TRANSPORTATION RESEARCH RECORD 917

Rail Freight

TRANSPORTATION RESEARCH BOARD

NATIONAL RESEARCH COUNCIL
NATIONAL ACADEMY OF SCIENCES
WASHINGTON, D.C. 1983

Transportation Research Record 917
Price $7.80
Edited for TRB by Naomi Kassabian

mode
3 rail transportation

subject areas
12 planning
54 operations and traffic control

Library of Congress Cataloging in Publication Data
National Research Council. Transportation Research Board.
Rail freight.

(Transportation research record; 917)
1. Railroads–United States–Freight–Congresses. I. National Research Council (U.S.). Transportation Research Board. II. Series.
TE7.H5 no. 917 380'.5s [385'.24'0973] 83-26967
[HE2355]
ISBN 0-309-03560-0 ISSN 0361-1981

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Contents

REVIEW AND ASSESSMENT OF TRAIN PERFORMANCE SIMULATION MODELS
Stephen M. Howard, Linda C. Gill, and Peter J. Wong 1

CAR MANAGEMENT OPPORTUNITIES: ACTUAL RETURN MILEAGE VERSUS OPTIMAL RETURN MILEAGE
Bernard P. Markowicz and Alain L. Kornhauser 6

POTENTIAL FOR NATIONWIDE POOLING OF VARIOUS TYPES OF RAILROAD CARS
Alain L. Kornhauser and Yen-Shwin Shan 14

MEASURING THE QUALITY OF FREIGHT SERVICE: ANALYSIS OF SHIPPER RECORDING PRACTICES WITH EMPHASIS ON RAILWAY USERS
Garland Chow and Richard F. Poist 21

TRACS: ON-LINE TRACK ASSIGNMENT COMPUTER SYSTEM
Peter J. Wong, Marilyn R. Hathorne, Carola V. Elliott, and Mary Ann Hackworth 26

LABOR PRODUCTIVITY IN RAIL TRANSPORT
Paul H. Banner and Francis D. Brosnan, Jr. 29

MINNESOTA'S RAILROAD INFORMATION SYSTEM
Cathy L. Erickson and Robert C. Johns 34

IMPACT OF COAL TRAIN MOVEMENT ON STREET TRAFFIC FLOWS: A CASE STUDY
A. Essam Radwan and Lee Alexander 37

RAILROAD CAR DISTRIBUTION PERFORMANCE: CONCEPTUAL FRAMEWORK AND UNDERLYING MATHEMATICAL RELATIONSHIPS
Carl D. Martland and Mark McCord 43

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Review and Assessment of Train Performance Simulation Models

STEPHEN M. HOWARD, LINDA C. GILL, AND PETER J. WONG

Train performance simulation (TPS) models are used extensively in railroad operations and research applications to simulate the operation of a train over a specific route. To increase the railroad industry's awareness of the current state of development, usefulness, and availability of these models, the Office of Freight and Passenger Systems of FRA initiated a study of TPS technology. Results from a comprehensive review of 27 existing TPS models are summarized. The primary sources of information were TPS designers, users, and researchers and the National Technical Information Service. A generic model, based on the capabilities of existing models, was developed to describe the basic component algorithms of TPS models as well as the overall architecture of these models. A brief summary and analysis of existing TPS models is given, which includes comments on their train-modeling and computer-programming characteristics.

A train performance simulation (TPS) or train performance calculation (TPC) model is a computer program that simulates the operation of a single train over a specified railway route. It does not model the interaction of multiple trains in a railway network. Numerical and graphical output from the model provides information on such performance variables as travel time, train velocity, and energy or fuel use as the train moves along the route. In addition, a TPS model may provide more detailed information describing brake applications, tractive effort, train resistances, and track profiles.

Although the TPS model concept can be implemented in various ways, the underlying structure of all TPS models is essentially the same and can be described generically.

GENERIC MODEL

The basic components of a TPS model, its overall architecture, and the process involved in applying it can be understood by delineating the steps in program use as follows:

1. Initial collection of the required input data and specification of the data in computer-readable form,
2. Simulation of the train run, and
3. Reporting of simulation results and postprocessing of simulation output data.

Each of these functions is described below.

Initial Data Collection and Specification

Three types of input data are required for a TPS run: route data, train data, and operating-scenario data. Route data are generally obtained from railroad track charts. Locomotive and car data are derived from manufacturers' data sheets and specifications. Data obtained from the manufacturer can differ significantly from the actual performance characteristics of a particular locomotive or car, which are affected by use, maintenance procedures, and age. The accuracy of the input specification can become important when the model is used for detailed analysis of fuel or energy use, but it may be somewhat less important for examining broader policy issues. Operating-scenario data are specified to describe the train-control parameters for the run.

Input data can be specified to the model as (a) hard-wired, internally coded program data that are unalterable at program execution time; (b) sequential card-image data that are read in at program initiation and that fully describe the track, locomotive, consist, or operating scenario for the run; and (c) higher-level descriptors that point to a data base containing complete routes (stored on a segment-by-segment basis) or train specifications.

Data bases facilitate both routine use of the model by operations personnel (by greatly reducing input requirements) and transfer of the data from one application to another.

Typical data requirements for route, train, and operating scenarios are described below.

Route Data

Any track segment can be specified by data that describe curves, grades or elevations, speed limits, and station stops (usually by milepost). Enhancements to these data can include specifications of equations of track, direction of travel or reverse segments, and complex curve descriptions of the point-tangent-spiral form.

Track data can be formatted in either point or interval form. Point data describe characteristics that hold at a single point on the track, such as elevation or station stops, whereas interval data describe a track characteristic that holds between two points, such as grade or speed limit.

Train Data

Train data requirements depend on the intended application of the model. Some models represent the propulsion system in great detail and consequently require extensive and detailed data. In general, the locomotive specifications include tractive-effort curves, aerodynamic and mechanical resistance characteristics, fuel or energy consumption, and brake-system parameters. Specification of the train makeup can range from the individual description of each car and locomotive in the consist to the number of cars of a single type.

Operating-Scenario Data

In addition to descriptions of the route and train makeup, certain operating parameters and strategies must be specified for the running of the train. These may include train starting time, train starting speed, place and time of stops along a route, temporary speed orders, consist changes en route, velocity and direction of prevailing winds, explicit throttle settings and brake application specifications, and maximum allowable acceleration and deceleration.

Simulation of Train Performance

The simulation of train performance requires several mathematical or algorithmic models, including a train operating and handling model, a resistance model, a power-system model, and a brake model. The train operating model drives the simulation by determining when to recompute the state of the train and by deriving the total forces acting on the train at a specific time point based on the resistance, power-system, and brake models. Each of these component models is described in more detail below.

Train Operating and Handling Model

The approaches used to control the overall simulation of the train operations can vary in mathematical terms as well as in terms of their correspondence to actual train handling.

In mathematical terms, the algorithms all use iterative computational cycles based on time, distance, or velocity increments. In some cases, a combination of incremental controls is used. For example, a model that uses a time step for basic iterative control may restrict the step length so that the corresponding change in velocity will not exceed a specific value. The models then compute, by means of numerical integration or differentiation techniques, the changes in the state of the train corresponding to the iterative variable change. Because most of the attributes describing the state of a train in motion are highly velocity dependent (including resistances and tractive and braking effort), the algorithms should generally recompute the state attributes at small increments of velocity (e.g., 1 mph).

A common mathematical approach in the TPS models is the use of variable-length simulation steps instead of a constant length. This improves algorithm efficiency by recomputing the train state frequently when the route conditions are rapidly changing and relatively infrequently when the train is in a fairly steady-state mode of operation.

The train can be represented as a single unit, as multiple point masses corresponding to cars or groups of cars, or as a line. Although the single-unit approach is computationally efficient, it can introduce inaccuracy when the terrain changes rapidly and the train is long. In passenger service applications, however, this approach is entirely adequate.

The overall simulation method used by most TPS models involves an n-record look ahead in the route data to determine the existence of speed restrictions and changes. When upcoming changes are sensed, a braking or acceleration point is computed and a braking or acceleration event is scheduled for that point.

The simulation of train handling is generally based on a simple philosophy: minimize running time by accelerating and decelerating the train at the maximum feasible and allowable rates. When explicit inputting of throttle and brake settings is permitted, the model can function in an interactive mode as an operational simulator.

Resistance Model

Resistance to forward motion on level, tangent track is computed by using an equation with the general form (1)

$$R = A + BV + CV^2 \tag{1}$$

where

R = train resistance on level, tangent track;
V = train speed;
A = mechanical or friction drags that are at least partly weight dependent;
B = all effects that depend on the first power of the velocity, such as flange resistance caused by the nosing action of the truck and car and the consequent impacting of flange on rail; and
C = effect of air resistance.

Resistance due to track grade and curvature is added to the resistance on level, tangent track. Curve resistance is usually taken as 0.8 lb/(ton•degree of curvature) and grade resistance as 20 lb/(ton•percentage of grade) (1,2).

The conventional approach is to use the basic or modified Davis coefficients in the resistance equation. The Tuthill modification (describing the coefficients as a matrix of velocity-dependent coefficients) to the Davis equation is usually recommended for speeds above 40 mph. Various other specialized equations for describing aerodynamic and rolling resistance of the total train are sometimes included to represent more accurately particular types of operations such as passenger service. Because the most widely used equations for modeling resistance of special car types, such as streamlined and unstreamlined passenger cars and trailer-on-flatcar and container-on-flatcar types, are of the same quadratic form, a TPS model that allows the input of each resistance equation coefficient for each car will enable the user to generate customized equations for a specific application.

Power-Systems Model

A central design feature of the TPS model that has a significant effect on input-data requirements is power-systems modeling. TPS models are generally written to simulate either diesel-electric or fully electric propulsion systems. Those models that optionally simulate both types of propulsion systems usually do so by modifying the tractive-effort curve and the units of energy consumption.

Power systems are modeled by either a component approach or a black-box approach, which represent different levels of detail. In either case, the primary function is to compute the available power for acceleration, the loss and use of power internally, and the energy consumption characteristics.

The component approach to modeling power systems entails decomposition of the complete power source into a number of interconnected components. The models for each component can then be selected from a library, and the TPS can be designed to interface the data flows between each component. This type of model generally computes and displays energy use in more detail than the black-box model.

The black-box approach involves the specification of the total power system by a tractive-effort curve, a transmission-efficiency curve, and a fuel-consumption or energy-demand curve. Tractive effort is usually input in tabular form at fixed velocity increments. Many models reference only a single tractive-effort curve, which does not represent the tractive effort by throttle position.

The modeling of diesel-electric propulsion systems is generally via the black-box approach, with emphasis on determination of available power for driving the wheels and overall fuel consumption. In some models, the fuel consumption is broken down into the component fuel use involved in overcoming resistances and losses in the transmission. The detailed breakdown of internal auxiliary loads, such as auxiliary alternators or generators and air compressors for train brakes and their individual effects on fuel use, is not ordinarily handled.

One other possible power-system modeling feature is the computation of regenerative energy or power available from the propulsion system due to electrical braking.

Brake-System Model

The brake-system model simulates the behavior of friction or air brakes, and in some cases dynamic brakes, and the blending of both types. Because many railroads promote a policy of extensive dynamic brake use by engineers, this is usually a desirable modeling capability. Also, because a fuel-consumption rate is associated with dynamic braking, the capability of modeling dynamic brake application realistically is required in fuel and energy use studies.

The two predominant approaches for computing the available braking force are

1. Use of brake-force, distance, and time equations derived from fundamental physical and mechanical system parameters (several factors are usually approximated, such as adhesion, coefficient of brake shoe, and brake pipe propagation time; more sophisticated equations improve the estimates by including variable brake-application rates and brake pipe leakage) and
2. Use of empirically derived braking curves that describe the braking performance of a particular vehicle type.

A third approach to brake modeling is to specify only a fixed deceleration rate that the train follows when braking.

Ordinarily, the assumptions in TPS models are that the air-brake system is fully charged and the transients due to release and reapplication of brakes are ignored. Dynamic braking capability is generally summarized in a single curve decribing force available by velocity. The usual approach to modeling brake blending is to attempt first to achieve a specified braking rate through the use of dynamic brakes and to increase the braking capability with friction brakes only when dynamic braking is inadequate.

Reporting of Simulation Results

A TPS model generally can produce, in tabular form, both detailed output and summary statistics of the train's performance. The detailed output provides results such as timetables, overall fuel consumption, energy and fuel use breakdowns, instantaneous speed, and so forth, at every program iteration or at a designated interval (such as every milepost), whereas the summary output includes total running time, average running speed, total fuel consumption, throttle position distribution, and tonnage ratings. In addition, track and train input data can be output in tabular form to facilitate verification of the accuracy of data coding.

A TPS model can also produce printer plots and off-line plots. Off-line plot features are usually based on a particular hardware plotting device such as CALCOMP or VERSATEC, and the data link from a TPS model is achieved through the use of a stand-alone program that processes TPS output data files to produce the necessary driver tape. Graphical profiles of the input track data may be produced, which facilitate the verification of data correctness. Since track data coding is a tedious and error-prone process, some form of data validation is desirable to avoid execution of the program with incorrect data. Plots of output variables are valuable for comparing the results of a number of simulation runs with one another or with data recorded in the field.

Use of TPS Models

The TPS model is frequently used in railroad operations and research to (a) determine fuel requirements and energy use, (b) estimate train operating costs, (c) determine scheduled operating time for a train, (d) determine the locomotive power necessary to make a run in a given time, (e) determine the effects of adding or dropping a locomotive unit or tonnage, (f) determine the route tonnage rating based on trains operating over the ruling grade at specified minimum speed, (g) study the effects of changing the scheduling and distribution of trailing tonnage among available locomotives, (h) determine minimum speed on the ruling grade, (i) compare running a specific train over different routes, (j) study the effects of changing speed restrictions or station stops, (k) determine the effects of slow orders, (l) study the effects of track relocation reconstruction or new construction, (m) determine the most desirable siding location, (n) model intercity passenger train service, and (o) generate data for lawsuits and legal hearings.

REVIEW OF EXISTING TPS MODELS

Twenty-seven existing TPS models were reviewed relative to computer and programming aspects, train and track data formats, general train-modeling capabilities, and availability. The models reviewed were from Aerospace Corporation; AiResearch Manufacturing Company of California; Association of American Railroads (AAR); Bechtel Corporation; Burlington Northern; Canadian National Railways; Canadian Pacific Limited; Carnegie-Mellon University (CMU); Chessie System; Day and Zimmermann, Inc.; Electro-Motive Division, General Motors; General Electric (GE); Transportation Systems Division, General Motors; Jet Propulsion Laboratory; TVS Program and VIP3 Program, Louis T. Klauder and Associates; Louisville and Nashville Railroad Company; Manalytics, Inc.; Missouri Pacific Railroad; Norfolk and Western Railway Company; Southern Railway; T.K. Dyer, Inc.; Transportation and Distribution Associates, Inc. (TAD); Transportation Systems Center (TSC), U.S. Department of Transportation; Union College; Union Pacific Railroad Company; and the Train Operations Simulator (TOS), AAR. Detailed abstracts of each model and an extensive bibliography of TPS research and methodology may be found elsewhere (3).

The available TPS models exhibit considerable variety in terms of implementation and considerable replication in terms of capabilities. The following comments summarize the characteristics of the existing models.

Programming Languages and Computer Aspects

Most TPS models (90 percent) are now written in FORTRAN but generally include a number of features not specified by the American National Standards Institute (ANSI). Program documentation--technical modeling information, programmer's information, user's information, and results of validation efforts--is limited for most TPS models. Consequently, the programs are not easily transportable from one computer facility to another. The lack of documentation leads to difficulties in maintenance and enhancements as well as redundancy in TPS design work. The TPS models of TSC, CMU, and Union College are exceptions in that the documentation is complete and of good quality. Many (60 percent) of the models run only in batch mode (i.e., specification of runs cannot be made iteratively via a cathode-ray tube).

Data Collection and Input

Obtaining accurate TPS input data describing the locomotive, cars, and track is difficult. The inaccuracy of input data is a primary source of error in fuel-use predictions. The difficulty in obtaining accurate data is compounded by the differences among various TPS models in format and content of input requirements. Moreover, because of these differences, users have difficulty in sharing data.

Roughly half of the current TPS models are reported to have locomotive and track data bases. Available documentation, however, sometimes does not indicate clearly whether a TPS model has a true key-access track data structure or simply a large collection of track data stored in an ordinary sequential data file.

Track data are generally obtained from railroad property track charts. As stated, the process of coding the track data for input to the TPS model is time consuming and subject to error. This is a major impediment to widespread TPS use.

