number of local trains
- LC Coefficient of removal for a local train (the reduction in daily through freight train capacity resulting from scheduling one local freight train)

The first step is to calculate the number of trains per day (No) that can move in each direction. This is simply the number of cycles per day after allowing time for track maintenance:

(7) $No = (1440 \text{ minutes/day} - tm)/tc$

The link capacity in trains per day must be reduced for several reasons. First, MR allows a reserve capacity Cr, expressed as a fraction of No. In addition, passenger trains and local freight trains typically take up more track capacity than typical freight trains. Hence, the actual capacity available for freight trains (Qt, measured in trains/day) is:

(8) $Qt = No/(1+RC) - Qp{*}PC - Ql{*}LC$

Using the maximum gross tons per train GTT and the ratio of net tons to total tons (RATIO), it is possible to obtain the gross tons per year per train, which is then adjusted for the seasonality of traffic and expressed in units of 10,000 net tons:

(9) Kt = (365 days/year)*GTT*(RATIO)/(SC*10,000)

Kt is the capacity of a single train operating for a year. The seasonality factor SC (a ratio greater than 1) provides a mechanism for reducing annual capacity when there is a marked seasonal (or weekly) peak in the demand for rail traffic. For example, the traffic volumes achieved during the grain harvest might not be sustainable year round. In effect SC is the inverse of the average load factor.

Finally, multiplying the capacity in units of freight trains by the net tons per train, we obtain the annual link capacity (K) in units of 10,000 net tons:

(10) K = Kt*Qt

Cost for Line Haul Links

As discussed above, a service unit costing approach is used to obtain link costs as a function of traffic, operating, track, and terrain characteristics. Total costs can be obtained by multiplying the number of service units in each category by the service unit costs, and summing over all the service units. "Variable" service unit costs are used in calculating the costs of operating over a link:

1. Energy cost per unit of energy consumption, by type of locomotive (i.e. unit energy costs)
2. Other cost per unit of energy consumption, by type of locomotive (i.e. costs such as locomotive maintenance that vary with the amount of energy required)
3. Costs per unit of tractive work, by type of locomotive (these costs include a portion of locomotive maintenance costs)
4. Costs per unit of resistance work, by type of locomotive (these costs include a portion of wagon and coach maintenance costs)
5. Cost per locomotive-hour, by type of locomotive (capital cost)
6. Cost per crew-hour, by type of locomotive
7. Cost per train-crew-hour, by type of locomotive
8. Cost per wagon- or coach-hour, by type of wagon

"Fixed" service unit costs are related to the fixed costs of providing the infrastructure:

1. Annual maintenance of right-of-way costs per km, by type of rail (the MR costing system considers all of these maintenance costs as fixed; a more complex system will be needed to evaluate changes that have major impacts on track maintenance, such as the possibility of increasing axle loads)
2. Annual maintenance cost of tracks at stations, by type of rail
3. Annual expenditures at an intermediate station
4. Annual expenditures at a district station
5. Annual maintenance cost for signals per km, by type of signal system
6. Annual expenditures for electrification equipment per transformer substation
7. Annual expenditures for catenary maintenance per km of electrified track

In the RIS study, the unit costs were based upon internal cost figures used by MR. The MR costing system is described by Allalouf (1992).

USING THE MODEL

The FPM was used to estimate the capacity of the 364 unidirectional railway links in the RIS study. These links represented 36,000 kilometers or roughly 2/3 of the national system. Two sets of runs were made. The initial runs were designed to evaluate the models and to determine where adjustments were necessary. Using 1989 as a reference year, it was then possible to compare the FPM estimates of capacity with previously developed MR estimates, as well as actual traffic volumes. Some adjustments were found to be necessary in the technical parameters concerning the length of maintenance windows and the effects of passenger and local train operations on capacity:

a. The average maintenance window was set to 90 minutes/day

b. The effect of passenger trains was found to diminish with increasing numbers of passenger trains. Therefore the coefficient of removal for passenger trains was expanded to be a table, rather than a constant. For example, on double track with fewer than 10 passenger trains a day, one passenger train is equivalent to 2.1 to 2.3 freight trains, depending upon the headways. If there are more than 40 passenger trains, then each is equivalent to 1.88 to 2.05 freight trains.

c. The effect of link-specific local trains (i.e. trains that stop to pick up and deliver cars at local stations along a link) was increased from 2.5 to 3, in terms of the reduction in through train capacity for each local train. Also, the average load factor was reduced to 50% for these local trains.

d. The RIS methodology was modified to include pricing variables that can be used to force a proportion of zone local traffic (i.e. traffic within an RIS zone) to move by truck. This adjustment allows some additional flexibility in freeing up rail line capacity for use by longer distance trains.

After these adjustments were made, the model provided reasonable predictions of the current situation. For 80% of the lines, the capacity estimates were within 25% of prior MR estimates, and the great majority of the outliers were the lighter density lines. More important, MR officials believed that the model correctly identified the most serious bottlenecks in the system.