Resistance Modeling

The inability to simulate accurately the forces due to aerodynamic and mechanical resistance is a significant factor in fuel and energy use prediction (1,4-7). When only a single resistance equation is hard coded in a TPS model, it is almost always the Davis or modified Davis equation. Studies of simulation model performance (4,8) indicate that the Davis and modified Davis equations have not been substantiated for use in modern train simulations. Therefore, further study is necessary.

Power-Systems Modeling

Power-systems models range from the low-detail black-box models to the high-detail, modular, component-by-component models. Five of the 27 TPS models reviewed perform detailed component modeling of electric propulsion systems, and half of the TPS models perform simplified modeling. More than 90 percent of the existing TPS models are used for diesel-electric propulsion systems.

Three models have been developed that compute regenerative energy or power available through electrical braking and apply this capability to an on-board or wayside energy storage system.

One limitation of the existing models is the use of a single tractive-effort curve to compute available force for acceleration. The tractive effort for each notch setting can be described, and simulating the application of tractive effort in this way is more accurate and realistic. Fuel and energy computations are based on the time spent in particular notch settings, so the existing models must compute approximate notch settings.

Brake-Systems Modeling

The two methods generally used to simulate air-brake systems are idealized theoretical brake equations or empirically derived brake curves. Many TPS models can now simulate dynamic braking and blending of dynamic and air brakes.

Other Modeling Considerations

Train-handling algorithms that minimize running time by accelerating and decelerating the train at the maximum feasible and allowable rate are not useful for studying the effects of train handling on fuel consumption or other dependent train parameters. Half the models reviewed represent the train as a single point or unit, and the others represent the train as multiple point masses or as a line.

Output Data

The visual summary of certain output values in the form of graphical display either by off-line pen plotting devices or on-line terminals and printers can facilitate making inferences about both the performance of the TPS models (as in validation studies) and the train system under study. Approximately 30 percent of the TPS models now have graphical printer or off-line plotting capabilities.

Availability

Six of the models were found to be readily available to the railroad industry or other interested users: AiResearch, AAR, Carnegie Mellon, TSC, and Union College TPS models and the AAR TOS.

Use

The majority of the TPS models are capable of modeling both freight and passenger service, although many are used predominantly for simulating one type of service. The TOS and 20 percent of the TPS models reviewed have been used only for modeling freight service, and 10 percent have been used solely for passenger service simulation.

The predominant uses for TPS programs at present are operational studies of scheduling, locomotive assignments, tonnage ratings, calculation of effects in speed-limit changes, and so forth. TPS models are also frequently used in fuel and energy studies involving train makeup, train handling, and engineering modifications.

The AAR TOS is used widely in safety studies involving the analysis of train makeup and handling to determine potentially hazardous operating practices and train consists.

Model Validation

Sensitivity analysis and validation of TPS models are still relatively undeveloped. However, a few models have been validated by using the following approaches: comparison with measured train fuel use (TSC, Chessie System, Norfolk and Western, Union Pacific, Southern Railway), graphical data comparison (AAR TOS), comparison with other TPS models (CMU, Bechtel, TAD, GE), comparison with dynamometer car output (Canadian National), and comparison of calculated running time with that of actual runs (GE, Canadian Pacific, Missouri Pacific, Union College, Union Pacific).

CONCLUDING REMARKS

An industry standard TPS model should satisfy a broad spectrum of software quality factors while meeting the requirements of industry (operational) and research applications. The TPS design should accommodate the requirements of the predominant use areas--i.e., fuel and energy use, safety, and common operational studies.

The three categories of fuel and energy use studies are (a) train handling, (b) engineering modifications, and (c) train makeup. Each category requires that certain characteristics be included in TPS model design, such as abilities to collect data describing train handling and fuel use as well as track characteristics at a detailed level; ability to simulate realistic train-control techniques; component-by-component representation of propulsion systems (as in the Carnegie-Mellon TPS model); high confidence in aerodynamic and mechanical resistance modeling; and the ability to specify train makeup car by car.

Safety studies entail analysis of train makeup and handling to determine potentially hazardous operating practices, train consists, and track locations. This area of analysis is somewhat beyond the capability of TPS models. The AAR TOS model is used widely in this area and is capable of detailed simulation of brake systems--a basic requirement in these studies.

Common operational studies involve scheduling, locomotive assignments, tonnage ratings, calculation of effects of changes in speed limits, and the like. These studies may be considered the core use of TPS programs at present and should continue to be well supported. Most existing TPS models produce results in this area. A major requirement for this study area (and all the other areas) is data accessibility in the form of up-to-date data bases.

The second major requirement for an industry standard TPS model is software quality. Software quality is defined by such general concepts as reliability, testability, usability, efficiency, maintainability, flexibility, and portability. Among the many TPS specific design requirements attached to these criteria that should be integrated into an industry standard model are

1. Up-to-date, easily modifiable library data bases for train and track data;
2. Interactive maintenance and access of the model and all supporting data for convenience of use;
3. Verification of data and graphical output representation of the input data;
4. Complete and accurate documentation, for example, technical modeling information, programmer's and user's information, sample runs, as well as results of validation work performed;
5. Ability to model various train-handling philosophies--a set of parameters that embody the variability in various approaches to train handling should be identified; possible models to work from include the AAR TOS (9-11) and the FUEL model by Muhlenberg (7); and
6. ANSI standard programming.

Many users of existing TPS models consider the models sufficiently accurate for the routine operational applications. Carefully executed studies (4,5), however, suggest that TPS models exhibit many limitations in fuel and energy use prediction. The major function of TPS validation currently is to identify limitations and sources of errors and to determine where further refinements can produce the greatest improvement.

One of the major limitations in validation attempts to date has been the lack of data-collection capabilities. The ability to collect data accurately and to synchronize the data with existing track data bases would greatly facilitate and improve determination of TPS accuracy and limitations. In this regard, the capabilities of computer-based data-collection instrumentation such as the Locomotive Data Acquisition Package (12-14) and the Advanced Locomotive Cab Instrumentation System (15) may be useful. These data-acquisition devices may be applicable to several different areas related to TPS use, including

1. Identification of the behavior of high-variance locomotive parameters such as fuel use and correlation of parameter values with particular operating conditions,
2. Identification of train-handling techniques and effects on fuel use, and
3. Precise recording of scenarios (a common problem in processing such train data as fuel consumption is identification of the conditions under which measurements are being made, such as idling and dynamic braking).

In the long run, on-board microcomputer technology may create an entirely new TPS application. With increased real-time information, engineers could improve run time, fuel economy, and safety. A TPS-type model may then be used to define control strategies based not on general situations but on specific situations measured through on-board microcomputer systems. Because the on-board microcomputer is capable of increasingly sophisticated functions, the insights gained through TPS simulations of train operations and statistical analysis of train operations data may be applicable in real time to assist in complex decision making that the engineer is otherwise incapable of making.

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Publication of this paper sponsored by Committee on Railroad Operations Management.

Car Management Opportunities: Actual Return Mileage Versus Optimal Return Mileage

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Recent developments in the research on car management currently undertaken by Princeton University under the sponsorship of the Association of American Railroads are described. The research makes extensive use of the Princeton Railroad Network Model and Information System. Car management opportunities are examined by comparing simulated actual empty return mileage (ARM) with optimal empty return mileage (ORM). ARM is the mileage obtained when empty cars that terminate on foreign roads are returned home under New Car Service Rule 2 (Rule 2) or Special Car Order 90 (SCO90) or both. ORM is the mileage obtained when empty cars that terminate on foreign roads are returned according to a cost (mileage-based) minimization criterion. The concept of ARM versus ORM is presented for the Southern Pacific Railroad by using 1980 1 percent waybill data for unequipped 50-ft boxcar traffic.

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PROBLEM DEFINITION

Empty cars on a foreign road (not the owner's or not part of the owner's system) can be either reloaded by the terminating road or sent back to the owner (it is assumed here that cars will not be reloaded en route to the owner). If sent back to the owner, the car will travel over foreign roads. Once on the owner's road or system, the car will be repositioned in order to meet the next load.

The current return of empty railroad cars to their owners is achieved mainly through a set of commonly accepted industry rules. The industry rules (chiefly SCO90 and Rules 2 and 6) provide member roads with instructions as to where cars for each owner should be received and forwarded. By a chaining process, in which they proceed from their unloading points back toward their home road, the cars eventually reach the owner's gateway.

SCO90 and Rule 2 have been designed to assure the direct return of empty cars to their owners, but under the current system, car hire penalizes the roads carrying empty foreign cars. Therefore, SCO90 and Rule 2 have also been designed to distribute the empty-car-mile obligations among roads for the sake of fairness. Carriers of empty rail cars, because of car hire, will forward the cars to the closest SCO90 third-party or owner junction (Rule 2) in order to minimize car-mile obligations. The car owner then has little power over where the empty cars are returned.

Once the cars have reached the owner's system, they may appear at junctions where reload opportunities are low. The owner then has to reposition the empty cars within the system, sometimes over considerable distance, in order to meet demand. The sum mileage of the SCO90/Rule 2 return and the system repositioning is referred to as ARM.

The owner can specify, however, through an incentive system, the best return path that would minimize repositioning efforts. The junction with foreign roads where empty cars are to be returned would be indicated. To minimize the incentive payoff, the owner would specify the optimal path over foreign roads from the unloading point to the specified owner junction.

In this paper, the ORM concept is introduced and its effectiveness in the case of the SP system is evaluated. [The system includes SP, the Cotton Belt Route (SSW), and the Northwestern Pacific (NWP).]

SIMULATION OF ARM

Data on the movement of SP 50-ft unequipped boxcars are obtained from the 1980 1 percent waybill sample (Interstate Commerce Commission). From all SP and Cotton Belt marked cars, the following data are selected from the sample: originating railroad, terminating railroad, terminating station, and number of cars.

Assessing Reload Behavior and Percentage of Return

From the selected waybill records, a percentage of reload has been computed for each railroad. The percentage of reload is defined on each road as the ratio of terminating SP cars to originating SP cars. The percentage of cars to be returned is defined on each railroad as (1 - percentage of reload). The location and number of cars to be returned are derived by uniformly factoring termination records by the return percentage on each road.

Figure 1. Return of SSW cars from sample termination points.

Simulating Return of Empty Cars to SP

Cars are returned railroad by railroad. At each program pass, records are moved from one railroad to the next by using delivery-junction tables (Figure 1). The iterative process is halted when all SP records have reached either an SP or a Cotton Belt gateway. The delivery-junction tables are

1. The junction table used for AAR Rule-2-type return (list of active railroad-to-railroad junctions from the enhanced waybill sample), and
2. The SCO90 table used for AAR SCO90-type return (comprehensive table of AAR directives concerning owner, railroad car is on, railroad to which car goes, and stations).

Four main routing-decision types form the return simulation process:

1. If the car terminated on SP or Cotton Belt, it is "frozen" and ready for repositioning.
2. If the car is on a road with junctions to SP, it is returned to the best possible junction (Rule 2).
3. If the car is on another road and SCO90 directives can be found for that road, the car is moved to the best SCO90 outlet. The record of that car will be processed until it has been returned to the owner under steps 1 or 2.
4. If no SCO90 outlets are found for the ownership or road that they are currently on, the cars are reverse routed.

The best junction or SCO90 outlet is defined as the point that minimizes mileage on service routes for the road currently holding the empty cars. [Specifically, it is an impedance metric of distance times line class (line class is a function of traffic and line quality: class 1, tracks with expedited train service; class 2, best through-train service; class 3, regular local service; class 4, irregular local traffic); the metric takes advantage of the shortest distances on the better tracks.] The closest point is determined by using a minimum-path algorithm and computing the best service route among all possible network combinations.

Repositioning Cars Within SP System

Once the appropriate cars have been returned to the owning road or system gateway, the cars are repositioned within that system to satisfy the demand for loads. Supply of and demand for cars are defined as follows. Cars are supplied from foreign cars reloaded on SP, private fleet terminated on SP, SP cars terminated on SP, and delta SP cars returned and currently at gateways.

Delta is defined as the percentage (close to 1) that ensures absolute equality between supply and demand. The supply and demand are fed into a linear program (transshipment problem), which computes the optimal repositioning flows over SP and Cotton Belt to minimize car miles on service routes. Demand points are 50-ft unequipped SP and Cotton Belt car origination points, and supply points are the termination points.

ORM

ORM is defined as the nationwide empty mileage to reposition SP empty cars that minimizes the fleetwide cost. The supply of empty railroad cars is defined as the set of SP cars terminated on foreign roads and not reloaded, SP cars terminated on the SP system, foreign cars terminated on SP and reloaded by SP, and private cars terminated on SP. The demand for cars is defined as the set of 1980 SP originations of boxcars.

The solution to the ORM problem is obtained by submitting the nationwide supply of and demand for SP cars to a linear program transshipment algorithm (OPTRAIL) over the entire North American rail network. The program will assign each empty car to a load and return it over the entire U.S. network so as to minimize the total cost.

In the incentive-based system, foreign roads charge SP for carriage of their empty cars. The fleetwide cost is the sum of off-line payments and on-line estimated empty-carriage costs.

In a first step, the mileage charge is assumed the same for all foreign roads but could be different for each road without damage to the methodology. The owner's perceived empty-mile cost is realistically less than the mileage rate charged by third roads. This is introduced in the ORM scheme by specifying a discounted mileage cost on the SP system. ORMn is defined as the mileage obtained when the owner's repositioning cost is n percent that to the owner on a foreign road. In this case study we will look at ORM100, ORM80, and ORM0. ORM80, for instance, means that the owner (the SP system), in specifying the best return paths, must consider that the cost of moving an empty SP car on the SP system is $0.40 mile when other roads are charging SP $0.50/mile. ORM0 reflects the fact that the owner's real or perceived cost is $0.00/mile when the cost on a foreign road is $0.50/mile.

SP EMPTY-CAR MILEAGE: ARM VERSUS ORM

Figure 2 shows the termination volumes of SP marked 50-ft unequipped boxcars in the United States from the 1980 1 percent waybill sample. Figure 3 shows the empty SCO90/Rule 2 return flows over the U.S. network of those cars not reloaded by foreign roads. The SCO90/Rule 2 return is computed from each termination point as described in the section on ARM. The flows are displayed by using rectangles proportional to the yearly volume of empties on each link. Figure 4 shows the supply of empty SP/SSW cars at the SP system gateways and at internal termination points. Figure 5 shows the demand for boxcar loads on SP and Cotton Belt for 1980. Although some of the boxcars are returned from Burlington Northern to SP in Oregon and close to the major loading points, the majority of the boxcars returned from the East are returned to SP at New Orleans (Figure 3). From the graphics (Figures 5 and 6), it is clear that the return of many empty cars at New Orleans forces SP

Figure 2. Nationwide 1980 terminations of SP/SSW-owned 50-ft unequipped boxcars sent home before SCO90/Rule 2 return.

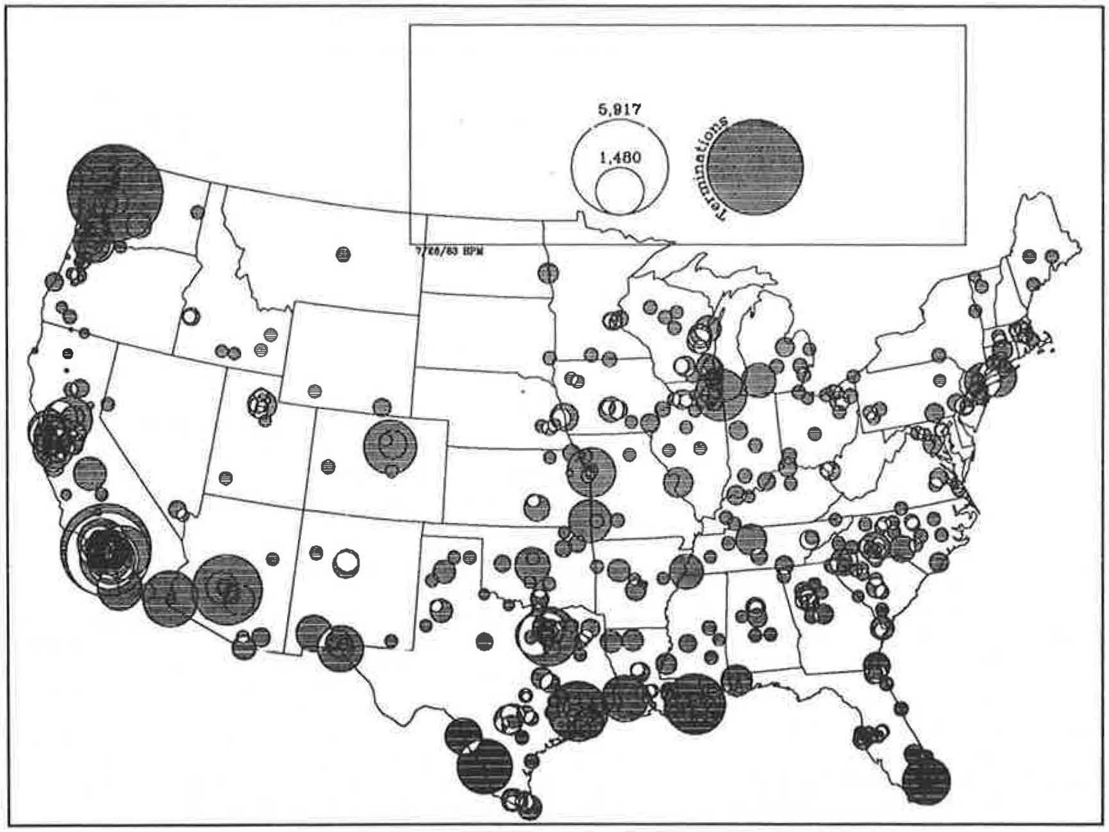


Figure 3. Simulated 1980 SCO90/Rule 2 return of SP/SSW-owned 50-ft unequipped boxcars.

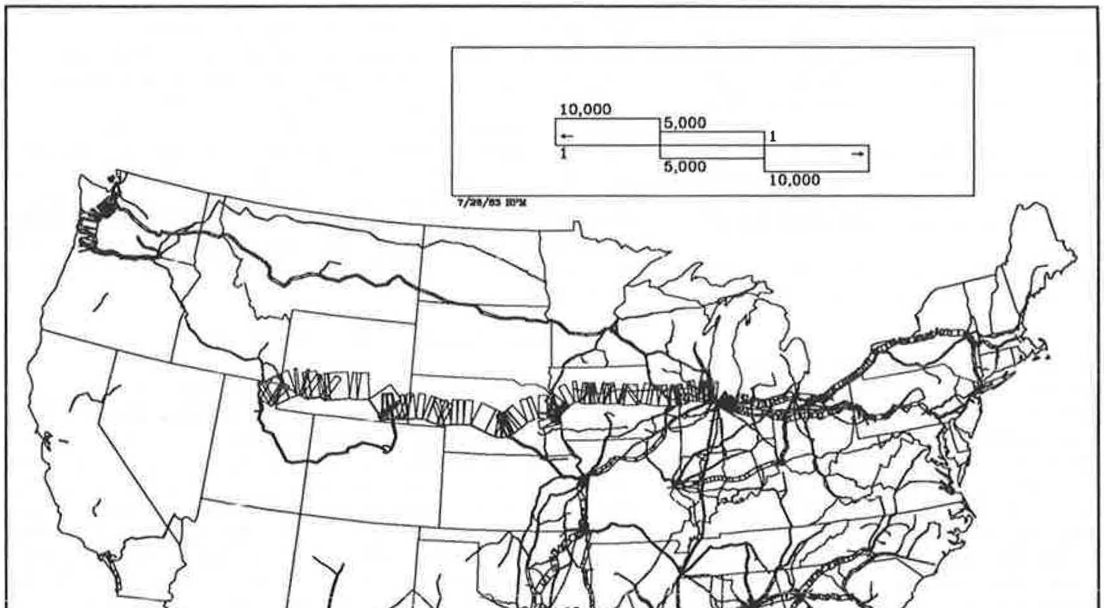


Figure 4. Supply of 1980 SP/SSW-owned 50-ft unequipped boxcars after SCO90/Rule 2 return.

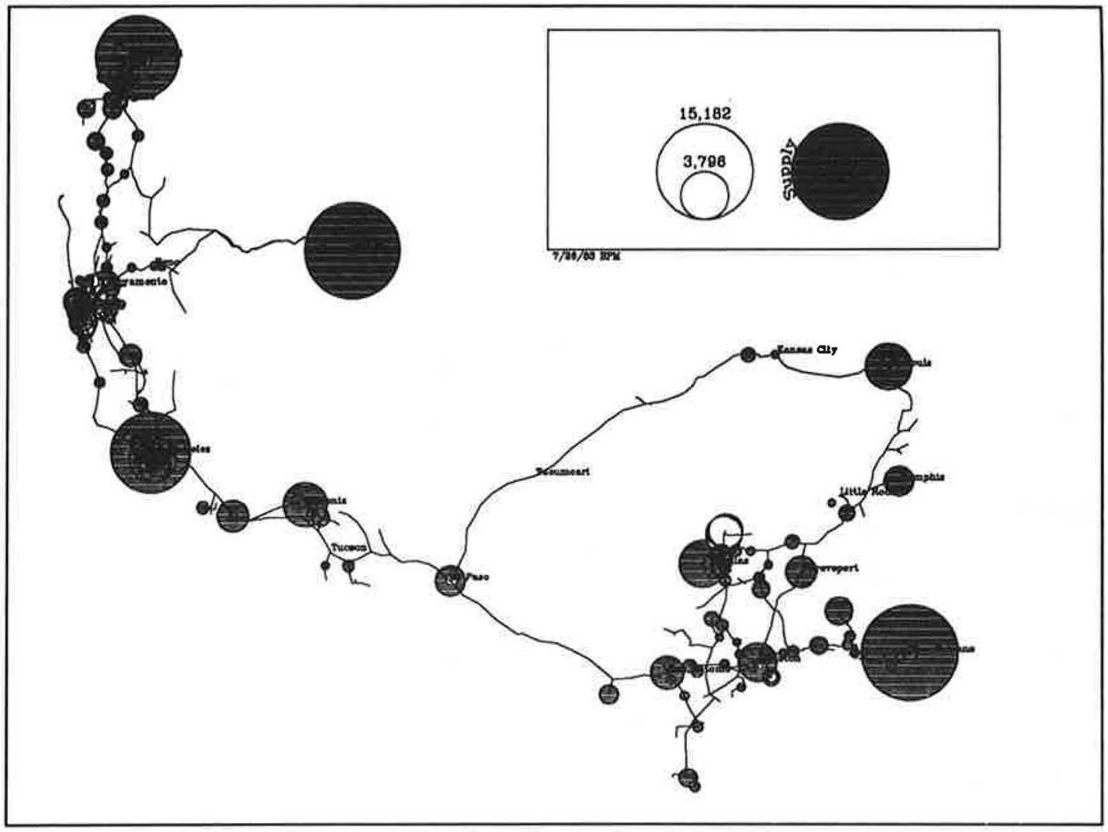


Figure 5. Home demand for 1980 SP/SSW-owned 50-ft unequipped boxcars.

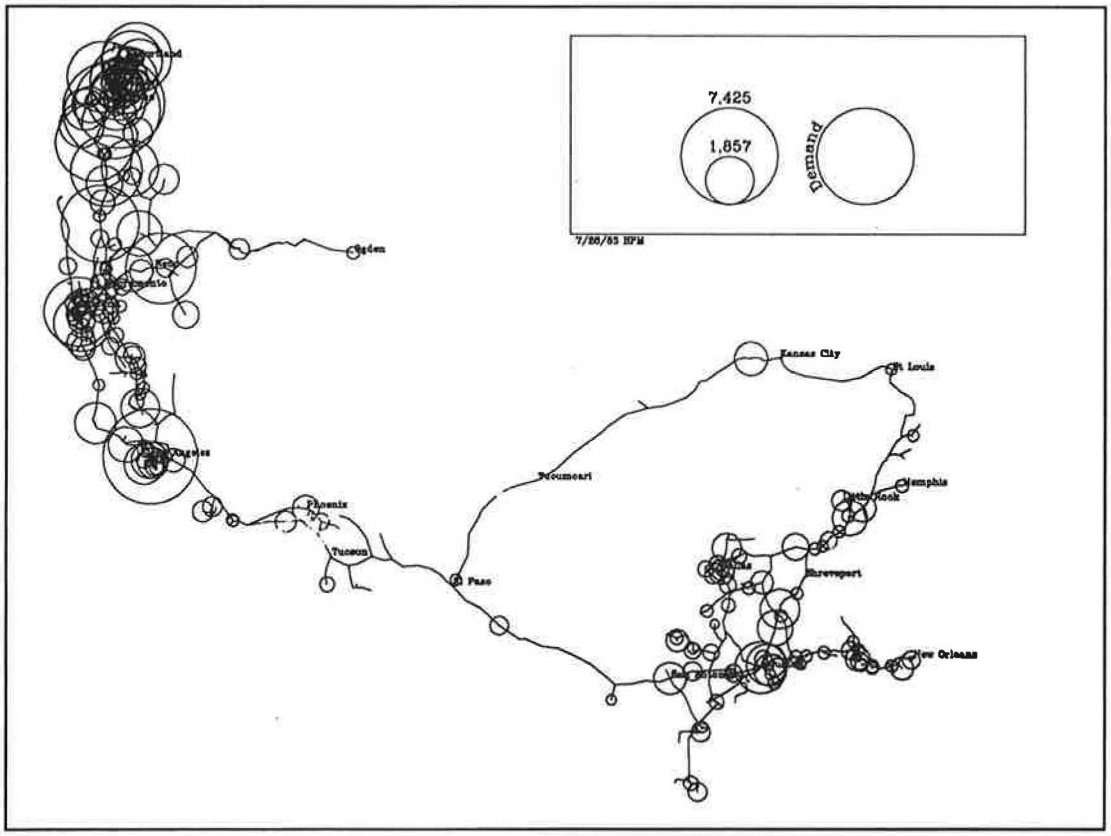
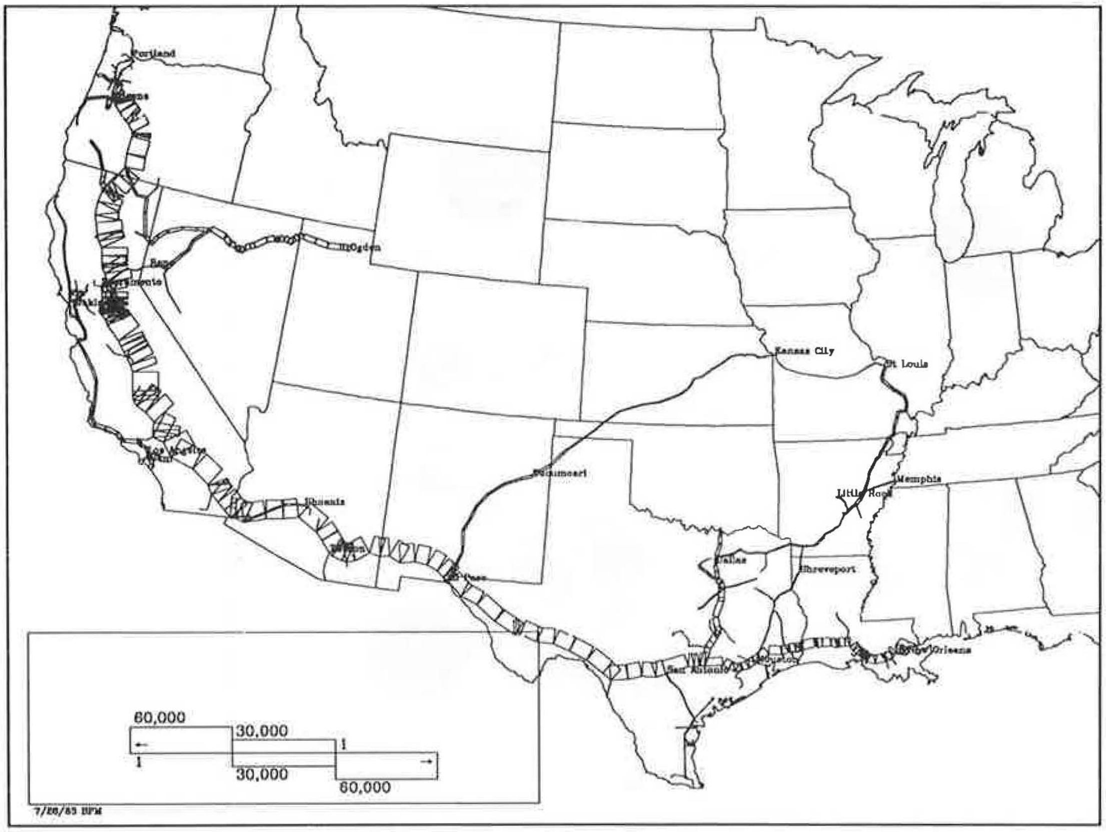


Figure 6. System repositioning of 1980 SP/SSW-owned unequipped boxcars after SCO90/Rule 2 return.



to haul them for a considerable distance to meet loads in Oregon. Figure 6 shows the optimal repositioning flow on SP given supply and demand. The majority of the empty traffic originates in Louisiana and Texas and is bound for Oregon.

Figure 7 shows the total ARM flow over the U.S. network. Figures 8, 9, and 10 show drastically different patterns for ORM100, ORM80, and ORM0, respectively. Table 1 compares ARM (SCO90/Rule 2) with the three ORM cases.

ORM100

Figure 7 clearly shows that a large portion of the cars returned from the Northeast are hauled across the continent from Chicago, Illinois, to Bieber, Oregon, on the Burlington Northern. Burlington Northern is the shortest way to get empty cars from the eastern states to the major demand points of northern Oregon and Washington. Traffic from the South accumulates at Memphis, Tennessee, where it is reloaded by Cotton Belt. A substantial volume of traffic still runs on SP's West Coast line between major consumption and production centers. The scale of Figure 7 indicates, however, that the top volumes are much less than those of Figure 5. It is important to note that under ORM100 there is no traffic of empty cars between northern California and Oregon. This is because the optimal solution indicates that cars returned from the eastern states satisfy the demand in the northwestern states and that cars made empty in Los Angeles and the South can all be reloaded between Los Angeles and southern Oregon.

Table 1 compares the simulated actual and optimal empty return mileages by carrier. Major differences are seen between SCO90 and ORM100 on Burlington Northern, Union Pacific (UP), and the Atchison, Topeka, and Santa Fe (ATSF). UP becomes the second largest carrier of empty SP/SSW 50-ft unequipped boxcars; under ORM100, UP carries more than 16 million car miles as opposed to 6 million under SCO90/Rule 2. ATSF follows; it carries 11 million car miles under ORM100 as opposed to 5 million under SCO90/Rule 2. Missouri Pacific, Louisville and Nashville Railroad Company, Consolidated Rail Corporation (Conrail), and Southern Railway Company all show a major car-mile decline. The largest shift in car-mile obligation, however, occurs on SP itself, where empty-car miles under ORM100 are four times less than they are under SCO90. Therefore, although the overall empty-car miles to return SP cars drops by 16 percent, from 233 million to 200 million car miles, SP itself has a mileage drop by a factor of 4.

ORM80

Major changes are graphically noticeable between ORM100 and ORM80. Because the cost of a system empty mile is only 80 percent that of a mile on a foreign road, SP will want to take control of its cars earlier than in the ORM100 solution. This is why the main stream of empty westbound SP cars now flows over UP. This change from ORM100 to ORM80 is noticeable in Table 1, where UP's empty-car mileage more than doubled. Although some cars returned from the southern states traveled on ATSF under ORM100, the discounted cost on SP-Cotton Belt drives those cars on SP to the East earlier.

Figure 7. Simulated 1980 nationwide return of 50-ft unequipped boxcars under SCO90/Rule 2.