Table 1 categorizes the lines in terms of the capacity predicted by the FPM. The units in this table are millions of net tons annually in one direction for a route segment. To convert these numbers to millions of gross tons (a more commonly used measure of traffic density), they should be multiplied by approximately 1.5. Bear in mind that the table shows unidirectional capacity only; for most routes, the capacity is roughly the same in both directions. The capacities shown here are quite impressive, especially given the high volume of passenger trains, which on the average carry 1,500 passengers in 25 coaches. The line with 31 pairs of passenger trains carries about 17 million passengers per year, which is equivalent to that carried by the TGV in France in 1988.

TABLE 1

Predicted Unidirectional Capacity for the RIS Segments

Predicted Capacity (Million net tons/year)	Miles	%
100+	7	0.001%
75-99	707	1.0%
50-74	6,627	9.2%
25-49	11,682	16.1%
10-24	27,649	38.2%
5-10	20,409	28.2%
0- 4	5,321	7.3
Totals	72,402	100.0%

Table 2 shows the level of capacity utilization for MR lines. Over 40% of these lines are operating at or beyond predicted capacity, which simply highlights the reason for conducting the RIS. Also note that there are very few light density lines: only 7% of these lines carry less than 5 million net tons annually. Following this analysis, the capacity predicted by the FPM was adjusted for those links with traffic greater than predicted capacity by determining actual conditions for train headway or for train size that differed significantly from the model assumptions. This allowed finer calibration of the base case.

Further validation of the capacity estimates of the FPM occurred as part of the Traffic Assignment Module calibration. Even with relatively unrefined data and assignment rules, estimated link traffic was within 15% or 1 million tons of actual traffic for 82% of the links in the RIS network. For links carrying more than 10 million tons per year, this measure reached 91%. These results compare favorably with rail traffic simulation results achieved in other countries (Friesz, Gottfried, and Morlok, 1986).

Another significant output of the FPM is an average variable and fixed cost per ton-km for each link. Although the Ministry of Railways (MR) does not keep cost records at

TABLE 2

Capacity Utilization
(Lines with at Least 15 million
net tons capacity)

Actual Traffic/ Predicted Capacity	Miles	%
1.16+	293	1.2%
1.00-1.15	6,441	27.4%
0.85-0.99	3,276	13.9%
0.70-0.84	3,021	12.9%
0.50-0.69	4,919	20.9%
< 0.50	5,537	23.6%
Total	23,487	100.0%

TABLE 3

Comparison of Estimated and Actual Costs
by Railway Administration
(1989 yuan per 1000 ton-km)

Administration	1989 Actual Cost	FPM Estimated Cost	Ratio
Harbin	195	146	0.74
Shenyang	146	148	1.02
Beijing	132	130	0.98
Huhe	159	132	0.83
Zhengshou	131	125	0.96
Jinan	127	121	0.95
Shanghai	151	147	0.98
Guangshou	144	144	1.00
Liushou	164	158	0.97
Chengdu	187	178	0.95
Lanshou	181	163	0.90
Wulumqi	225	162	0.72

this level of detail, it was possible to compare average costs by each of 12 MR administrations (see Table 3). By multiplying the 1989 traffic density for all links in each administration by the RIS variable costs for each link, adding the fixed costs, and dividing by total tonnage, it was possible to compute the average FPM financial costs per ton-km for each MR administration. This was then compared with the actual average cost per ton-km from MR statistics. Some differences were expected due to the fact that the RIS network excluded branch lines, which were very important for some administrations, especially in coal mining areas. Nevertheless, the estimated costs from all but three administrations were within 10% of the actual averages. The two administrations with the largest discrepancies were Harbin and Wulumqi, which are on the periphery of the region studied in the RIS.

The model was used extensively in the RIS, in the subsequent development of MR's railway strategy (World Bank, 1993), and also in a regional study of multi-modal freight movements in Yangtze (PPK Consultants et al, 1992). In the Yangtze study, the allocation between fixed and variable costs was improved. A CANAC study (Allalouf, 1992) indicated that approximately 75% of MR costs are variable in the long run, whereas the cost parameters used in the RIS reflected short run costs, of which only 30% were variable. The allocation between fixed and variable costs was therefore refined for the Yangtze study. For example, maintenance cost, which is viewed as fixed by MR, was made to vary with traffic volume.

CONCLUSIONS

As part of the RIS, a technique (FPM) for estimating line performance was developed. FPM can be used to estimate link capacity as well as fixed and variable costs as a function of route, traffic, and operating parameters. The level of detail used in this technique is midway between what is needed for detailed simulation models and what is commonly used in network models. This mid-level of detail is sufficient to model the effects of a great many investment options for increasing railroad capacity. FPM was used to generate link cost and capacity parameters for use in a state-of-the-art transportation network study. While a few other network studies have used similar mid-level approaches to estimating link costs, this was the first to develop a technique for providing mid-level estimates of rail line capacity.

The initial application of the FPM in China was successful, despite the level of simplification involved and the problems in obtaining sufficiently accurate field data for inputs and for calibration. The accuracy of the results compare favorably with modeling results in the United States and other countries. The preliminary results of the RIS analysis were consistent with past observations concerning transport constraints and the location of bottlenecks.

Two areas were identified for improving FPM. For changes in signalling, it is necessary to relate projected improvements in headway more carefully to planned investments in signalling or other train control measures. For examination of heavy haul options, it would be necessary to make maintenance costs a function of axle loads.

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