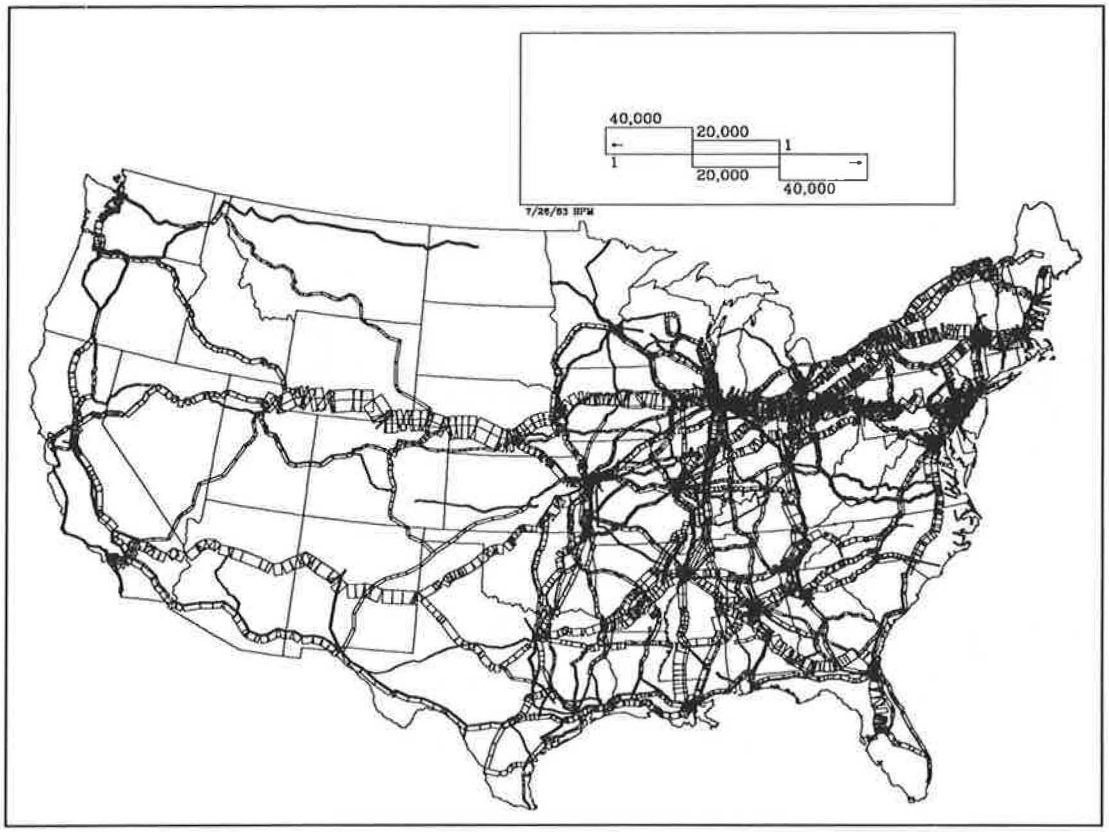


Figure 8. Optimal return of SP/SSW 50-ft unequipped boxcars under ORM100.

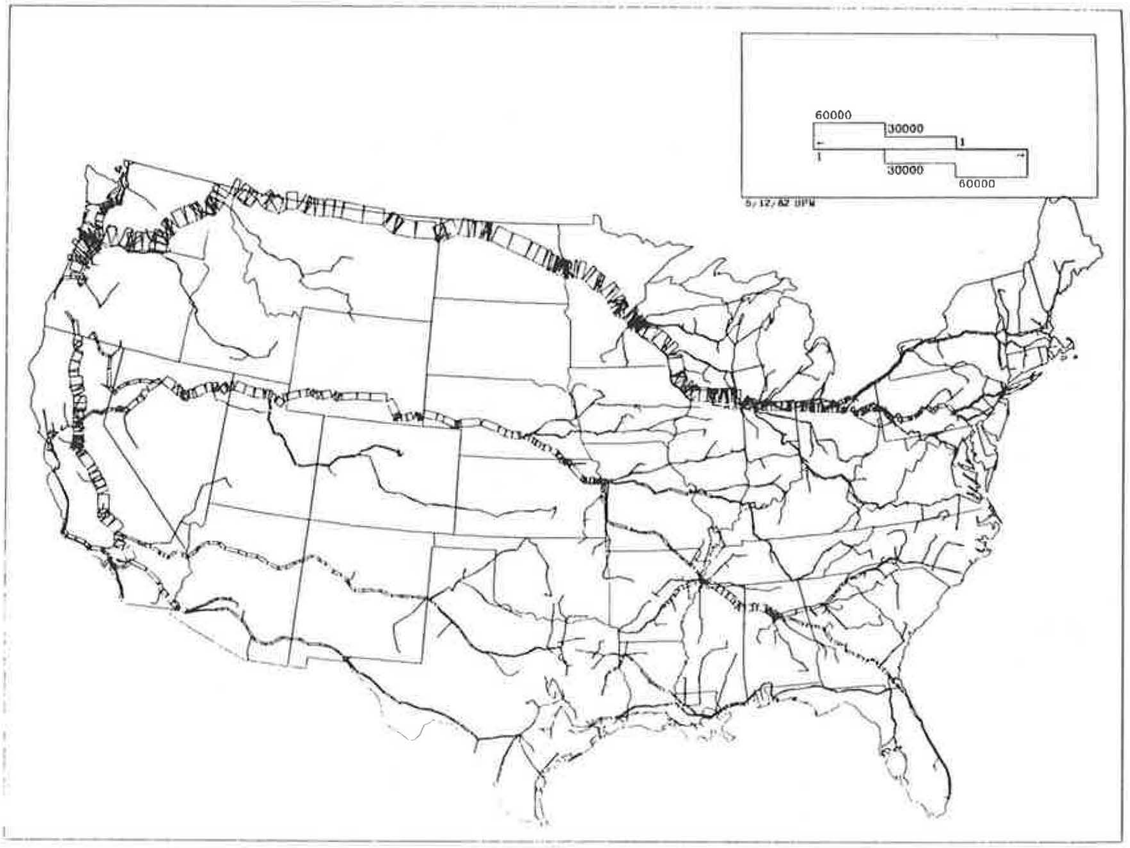


Figure 9. Optimal return of SP/SSW 50-ft unequipped boxcars under ORM80.

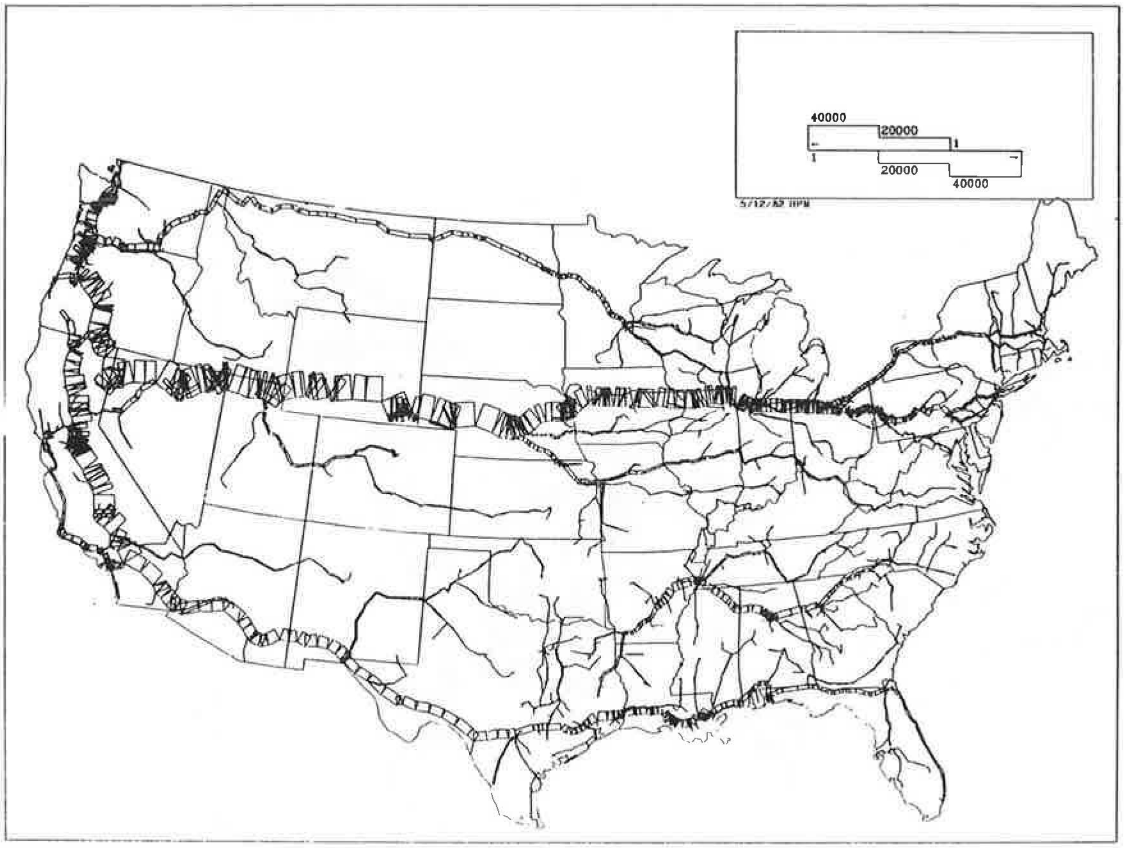


Figure 10. Optimal return of SP/SSW 50-ft unequipped boxcars under ORM0.

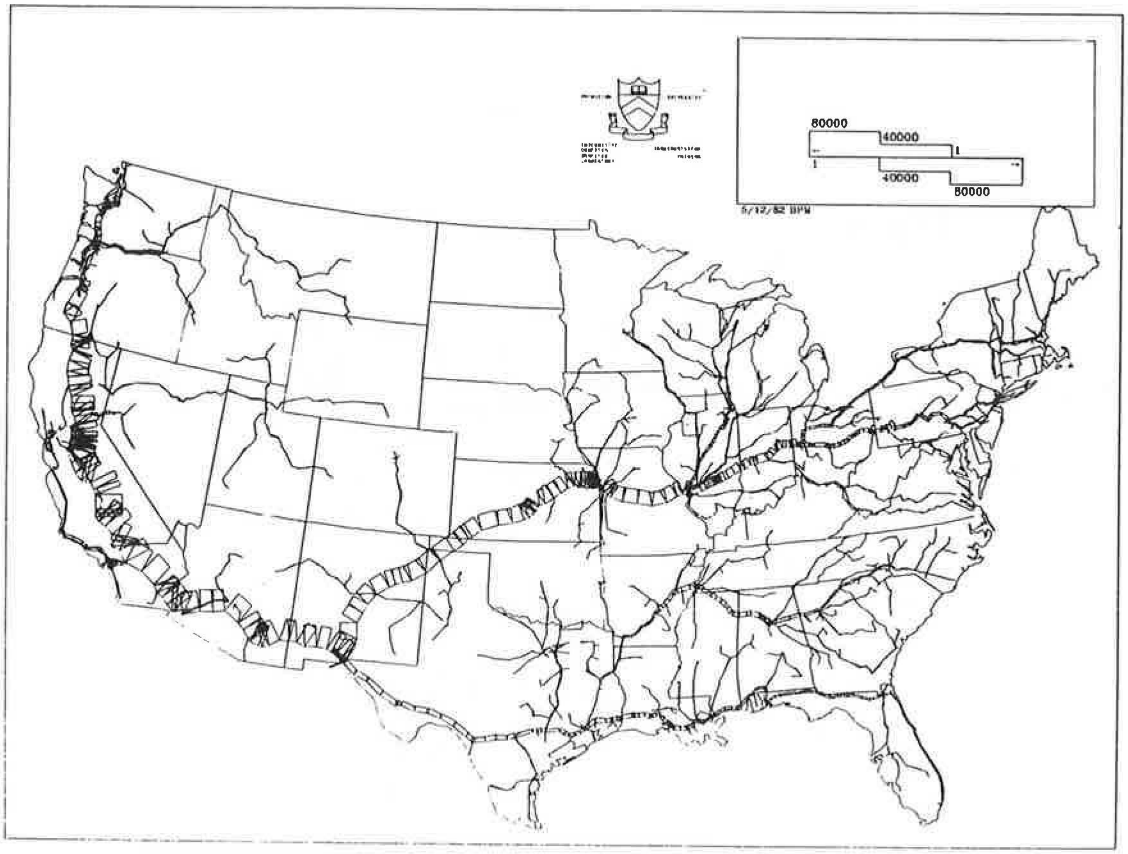


Table 1. Comparison of simulated actual and optimal empty return mileages by carrier for 50-ft unequipped boxcars.

Railroad	Total Empty Car Mileage by Major Carrier (000,000s)			
	SCO90/ Rule 2 (ARM)	ORM100	ORM80	ORM0
Missouri Pacific	7.400	3.286	2.201	1.980
Conrail	6.536	7.290	7.120	16.619
Southern	6.926	3.221	3.348	3.633
Louisville and Nashville	4.061	2.113	3.756	2.800
Burlington Northern	11.707	82.120	19.453	5.221
Union Pacific	5.790	16.084	36.531	0.539
Chicago and North Western	2.707	2.577	13.632	1.062
Milwaukee Road	2.454	0.526	0.579	0.209
Norfolk and Western	1.480	2.808	3.297	2.019
Seaboard Coast Line	2.856	2.939	2.173	2.264
Atchison, Topeka, and Santa Fe	4.416	11.984	6.554	9.056
Illinois Central Gulf	1.653	0.752	0.487	2.608
Chesapeake and Ohio	0.944	5.442	5.326	1.570
St. Louis-San Francisco	0.759	5.066	2.306	2.703
Denver and Rio Grande Western	0.602	1.680	1.689	0.265
Chicago, Rock Island and Pacific	0.375	1.566	1.632	43.485
Kansas City Southern	0.849	0.448	0.265	0.207
Baltimore and Ohio	0.256	0.732	0.555	0.580
Boston and Maine	0.113	0.394	0.394	0.394
Florida East Coast	0.249	0.892	0.859	0.859
Delaware and Hudson	0.377	0.043	0.043	0.043
Soo Line	0.175	0.734	0.734	0.587
Grand Trunk Western	0.288	1.231	1.134	0.074
Missouri-Kansas-Texas	0.158	0.175	0.111	0.018
Western Pacific	0.108	0.815	0.009	0.009
Ft. Worth and Denver	0.044	0.062	0.064	0.208
Maine Central	0.034	0.034	0.034	0.034
Southern Pacific	169.306	44.054	90.906	151.829
Total	238.838	200.505	205.771	251.873

Note: Data were obtained for all carriers in the analysis, including a number of carriers with minor volumes, which are not shown in this table.

As in ORM100, the traffic of empty SP unequipped 50-ft boxcars returning through Chicago is sufficient to satisfy the SP demand for that car type in the northwestern states. This is again shown in the graphics by the absence of traffic between northern California and northern Oregon. In Table 1, it is shown that the total mileage under ORM80 is greater than that under ORM100. Although ORM100 really minimized total car miles, ORM80 minimizes cost based on a different objective function, as shown in Table 2.

From Table 2 it can be verified that ORM80 is indeed a better solution than ORM100 when the discounted system mileage cost is $0.40/mile. With an actual system empty-mile cost of $0.40, the total cost for the ORM100 empty flows would be calculated as follows:

($0.50 x 156,451,000) + ($0.40 x 44,054,000) =
$95,441,000.

This is more than the total cost of $93,794,000 obtained under ORM80. Empty mileage under ORM80 is slightly better distributed among railroads. Although SP's mileage is only cut by half over the ARM internal repositioning effort, the total return mileage is still decreased by 12 percent.

Table 2. Comparison of costs under ORM100, ORM80, and ORM0.

Item	ORM100	ORM80	ORM0
Mileage cost ($)			
Base	0.50	0.50	0.50
On foreign road	0.50	0.50	0.50
On SP/SSW	0.50	0.40	0.00
Mileage (000,000s)			
On foreign road	156.451	114.865	100.044
On SP/SSW	44.054	90.906	151.829
Total	200.505	205.771	251.873
Cost ($000,000s)			
On foreign road	78.225	57.432	50.022
On SP/SSW	22.027	36.362	0
Total	100.252	93.794	50.022

ORM0

ORM0 is closer to ARM than the other solutions, as seen from both the graphics and Tables 1 and 2. Cars are channeled from the East to St. Louis, south on the Cotton Belt to Kansas City, and west on the Tucumcari line. This solution is reached because empty mileage on the SP system is considered free (0 percent) as compared with mileage on foreign roads (100 percent).

CONCLUSION

The comparison between ARM and ORMn shows global reductions of 16 percent (ORM100) and 12 percent (ORM80) in the case of SP. This reduction in total mileage could have a major impact on car cycle, maintenance, and availability of equipment. Under a payment-based system in which the SP system would pay foreign roads for the return of its equipment, the savings to SP would amount to $19 million annually under ORM100 and $10.5 million under ORM80.

In addition, it has been shown that the specification of optimal return paths, in which the objective is to minimize total car miles, could have a drastic impact on the owner's own repositioning effort. SP's empty mileage is decreased by factors of 3 (ORM100) and 2 (ORM80).

Finally, it has been shown that relatively small changes in the objective function (20 percent perceived discount on system empty miles) lead to drastic changes in the corresponding optimal routing specifications. Although traffic would be routed primarily on Burlington Northern for ORM100, it is shown to travel mostly over UP under ORM80.

ACKNOWLEDGMENT

This research is part of an ongoing effort in the area of freight-car management supported by the Freight Car Management Program (FCMP), AAR. The research team wishes to thank Peter French, manager of the FCMP, and his staff for material and technical support. We are also grateful to Yehonathan Hazony, director of the Interactive Computer Graphics Laboratory, for his assistance.

Publication of this paper sponsored by Committee on Railroad Operations Management.

Potential for Nationwide Pooling of Various Types of Railroad Cars

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All opportunities for triangularizing loaded-car movements in order to minimize empty-car miles are investigated. The minimum empty-car-mile repositioning requirements of various railroad car types are presented from the perspective of the entire United States, regardless of car ownership. The optimization algorithm (a car-mile minimization transshipment over the U.S. railway system) ensured that supply and demand for specific types of cars were satisfied. This analysis simulates an efficient utilization of a nationwide pool of each type of car. Supply-and-demand data were obtained from the 1980 1 percent waybill sample. Data on loaded-car miles (L), minimum empty-car miles (E), and E/L ratios are given. Also presented are computer-graphic renderings of the nationwide distribution of the supply and demand for each type of car and directionally specific actual loaded and simulated optimal empty-car flows. Cars analyzed were trilevel automobile carriers, 50-ft gondolas, refrigerated boxcars, open-top hoppers, open-top hoppers carrying coal, covered hoppers, and tanks carrying corn sweetener.

It is well recognized that a major opportunity for the U.S. railroad industry to increase productivity is through improved use of freight cars. Even though there currently exists a glut of equipment, significant operating-cost savings are thought to exist as a result of a better assignment of the supply of empty cars to the demand for loads so as to minimize the accumulation of empty-car miles. In a recent verified statement to the Interstate Commerce Commission (ICC), Kornhauser estimated that in 1980 there existed as much as a billion excess empty-car miles in 50-ft unequipped boxcars (ICC Ex Parte 346, Sub No. 8, April 30, 1982). At what is considered a low marginal cost of $0.30/car mile, this represented a net loss of $300 million to the railroad industry for this car type alone.

Excess empty-car miles are fundamentally unproductive. This is not even a good way to increase the ambient air temperature. But there are many good reasons why empty-car miles are accumulated over the U.S. railway system. One is that car owners want to load or have shippers on their railroad load their own cars because their own cars better meet shipper needs: They have the correct doors, are properly equipped, do not need to be cleaned, and so on. Second, the nature of the business is that raw materials are produced at one location and consumed at another; little material goes back. This skewness in supply and demand is considered to be the root cause of empty-car movements. What could possibly be backhauled in open-top hoppers that carried coal from West Virginia to Norfolk, Virginia? Qualitatively it is clear, but quantitatively the following fundamental question remains: What are the minimum empty-car miles that can be achieved given the current loaded-car movement patterns for various car types? The answer to this question is important in order to identify any missed opportunities that can reduce empty-car miles, and thus cost, that are imbedded in current empty-car management practices. In areas where significant deficiencies are identified, the minimum empty-car-mile solution can suggest where attention should be focused.

In this paper a solution to the minimum empty-car-mile problem is described, the results of applying the procedure to several car types are presented, and the implications of the analysis are discussed. The procedure, MTOPT, is based on the analytical capabilities of the Princeton Railroad Network Model (PRNM) and the 1980 1 percent waybill sample.

PROBLEM FORMULATION

The fundamental question is how big the productivity opportunities are that are associated with a car management philosophy that focuses heavily on the minimization of empty-car miles.

To answer this question, one needs to know the value of some idealistic, optimum empty-car-mile measure and compare it with actual empty-car-movement statistics. If little difference exists between the optimum and the actual figures, then no further investigation is necessary. If a significant difference exists, however, then further investigation is warranted.

One means of obtaining the idealistic optimum value is to pose the following problem:

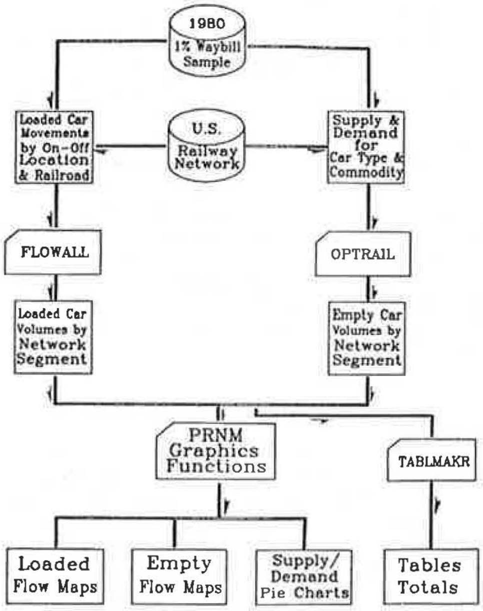
> Given the supply of empty cars of a specific type k (S_i^k), i = 1,...,n, where S_i^k is the number of type-k cars demanded at location i around the nation, i = 1,...,n; n is the number of specific locations on the U.S. railway system where traffic is assumed to originate or terminate (there are 17,000 nodes in the U.S. portion of the PRNM); D_j^k is the demand, i.e., number of type-k cars needed to load at location j around the country; and N_{mn} is the network geometry of the U.S. railway system, including distance (DIS_{mn}) and line code (LC_{mn}), and m and n are the end nodes of each segment of the U.S. railway network.
>
> Find the empty-car volumes for each network link (V_{mn}) such that the supply satisfies the demand over the network and the summed and weighted carload distances:
>
> $$\sum_{mn} DIS_{mn} \times LC_{mn} \times V_{mn} \text{ is minimized}$$
>
> where V_{mn} is the volume of empty cars traveling from location m to n.

The above problem is a classical transshipment-type linear programming problem. Supply data (S_i^k), demand data (D_j^k), and network data (DIS_{mn} and LC_{mn}) are given. The objective is to minimize a weighted car-mile objective that tends to route cars on segments that have a smaller value of LC_{mn} (main lines) than those with a higher value (branch lines). This weighted minimization is necessary in order to add realism to the solution, because railroads tend to move empty cars on main lines rather than on branch lines.

Many solution procedures exist to the transshipment problem. One developed by Mulvey (1) and called LPNET is particularly efficient and is structured to handle networks with a large number of nodes and links, which is a necessity because the U.S. railway system as defined in PRNM (2) consists of 17,000 nodes and 18,000 links. PRNM uses LPNET to solve the transshipment problem in the empty-car-mile minimization program called MTOPT.

MTOPT structures the supply-and-demand data from the traffic source, e.g., 1 percent waybill data (3); forms the transshipment network; solves the

Figure 1. Computational procedures of MTOPT.



transshipment problem (LPNET); and produces directional volumes of optimal empty-car movements. The empty-car movements are plotted by using the graphic functions of PRNM (see Figure 1). MTOPT also extracts the loaded-car movements, plots the flow on the U.S. railway system by using ALKFLOW (efficient traffic-assignment algorithm of PRNM), and displays the loaded-car flow by using the same graphic utilities that display the empty-car flow. Summary statistics of loaded- and empty-car miles and ratios are also computed.

QUANTITATIVE FINDINGS

The MTOPT program was executed on seven specific combinations of car type and commodity [Standard Transportation Commodity Code (STCC)]:

Car Type	AAR Car-Type No.
Trilevel automobile carrier	V4, V6, V8
Gondola, 50-ft	G2
Open-top hopper	H3
Open-top hopper carrying coal	H3 (STCC = 11)
Covered hopper car	L 53, L 54
Refrigerated boxcar	R
Tank car carrying corn sweetener	T (STCC = 2046)

The supply of (termination of loaded movement) and demand for (origination of loaded movement) empty equipment for each car type were obtained from the 1980 enhanced 1 percent waybill sample (3). These traffic data are convenient because the sample is of reasonable size; they are coded with the PRNM network node numbers for originations, interline junctions, and terminations; and the sample has been annualized based on 1980 Freight Commodity Statistics (FCS).

Loaded-car miles and optimum empty-car miles were computed by using the MTOPT procedure described in Figure 1. The summary quantitative findings are given in Table 1. Note that the optimum empty/loaded (E/L_{opt}) ratio was found to be highest for 50-ft gondolas (0.904) and lowest for trilevels (0.314). Somewhat surprisingly, open-top hoppers carrying coal have some significant triangularization potential; the E/L_{opt} is 0.793, which annually could save as much as 120 million empty-car miles. Removing the commodity restriction from open-top hoppers suggests that E/L_{opt} could be as low as 0.697. Even tank cars carrying corn sweetener have some triangularization potential; E/L_{opt} is 0.759. Covered hopper cars and refrigerated cars gain the most in terms of optimum empty-car miles relative to loaded-car miles; for covered hopper cars, E/L_{opt} is 0.496, which yields 1.2 billion less empty miles than loaded miles, and for refrigerated cars, E/L_{opt} is 0.326, which yields 700,000 fewer empty miles than loaded miles.

Table 1. Minimum empty-car miles and loaded-car miles for various car types.

Car Type	1980 Car Miles (000,000s) Loaded	Minimum Empty	E/L_{opt}
Trilevel	357	112	0.314
Gondola, 50-ft	105	95	0.904
Open-top hopper	876	570	0.697
Open-top hopper carrying coal	639	507	0.793
Covered hopper	2,434	1,207	0.496
Refrigerated boxcar	1,035	338	0.326
Tank car carrying corn sweetener	59	45	0.759

DETAILED FINDINGS

Each of the combinations of car type and commodity is described further in this section. For each, the following data are given:

1. Pie charts show the volume of cars originated and terminated by location at the major origins and destinations in the United States. The pie charts have been drawn so as to be centered on the location and with an area proportional to the sum of originations plus terminations of that car type. Slices delineate the originations from the terminations.
2. Loaded-flow volumes show the directionally specific volume of loaded-car movements over the most densely traveled segments of the U.S. railway system (not all segments are shown, to avoid cluttering the maps). The flow volumes are depicted by using a right-hand rule: The height of the bar chart perpendicular and to the right of a line segment is proportional to the volume of flow in the facing direction.
3. Minimum empty-car-mile flow charts can be used to compare with the loaded volumes. These maps also have net supply minus demand superimposed. These graphs clearly show the flow of empty cars from points of net supply to points of net demand. Note that the nature of the optimal solution is such that empty cars flow in at most one direction on any track segment.

Specific findings by car type are as follows.

Trilevel Cars

Figure 2 shows the nationwide distribution of the supply and demand of trilevel equipment. Some locations such as Dallas, Los Angeles, Atlanta, and Kansas City are fairly balanced in their supply and demand. Major net supply points are Denver, Phoenix, Salt Lake City, Florida, Mississippi, Tennessee, Alabama, and North Carolina. A major net demand area is Michigan.

Figure 3 shows the loaded flow of trilevel cars. Note the westbound imbalances on the Atchison, Topeka, and Santa Fe (ATSF); Union Pacific (UP) to Ogden; and Southern Pacific (SP) on the central corridor and the eastbound imbalances on the Burlington Northern (BN), UP from Oregon to Ogden, and the old New York Central of Consolidated Rail Corporation (Conrail); the flow is exclusively southbound on the Family Lines, Florida East Coast Railway Company (FEC), and Cotton Belt Route (SSW).

Figure 2. Gross supply and demand of empty trilevel cars.

Figure 4 shows the optimum empty-car flow on the same scale as that in Figure 3. Note the stunning difference in the traffic flow densities. Because the total car miles in each chart is simply the summed area of all of the flow boxes, one immediately sees that the empty-car miles are much less than the loaded-car miles. In fact, almost no trilevels need to be shuttled empty across the Rockies. Empty trilevels need to be reallocated along the West Coast; from Houston to Oklahoma City; from Miami through Jacksonville, Atlanta, and Cincinnati to Detroit; from Mississippi and Memphis to Detroit; and from North Carolina through Virginia to western Pennsylvania. Other major empty flows are southward from Albany to northern New Jersey; eastward from Denver through Chicago to Detroit; and from Minneapolis to Milwaukee.

Gondolas

Figure 5 shows the supply-and-demand aspects of 50-ft gondolas. These cars exhibit a different spatial distribution of supply and demand from that of trilevels. There are a few major generation points and many minor ones. No region both originates and terminates this equipment. Major originations are in the coal areas of Wyoming and Colorado and steel-producing areas of western Pennsylvania. Consumption seems to be at major inland waterway

Figure 3. Loaded flow of trilevel cars.

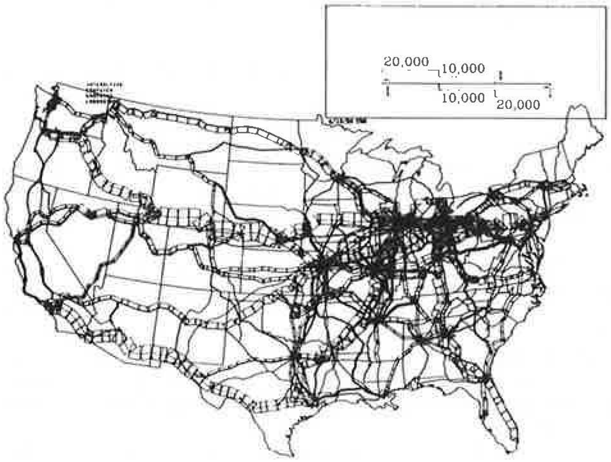


Figure 4. Net supply and demand of empty trilevel cars.

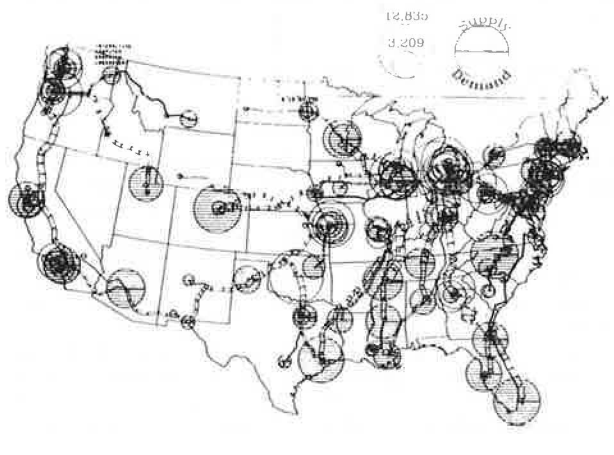


Figure 5. Gross supply and demand of empty 50-ft gondolas.

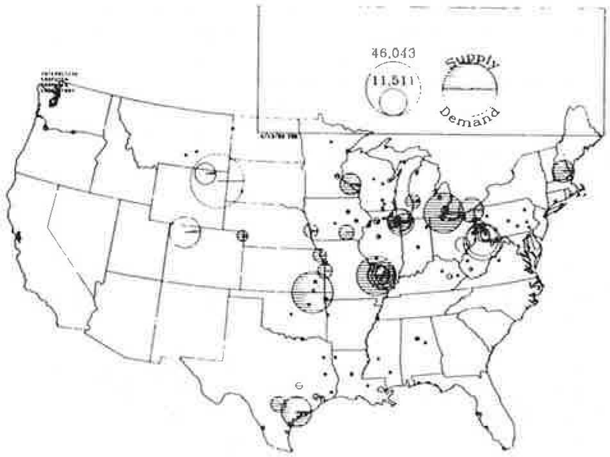
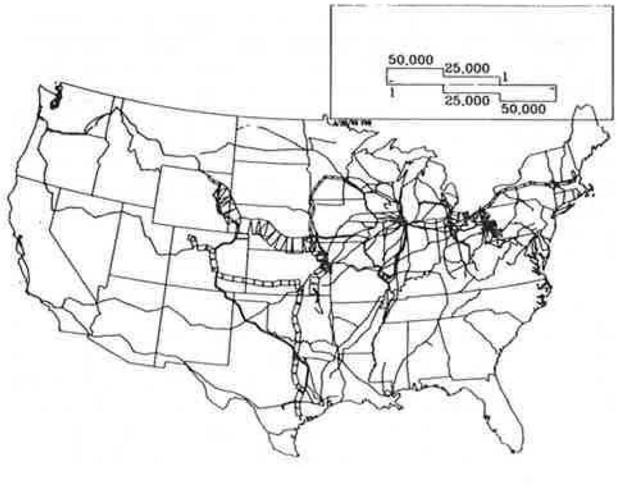


Figure 6. Loaded flow of 50-ft gondolas.



locations along the Missouri and Mississippi Rivers, the Gulf Coast, and the Great Lakes.

Figure 6 shows the loaded flow, which is primarily one-directional. It is not surprising that the E/L_{opt} for this car type is close to 1.0 (0.904).

Figure 7. Net supply and demand of empty-50-ft gondolas.

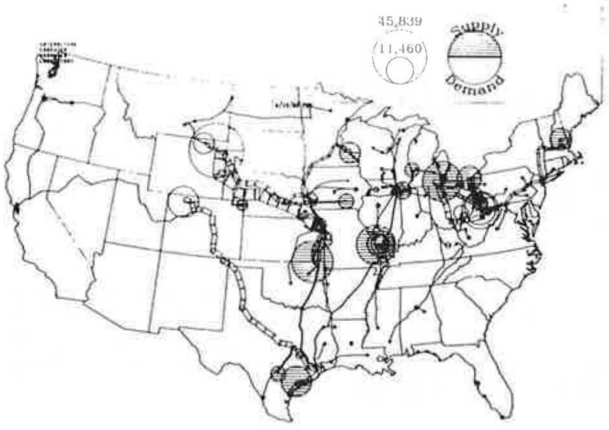


Figure 8. Gross supply and demand of empty open-hopper cars.

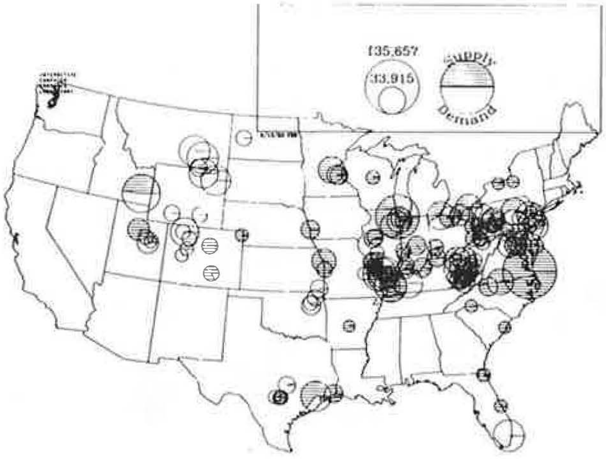


Figure 9. Loaded flow of open-hopper cars.

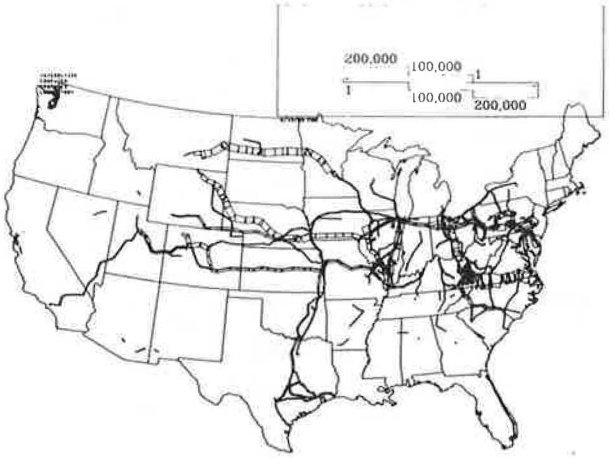


Figure 7 shows the optimal empty flow. This is the exact reverse of the loaded flow except that the empty cars are routed on the most direct service route (minimum impedance = DIS x MLC) to the demand point irrespective of rail ownership. The effect of the disregard of railroad ownership is discussed in the next section.

Open-Top Hoppers

Open-top hopper cars carry primarily coal; however, they also transport other bulk commodities such as sand and crushed stone. The nationwide distribution of the supply and demand for empty open-top hoppers is shown in Figure 8. The supply and demand for the hoppers used to move coal is easily recognized in Wyoming, Utah, Colorado, and the East. The Florida supply and demand is an example of sand and gravel movements.

Figure 9 shows the flow volume of loaded open-top hoppers. Note the propensity of one-way flows from the mining areas in Montana, Wyoming, and West Virginia to the unloading points of Minneapolis, Norfolk, and Toledo. Note also the one-way flow northbound on FEC.

The one-way loaded flow suggests that little triangularization may be available except in areas of Texas and Pennsylvania. Computation of the minimum empty-car-mile strategy did uncover some signif-

Figure 10. Optimal repositioning of empty open-hopper cars.

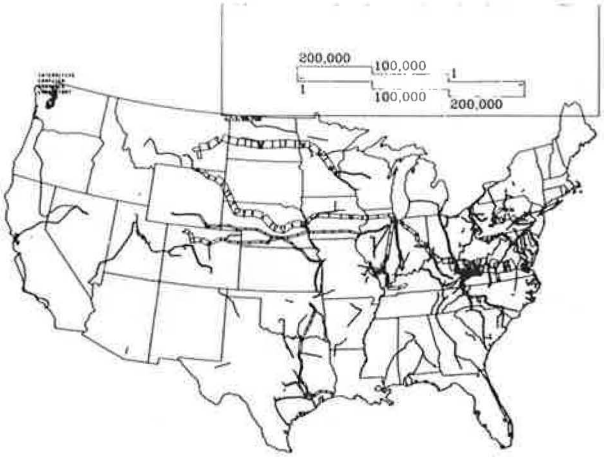
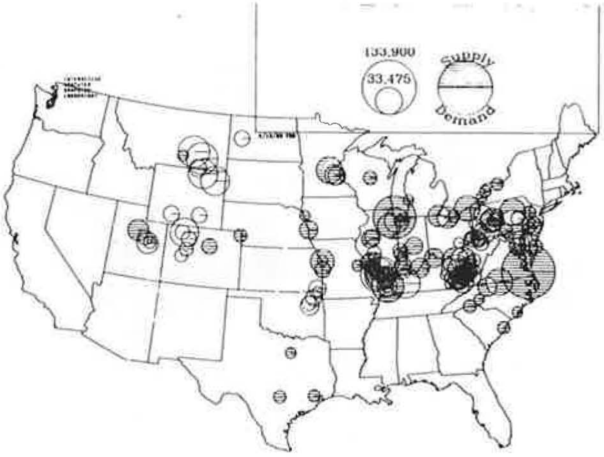


Figure 11. Gross supply and demand of empty open-hopper cars that carried coal.



icant reductions in car miles relative to the loaded-car miles. An E/L_{opt} of 0.697, which yielded 250 million less empty-car miles than loaded-car miles, resulted. Figure 10 shows the optimal empty-car flow. Note that no savings were found in Florida, West Virginia to Norfolk, or out of Wyoming and Montana. Significant opportunities exist, however, in Illinois, Indiana, Ohio, and Pennsylvania as well as in Texas and Colorado.

It is recognized that to achieve such savings would require extreme cooperation among competing railroads; however, the magnitude of the benefits that appear to exist may make desirable such cooperative undertakings.

Open-Top Hoppers Carrying Coal

A criticism of the previous section may be that the analysis failed to realize that hopper cars that carry coal are fundamentally different from those used to carry other bulk commodities. For this reason, traffic flow of open-top hoppers carrying coal was analyzed. Figure 11 shows the supply and demand for this case. Note that it is similar to the previous case except for the Florida traffic and some other minor changes. The loaded-car flow of Figure 12 is similar to that of Figure 9.

Given the restrictions on commodities, one would expect fewer opportunities to triangularize loaded movements. This was found to be the case. The E/L_{opt} increased 10 percentage points to 0.793. Figure 13 shows the optimal empty-car flow. This suggests that restricting open-top hoppers to coal traffic significantly reduces the opportunity to save empty-car miles. If the commodity restriction is more beneficial than the potential savings, then so be it; however, one can now quantify the opportunities and evaluate the trade-offs.

Covered Hoppers

The nationwide distribution of the supply and demand for covered hoppers is shown in Figure 14. This distribution is significantly different from that of the other car types in that there exist a few large supply points (Superior/Duluth, Houston, and Tampa) but many nearly equal medium-sized supply-and-demand points (Figure 14 shows only the largest 150 supply-and-demand points so as not to overly clutter the diagram).

Figure 15 shows the 2,500 segments with the highest loaded covered-hopper volume of the U.S. railway system. Note the uniformity of flow as well as the balanced two-way flow on many segments, particularly on UP's central corridor.

Figure 12. Loaded flow of open-hopper cars carrying coal.

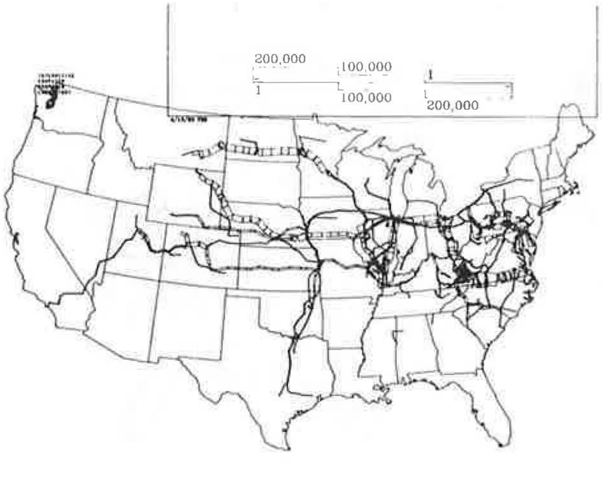


Figure 13. Net supply and demand of empty open-hopper cars that carried coal.

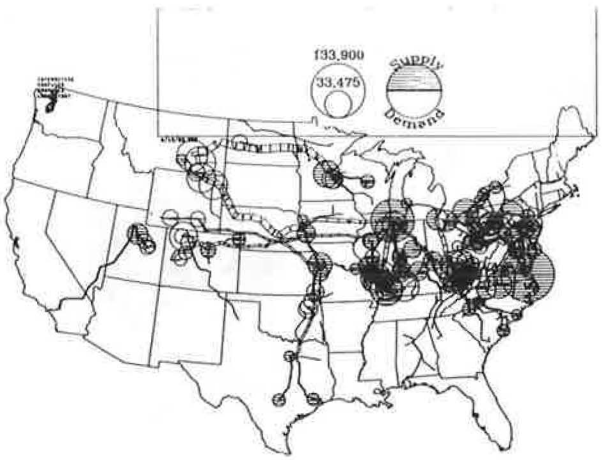


Figure 14. Gross supply and demand of empty covered-hopper cars.

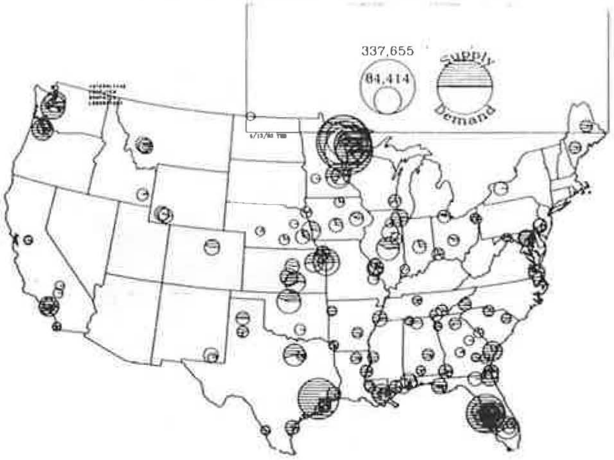
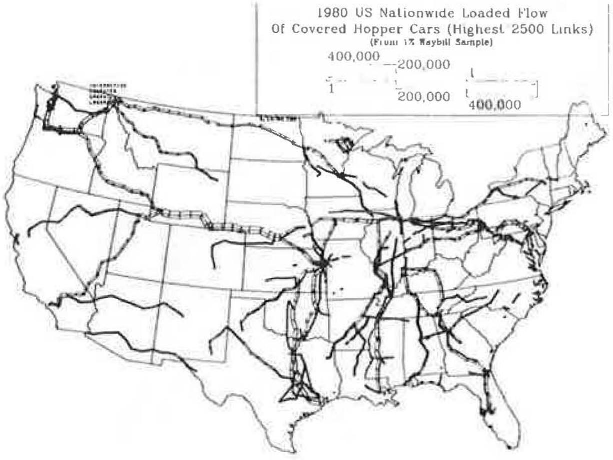


Figure 15. Loaded flow of covered-hopper cars.



The loaded flow of Figure 15 suggests the great opportunity for backhaul loading of covered hoppers. Optimal repositioning of the supply of empty cars to loaded cars led to an E/L_{opt} of 0.496, which suggested the movement of two loaded cars for each empty one. The empty-car flow is shown in Figure 16, which exhibits the following interesting aspects: (a) no empty covered-hopper movements on UP's central corridor, ATSF, or SP; (b) few westbound movements on BN; (c) significant westbound repositioning from eastern points of Conrail to Chicago and high volumes northbound out of Houston and New Orleans to the grain areas of Iowa and Nebraska; and (d) self-sufficiency of the Superior/Duluth and Tampa markets.

Refrigerated Cars

In Figure 17 the nationwide supply-and-demand distribution of refrigerated boxcars is shown. The distributions follow that of perishable commodities, as expected.

The loaded flow of refrigerated cars (Figure 18) shows good directional balance on the ATSF, SP, and parts of UP and Seaboard Coast Line; strong eastward imbalance exists on Conrail.

The loaded flow suggests good reload opportunities, which do in fact exist. The optimum repositioning of empties suggests an E/L_{opt} of 0.326--three loads for every empty movement. The empty flow, shown in Figure 19, is much smaller than the loaded flow. A predominantly transcontinental westward repositioning is shown. Although some cars are repositioned empty coast to coast, many more are reloaded nearby.

Tank Cars Carrying Corn Sweetener

In order to study an example of a specific combination of car type and commodity, tank cars carrying corn sweetener were chosen. It was thought that such specificity would eliminate all opportunity for reload. The supply and demand for this case are shown in Figure 20. Although the demand for such cars seems to be centered in Illinois, the supply is well distributed nationally.

The loaded flow, primarily Coastbound from Illinois, is shown in Figure 21. The computation of the optimum repositioning gave an E/L_{opt} of 0.759--three empty movements for every four loads. Surprisingly, there are some opportunities for reload short of return to shipper. As can be seen from the optimum empty-car flows in Figure 22, some of the empty-car miles are saved because of a more direct return of empty cars to the loading point as

Figure 16. Optimal repositioning of empty covered-hopper cars.

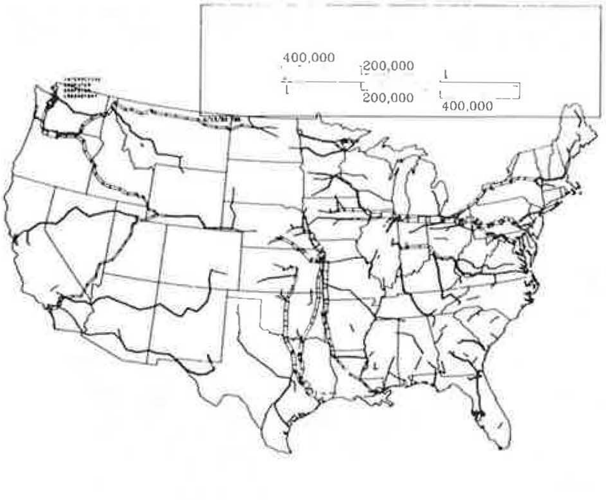


Figure 17. Gross supply and demand of empty refrigerated cars.

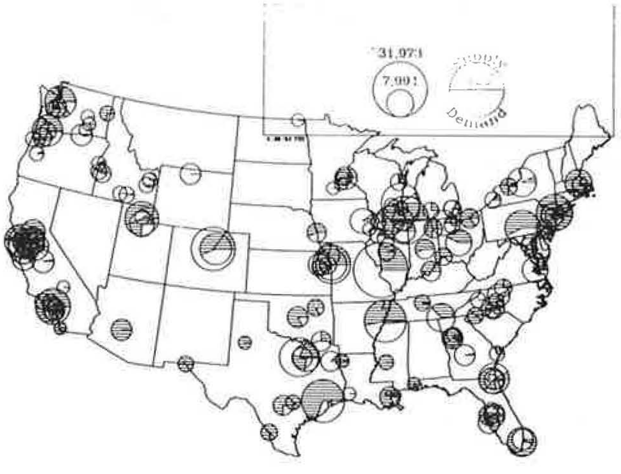


Figure 18. Loaded flow of refrigerated cars.

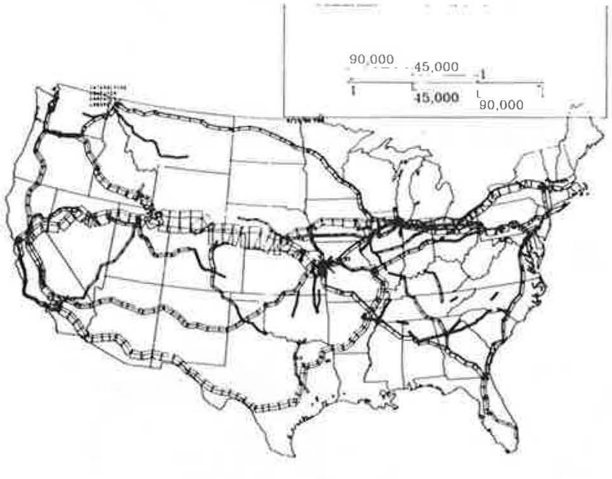
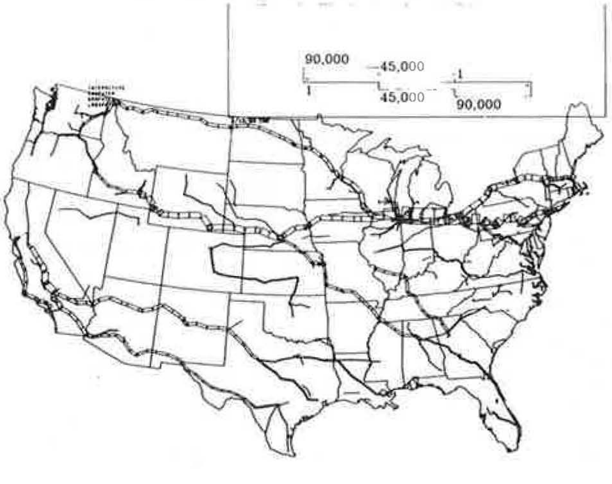


Figure 19. Optimal repositioning of empty refrigerated cars.



compared with their route when loaded. This difficulty is analyzed in the following section.

IMPACT OF NON-RAILROAD-SPECIFIC EMPTY RETURN

The algorithm that computed the minimum empty-car miles did so over a network representation of the U.S. railway system in which the distance and quality of service on each segment were considered but no attempt to enforce continuity of ownership was made. The optimization objective was a service-weighted distance minimization. Thus empty cars were repositioned over the shortest, best-served routes, and branch and corridor lines of the National Railroad Passenger Corporation (Amtrak), which may have been shorter, were generally circumvented. Nevertheless, a loaded single-carrier movement may occasionally have the car returned to the shipper via an unrealistic multicarrier route. Inspection of the empty-car flow suggests that this is generally a minor problem, because main lines tend to run parallel or orthogonally rather than in a close-weaving pattern. The only area in which this is not true is corridors radiating in and out of Chicago. What the optimal empty flows do point out is that in some cases there exists a routing back to the shipper that is less circuitous than that of the loaded movement.

The circuity effect is estimated by generating routes on a unified rail network. These routes are computed from origin to destination independent of track ownership and historical interline locations. This computation, in which loaded service-route car miles were minimized, when compared with the actual loaded-car miles provides a measure of the service-route circuity of loaded-car movements. Table 2 summarizes the computation for each car type and commodity. Presented are actual loaded-car miles, service-route minimum loaded-car miles, service-route minimum empty-car miles, and optimum ratios of empty- to loaded-car miles (E/L_{opt}) based on each loaded-car-mile computation. Note that from Table 2 there is relatively little circuity introduced by the actual loaded route as compared with a service-route optimization. The difference ranges from 5 to 10 percent. The effect on E/L_{opt} is roughly five percentage points. This suggests that there is some

Figure 20. Gross supply and demand of empty tank cars that carried corn sweetener.

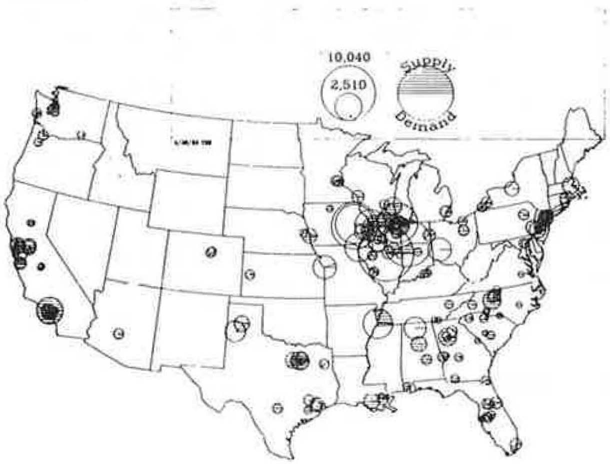


Figure 21. Loaded flow of tank cars carrying corn sweetener.

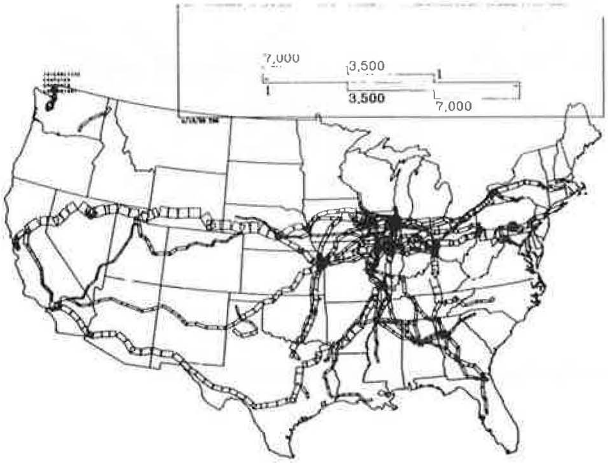


Figure 22. Optimal repositioning of empty tank cars that carried corn sweetener.

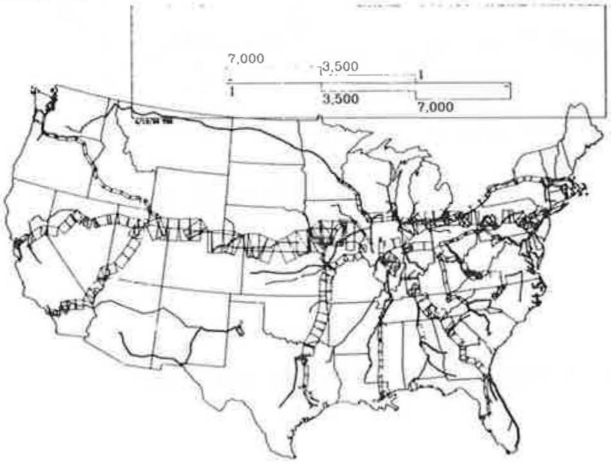


Table 2. Loaded- and empty-car miles by using service-route optimization.

Car Type	1980 Car Miles (000,000s) Actual Loaded	Minimum Service-Route Loaded	Minimum Service-Route Empty	E/L^a_{opt}	$E/L*^b$
Trilevel	357	324	112	0.314	0.345
Gondola, 50-ft	105	100	95	0.904	0.954
Open-top hopper	816	753	570	0.697	0.756
Open-top hopper with coal	639	597	507	0.793	0.849
Covered hopper	2,434	2,231	1,207	0.496	0.541
Refrigerated boxcar	1,035	934	338	0.326	0.361
Tank cars with corn sweetener	59	52	45	0.759	0.853

[a] Column 3 divided by column 1. [b] Column 3 divided by column 2.

effect and opportunity associated with service-route minimization; however, the effect is small compared with the opportunities to minimize empty-car miles by repositioning cars so as to maximize reload opportunities.

CONCLUSION

A study has been presented of the loaded flow, empty-car supply and demand, and opportunities for car-mile minimization by empty-car repositioning for a variety of car type and commodity combinations. The analysis is entirely quantitative and suggests that although there is a sizeable skewness in the supply and demand for specific equipment types, the degree of skewness varies greatly. This suggests good opportunities for finding backhauls, thus reducing empty-car miles, which was unexpected for some equipment types. The analysis suffers only slightly from studying only spatial skewness without temporal effects. The temporal or seasonal effects can be minimized in a period of large surpluses in equipment by maintaining proper strategic inventories of the surplus cars so that temporal imbalances can be smoothed. Minimizing empty-car miles can add to the surplus, which should lead to further smoothing of any temporal imbalances.

Significant further research and analysis needs to be carried out. The optimal empty-car flow needs to be compared with the actual flow. The difficulty is that there exists no publicly accessible data source on empty-car movements. Nevertheless, railroad companies, shippers, and car owners do (or should) maintain proprietary data bases on these movements. Those companies that do have access to these data sources should utilize the MTOPT methodology to analyze opportunities for improved car management.

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Publication of this paper sponsored by Committee on Railroad Operations Management.

Measuring the Quality of Freight Service: Analysis of Shipper Recording Practices with Emphasis on Railway Users

GARLAND CHOW AND RICHARD F. POIST

The purpose of the study was to determine the extent to which quality of freight service is measured and recorded by transportation buyers. To be specific, a mail questionnaire was sent to a sample of traffic managers to assess their recording behavior with respect to 22 quality-of-service attributes. Overall, the results indicate that although service measurement generally does take place, it tends to be accomplished on an informal basis rather than through formally recorded reports. Likewise the results indicate that recording practices do differ somewhat, depending on the degree of rail use by the shipper. Some managerial implications of these results for both buyers (i.e., shippers or users) and sellers (i.e., carriers) of freight service are presented.

In every industry, attention must be given to customer needs and preferences, or what is commonly referred to as the marketing concept (1, pp. 22-25). For the rail and trucking industries, this attention takes an increased significance as both industries move toward a more competitive environment spurred by regulatory relaxation and greater economic pressures.

The significance of researching the shipper's transport selection decision is great. In the long run, product and pricing strategy is based on knowledge of the mode and carrier characteristics rated highly by shippers. Over shorter time horizons, the carrier wants to identify shippers with similar needs or preferences. In this way sales resources can be allocated more efficiently and sales approaches or strategies can be planned more effectively.

Research regarding the transportation selection decision is important also to the buyer of transport services. The responsibility for so-called right and wrong transport selection decisions generally rests with the traffic manager, and the results of such decisions can mean the difference of hundreds of thousands of dollars to a company. Whatever traffic managers can do to make themselves better informed and educated consumers is obviously to their advantage.

Over the past decade, the transport selection decision has been the subject of numerous survey analyses. It is not our intention to review these surveys in detail, since this has been done previously (2, pp. 5-9). It is relevant, however, to note in passing that these studies vary in technique, objective, and, in many cases, conclusions (3-10). Generally, these studies are characterized as follows:

1. Some studies analyze the importance of various quality-of-service attributes or factors solely for the mode selection decision. Other studies analyze only the carrier selection decision. Others look solely at the private versus for-hire decision. Some studies analyze two or more of the

preceding decisions, and some studies do not distinguish as to the type of transport decision (e.g., modal, carrier, for-hire) being investigated.

2. Some studies contrast importance ratings between buyers (i.e., shippers), types of buyers, and sellers (i.e., carriers). Significant differences in ratings suggest remedial policies for the carrier.

3. Past studies, to varying degrees, differentiate importance ratings by characteristics of the decision maker, the commodity, the firm's traffic pattern, the firm's distribution organization and competitive environment, use patterns, and other demographic variables.

In summary, most selection criteria studies to date have attempted to identify and analyze the importance of various factors that traffic managers consider when arriving at a modal or carrier choice. What has been virtually ignored by these studies is the measurement aspects of service quality. For example, do shippers keep records of the service quality and performance of carriers with regard to key selection variables? If so, to what extent and for which variables?

In other words, it is simply not enough to identify and determine the importance of various selection variables or factors. Specific measures and techniques for recording the quality of service associated with these variables are also necessary for making effective transport purchase decisions.

PURPOSE AND METHODOLOGY

The purpose of this paper is to determine the extent to which quality of service is currently measured or recorded by transport buyers. More specifically, the paper examines the following questions:

1. To what extent are quality-of-service factors formally recorded or measured by shippers?
2. To what extent are quality-of-service factors recorded or not recorded by shippers?
3. To what extent do recording practices differ by degree of railway use?
4. To what extent do recording practices differ between all shipper respondents and high-use rail shippers?

It is important to note that the scope of the paper is limited to examining the extent to which quality-of-service measurement or recording takes place and not the specific measures being recorded. The latter topic will be addressed in a separate paper. Likewise, in this paper we do not address the question of measurement differences based on demographic variables with the exception of degree of rail use, as mentioned above.

An important prerequisite of the study was to identify the quality-of-service factors that act as important determinants of transport selection. From a review of the literature, 22 factors were identified. Overall quality of service was defined to be a function of these factors. For classification purposes, the factors were grouped arbitrarily into seven categories of factors: rate-related, operations-related, people-related, time-related, claims-related, equipment-related, and miscellaneous. The 22 factors and group designations are presented in Table 1.

To obtain the required information, mail questionnaires were sent to 1,000 traffic and distribution managers selected randomly (11). Nondeliverable questionnaires ultimately reduced this number to 908. Of this number, 202 usable questionnaires were returned; the response rate was approximately 23 percent. Given the length and detail of the questionnaire, this response rate was regarded as good and more than adequate for analysis purposes. Likewise the respondents were judged, based on demographic characteristics, to be highly representative of a wide variety of shipper organizations and traffic executives.

The survey instrument was a very detailed two-part, five-page questionnaire. Part 1 requested information on the importance of the 22 carrier or mode quality-of-service attributes and demographic information about the decision maker, the company,

Table 1. Measurement of quality-of-service factors by all shipper respondents.

		Percentage of Respondents Indicating Factors as			
Quality-of-Service Factor	Category Designation[a]	Recorded Formally	Recorded Informally	Not Recorded	Total Recorded[b] (%)
Door-to-door transportation rates or costs	R	45.0	36.3	18.7	81.3
Freight loss and damage experience	C	43.4	35.3	21.3	78.7
Claims-processing experience	C	39.8	35.5	24.7	75.3
Transit-time reliability or consistency	T	30.9	47.4	21.7	78.3
Experience with carrier in negotiating rate changes	R	27.3	41.2	21.5	68.5
Shipment tracing	O	26.7	44.2	29.1	70.9
Total door-to-door transit time	T	23.8	44.2	32.0	68.0
Quality of pick-up and delivery service	O	22.8	41.4	35.8	64.2
Availability of single-line service to key points in shipper's market area	O	22.4	41.2	36.4	63.6
Equipment availability at shipment date	E	21.1	47.6	31.3	68.7
Shipment expediting	O	18.6	49.7	31.7	68.3
Experience with carrier in negotiating service changes	O	17.0	43.6	39.4	60.6
Specialized equipment to meet shipper needs	E	16.8	36.5	46.7	53.3
Frequency of service to key points in shipper's market area	O	15.6	46.1	38.3	61.7
Physical condition of equipment	E	12.7	37.0	50.3	49.7
In-transit privileges	O	11.9	27.1	61.0	39.0
Diversion or reconsignment privileges	O	11.2	22.8	66.0	34.0
Quality of operating personnel	P	5.6	42.8	51.6	48.4
Carrier image or reputation	M	3.1	41.4	55.6	44.5
Reciprocity	M	2.6	23.2	74.2	25.8
Quality of carrier salesmanship	P	2.5	32.9	64.6	35.4
Gifts and gratuities offered by carrier	M	2.0	13.0	85.0	15.0

[a] R = rate-related factor; T = time-related factor; C = claims-related factor; E = equipment-related factor; P = people-related factor; O = operations-related factor; and M = miscellaneous factor.

[b] Represents the sum of percentages indicated for formally and informally recorded.

traffic characteristics, and transportation use patterns. In part 2, the questionnaire sought information regarding the extent to which the quality-of-service factors were measured or recorded. Pretesting had indicated that there are generally three levels of recording: formal, informal, and none. (These levels are analogous, in a sense, to precise measurement, imprecise measurement, and no measurement.) Distinctions among these levels are as follows:

1. Formal recording: There exists a systematic procedure for written recording of data relating to the quality-of-service factor.
2. Informal recording: Data relating to the factor are noted or recorded, but no systematic procedure has been established for doing so. Recording may be either written or unwritten.
3. No recording: Data relating to the factor are not recorded.

To be specific, for each of the 22 factors, respondents were asked to indicate whether the factor is recorded formally, informally, or not at all when the quality of freight service is measured. The recording information collected in part 2 of this survey was used as the basis for this paper.

SURVEY FINDINGS

Recording Practices of All Shipper Respondents

Table 1 indicates the extent of measurement with respect to the 22 quality-of-service factors. These factors are ranked from high to low depending on the percentage of respondents indicating formal recording or measurement of a given factor.

Overall, it appears that most quality-of-service measurement takes place on an informal basis and not through formally recorded reports. Only six of the factors were formally recorded by as many as one in four (i.e., 25 percent) of respondents. These factors were as follows: door-to-door transportation rates or costs, freight loss and damage experience, claims-processing experience, transit-time reliability or consistency, experience with carrier in negotiating rate changes, and shipment tracing. With one exception, these factors tended to be related to rates, claims, or time.

At the other extreme, five of the factors were not formally recorded by as many as 1 in 10 respondents (i.e., 10 percent). These included gifts and gratuities offered by carrier, quality of carrier salesmanship, reciprocity, carrier image or reputation, and quality of operating personnel. All of these factors tended to be in the people-related and miscellaneous categories. The remaining factors in Table 1 were recorded formally by between 10 and 25 percent of the shipper respondents.

Thus it appears that relatively few factors are recorded formally to any degree. In effect, we witness the Pareto principle, in which a small percentage of the factors accounts for a disproportionately large percentage of the formal recording. Higher percentages were indicated for formal recording than for informal recording for only three factors--door-to-door transportation rates or costs, freight loss and damage experience, and claims-processing experience. In all other cases, the quality-of-service factors were more likely to be recorded informally.

It is interesting to note that the factors with the highest formal recording percentages generally are similar to those shown to be most important in previous carrier- or mode-selection studies. This is especially true with respect to transportation rates and transit-time reliability. Given the cost and time associated with developing a formal recording system, it makes sense that only the most important factors warrant systematic written recording. At the same time, it should be noted that certain traffic activities by their very nature require more formalized recordkeeping. For example, the successful handling of claims requires necessary support documentation. The same can be said for rate negotiation and tracing activities, among others. Undoubtedly this fact helps explain the relatively high level of formal recording with respect to some factors.

A mild surprise from the study was the low level of formalized recording in the area of people-related factors, such as quality of carrier salesmanship and quality of operating personnel (e.g., drivers). It would appear that this would be a major area of contact between carrier and shipper organizations and hence deserving of formal recording. However, this was not the case. What appears to be happening is that these people-related factors are receiving much more in the way of informal recording (see Table 1).

It is also interesting to note the relatively high extent of recording currently taking place with regard to experience with the carrier in negotiating rate changes. In the future this figure can be expected to increase as efforts are made by more companies to emphasize negotiations and bargaining to take advantage of greater pricing flexibility under deregulation.

Finally, the results show that, for a majority of the quality-of-service factors studied, measurement was more likely to take place than not. This can be seen in Table 1 in the column headed Total Recorded. Overall recording was more likely to take place with respect to the factors related to rates, claims, time, and equipment.

Recording Practices Based on Rail Use

Although there are many demographics that could be examined in conjunction with recording practices, it was decided to analyze differences in recording practices based on the degree of railway use by shippers.

The demographic information was gathered in the survey by asking shippers to estimate the percentage of their unit's freight tonnage that regularly moves by each transportation alternative. For rail, the breakdown was as follows:

Percentage of Tonnage Shipped by Rail	No. of Shippers	Percentage of Total Shippers
0-10	107	53.0
11-20	13	6.4
21-30	8	4.0
31-40	9	4.4
41-50	4	2.0
51-75	19	9.4
76-100	42	20.8
	202	

Based on this breakdown, a decision was made to classify shippers into the following categories for analysis purposes: low use, 0-10 percent; moderate use, 11-50 percent; and high use, 51-100 percent. The resulting analysis is shown in Table 2.

In general, the results are similar to those identified in Table 1. Again relatively few factors are formally recorded to any great extent, and recording (whether it be formal or informal) is more likely to take place than not.

With respect to categories of use, five factors with statistically significant recording differences were identified. In general, these factors tended

Table 2. Recording practices based on degree of railway use.

Quality-of-Service Factor	Category Designation[a]	Rail Use by Percentage of Tonnage Shipped								
		High (51-100 percent)			Moderate (11-50 percent)			Low (0-10 percent)		
		F[b]	I[c]	N[d]	F	I	N	F	I	N
Door-to-door transportation rates or costs	R	53.6	26.8	19.6	48.1	29.7	22.2	44.4	38.6	17.0
Claims-processing experience	C	44.3	28.8	26.9	42.9	35.7	21.4	36.0	39.5	24.4
Freight loss and damage experience	C	42.6	31.5	25.9	50.0	25.0	25.0	41.7	40.7	17.6
Experience with carrier in negotiating rate changes	R	37.0	35.2	27.8	17.7	43.8	38.5	27.0	41.2	31.8
Transit-time reliability or consistency	T	34.5	40.0	25.5	32.1	42.9	25.0	28.2	53.3	18.5
Shipment tracing	O	27.8	44.4	27.8	14.2	42.9	42.9	30.0	44.4	25.6
Quality of pick-up and delivery service	O	25.5	25.5	49.0	8.0	44.0	48.0	24.7	50.6	24.7[e]
Total door-to-door transit time	T	24.1	44.4	31.5	28.6	32.1	39.3	22.2	47.8	30.0
In-transit privileges	O	24.1	29.6	46.3	4.0	20.0	76.0	6.2	27.5	66.3[e]
Equipment availability at shipment date	E	23.6	49.1	27.3	7.7	57.7	34.6	23.6	43.5	32.9
Availability of single-line service to key points in shipper's market area	O	22.2	35.2	42.6	25.0	42.9	32.1	21.6	44.3	34.1
Shipment expediting	O	20.7	29.1	30.2	14.3	46.4	39.3	18.6	51.2	30.2
Specialized equipment to meet shipper needs	E	20.0	36.4	43.6	7.5	48.1	44.4	17.7	32.9	49.4
Experience with carrier in negotiating service changes	O	19.3	44.2	36.5	11.5	42.3	46.2	17.2	43.7	39.1
Frequency of service to key points in shipper's market area	O	15.5	38.5	46.2	17.8	42.9	39.3	15.0	51.7	33.3
Diversion or reconsignment privileges	O	14.8	31.5	53.7	3.7	18.5	77.8	11.1	18.5	70.4[f]
Physical condition of equipment	E	11.5	48.1	40.4	7.7	19.2	73.1	15.0	35.6	49.4[f]
Quality of operating personnel	P	5.8	32.7	61.5	0	46.2	53.8	7.2	48.2	44.6
Carrier image or reputation	M	5.7	30.8	63.5	0	34.6	65.4	2.4	50.0	47.6[f]
Reciprocity	M	4.0	18.0	78.0	0	23.1	76.9	2.6	26.7	70.7
Quality of carrier salesmanship	P	2.0	23.5	74.5	0	30.8	69.2	3.6	39.3	57.1
Gifts and gratuities offered by carrier	M	2.0	12.0	86.0	0	7.7	92.3	2.6	15.6	81.8

[a] R = rate-related factor; T = time-related factor; C = claims-related factor; E = equipment-related factor; P = people-related factor; O = operations-related factor; and M = miscellaneous factor.

[b] Percentage of group indicating the factor as recorded formally.

[c] Percentage of group indicating the factor as recorded informally.

[d] Percentage of group indicating the factor as not recorded.

[e] Statistically significant at the 0.10 level or less by using a chi-square test.

[f] Statistically significant at the 0.05 level or less by using a chi-square test.

to be related to operations and equipment. The factors are indicated in Table 2 and include in-transit privileges, diversion or reconsignment privileges, physical condition of equipment, quality of pick-up and delivery service, and carrier image or reputation. The high-use group indicated greater overall recording for the first three factors, whereas the low-use group indicated greater recording for the last two factors.

These differences can be largely attributed to the basic nature of rail operations. For example, in-transit privileges and diversion or reconsignment are likely to be more relevant in connection with rail use than with other modes. The same can be said for the physical condition of the equipment, an area in which rail shippers typically have experienced more problems. Likewise, quality pick-up and delivery service would tend to be more important to less-than-carload-lot, air, and truck shippers as opposed to large-volume rail shippers. Finally, given the relatively small number of rail carriers in a given geographical area compared with the number of motor carriers, one would not expect carrier image or reputation to be as relevant in the transport purchase decisions of rail-oriented shippers.

Recording Practices of All Respondents Versus Those of High-Use Rail Shippers

A final comparison that leads to some interesting observations is shown in Table 3. Here the recording practices of all shipper respondents and high-use shippers were compared. The relevant figures in Tables 1 and 2 relating to formal and informal recording were added together to arrive at the total recorded figures shown in Table 3. It was hoped that this analysis would identify factors for which there was a noticeable difference in recording practices.

There was a 10 percent or greater difference found between the responses of the groups for six factors, namely, physical condition of equipment, in-transit privileges, diversion or reconsignment privileges, quality of pick-up and delivery service, quality of operating personnel, and quality of carrier salesmanship. The first three factors were indicated as being more often recorded by the high-use rail shippers, whereas the latter three were indicated as being more often recorded by the total-respondent group.

For the most part, these factors are the same as those identified previously in the analysis by degree of rail use. The major exceptions pertain to the people-related factors--quality of carrier salesmanship and quality of operating personnel. Again the explanation most likely rests with the nature of rail operations compared with other modes and the resultant fact that rail-oriented shippers typically have less personal contact with carrier personnel in day-to-day operations than is true, for example, of truck-oriented shippers.

A final observation that should be made is that although a number of noticeable differences in recording practices were found, these differences for the most part involved factors that tended to receive relatively little overall recording. In contrast, there were very little in the way of differences in recording practices involving factors that tended to be recorded often (see Table 3). This leads to the conclusion that there is considerable agreement as to the factors deserving greatest measurement and the level or extent of that measurement.

MANAGERIAL IMPLICATIONS

These results should prove useful to traffic and carrier managers alike. The data should prove valuable to traffic and distribution managers by indicating what their contemporaries are doing currently in the area of measurement and recording. In this

Table 3. Recording practices of all shipper respondents versus high-use shippers.

		Percentage of All Respondents		Percentage of High-Use Rail Shippers	
Quality-of-Service Factor	Category Designation[a]	Total Recorded[b]	Not Recorded[c]	Total Recorded	Not Recorded
Door-to-door transportation rates or costs	R	81.3	18.7	80.4	19.6
Freight loss and damage experience	C	78.7	21.3	74.1	25.9
Transit-time reliability or consistency	T	78.3	21.7	74.1	25.5
Claims-processing experience	C	75.3	24.7	73.1	26.9
Shipment tracing	O	70.9	29.1	72.2	27.8
Equipment availability at shipment date	E	68.7	31.3	72.7	27.3
Experience with carrier in negotiating rate changes	R	68.5	31.5	72.2	27.8
Shipment expediting	O	68.3	31.7	69.8	30.2
Total door-to-door transit time	T	68.0	32.0	68.5	31.5
Quality of pick-up and delivery service	O	64.2	35.8	51.0	49.0[d]
Availability of single-line service to key points in shipper's market area	O	63.6	36.4	57.4	42.6
Frequency of service to key points in shipper's market area	O	61.7	38.3	53.8	46.2
Experience with carrier in negotiating service changes	O	60.6	39.4	63.5	36.5
Specialized equipment to meet shipper needs	E	53.3	46.7	56.4	43.6
Physical condition of equipment	E	49.7	50.3	59.6	40.4[d]
Quality of operating personnel	P	48.4	51.6	38.5	61.5[d]
Carrier image or reputation	M	44.5	55.6	36.5	63.5
In-transit privileges	O	39.0	61.0	53.7	46.3[d]
Quality of carrier salesmanship	P	35.4	64.6	25.5	74.5[d]
Diversion or reconsignment privileges	O	34.0	66.0	46.3	53.7[d]
Reciprocity	M	25.8	74.2	22.0	78.0
Gifts and gratuities offered by carrier	M	15.0	85.0	14.0	86.0

[a] R = rate-related factor; T = time-related factor; C = claims-related factor; E = equipment-related factor; P = people-related factor; O = operations-related factor; and M = miscellaneous factor.

[b] Percentage of group indicating the factor to be recorded either formally or informally.

[c] Percentage of group indicating the factor as not recorded.

[d] Factors for which there was a 10 percent or greater difference between the overall respondents and high-use rail shippers.

way comparisons can be made to determine whether or not a firm's recording system is above or below the standards indicated. It is hoped that measurement areas for further study and improvement will be indicated by this study.

In turn the findings also have meaning for carrier management. For example, the survey indicates the factors for which shippers are making the greatest efforts to measure and record quality of service. Certainly these should be areas in which special attention is paid by carriers to service and performance. The reason for this is that deviations in performance in these areas are much more likely to be detected. This detection ultimately may result in the traffic manager's switching to another carrier or mode. In contrast, it appears possible to have greater service and performance variability with respect to informally recorded or nonrecorded factors because such variability is less likely to be detected or remembered.

An additional interesting possibility is for the carrier to formally record some of these data (e.g., transit-time reliability, door-to-door transit time) with regard to a specific company's shipments and to present summaries to the traffic manager on a monthly or quarterly basis. This information itself might be used as a powerful competitive selling tool by the carrier.

In conclusion, both shippers and carriers have an important stake in quality-of-service measurement. For shippers, measurement and recording permits greater sophistication in modal and carrier selection. For carriers, measurement feedback can represent an important diagnostic technique for planning and implementing future service offerings. For both, measurement and recording can be a useful tool for the dynamic management needed in today's highly competitive environment.

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Publication of this paper sponsored by Committee on Railroad Operations Management.

TRACS: On-Line Track Assignment Computer System

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Track Assignment Computer System (TRACS) is a yard computer system for dynamically assigning blocks to classification tracks with the dual objectives of maximizing use of classification tracks and minimizing trim-engine effort. To quantify the benefits of using the procedures and program logic, operational data were obtained for 6 days from Southern Pacific's Roseville Yard to simulate the use of TRACS in yard operations. The results from the simulation were compared with actual operations in the yard on those days. The results indicate that use of TRACS would have permitted classification of about 200 more cars per day because 200 fewer cars would have required rehumping. With fewer cars to be rehumped, the average car detention time would have been reduced by about 5 hr. Roseville Yard at the time data were collected was not at capacity and had substantial rehump traffic. The results at other yards could therefore be different. Nevertheless, the results of the TRACS simulation reported here demonstrate the value of the program.

Recent studies of railroad operations indicate that the rail classification yard is the primary culprit in adversely affecting freight car utilization and service reliability (1). These studies also show that substantial improvements can be attained through better operations and planning. A logical inference is that the control and planning of yard operations would be improved and high potential payoff realized through the application of modern computer technology and management techniques. This paper describes a state-of-the-art on-line computer program called Track Assignment Computer System (TRACS) that assists the yardmaster in assigning blocks to classification tracks (i.e., in dynamically swinging the bowl tracks).

Traditionally, computer technology has been applied to yard operations in the areas of process control, car inventory systems, and management reports. TRACS represents a substantial advance in the use of computers to control yard operations. It is one example of a new type of railroad computer system that has on-line decision-making capability to assist yardmasters in the real-time decisions required to operate the railroad. Specifically, TRACS makes real-time track assignment decisions that the yardmaster can approve, modify, or override. [An example of another on-line decision system may be found in a paper by Wong and others (2).]

The development of TRACS began in 1978 under the auspices of the Association of American Railroads (AAR) Freight Car Utilization Program (FCUP), in which Southern Pacific (SP) was the host railroad (3). The TRACS program was evaluated at SP's Roseville Yard in June 1981 (4). In this paper, we describe the program and the Roseville Yard evaluation.

DYNAMIC VERSUS STATIC TRACK ASSIGNMENTS

The purpose of a dynamic track assignment procedure is to assist the yardmaster in assigning cars to classification tracks on the basis of the current projected traffic demand and the current state of the bowl. The goals are to achieve maximum use of the classification tracks and to minimize trim-engine effort. To be specific, classifications should be reassigned daily to tracks that accommodate the projected number of cars for that day, and classifications for the same departing train should be grouped closely in the bowl to minimize trim-engine travel, trim-engine conflicts, and crossover moves. The overall effect of meeting these goals is an improvement in the movement of cars through the terminal.

Dynamic track assignment contrasts with the usual industry classification procedure in which the same blocks are assigned to the same tracks every day. The selection of the static track assignment is based on the average number of cars expected in the block. This is the normal procedure because it is the easiest to comprehend and administer by yardmasters and not because it is the most effective. The principal objections to static assignments are as follows:

1. The number of blocks required almost exceeds the number of classification tracks, which requires the unplanned mixing of several blocks on a single track and hence slows down trim-engine operations;
2. Because few days are average, many assigned tracks are either overflowing or underutilized; and
3. A large block of cars that arrives unexpectedly may be inadvertently reassigned to a track, which causes excessive trim-engine activity to build the departing train.

PROCEDURE AND PROGRAM LOGIC

Basic Definitions and Procedures

As a basis for understanding the TRACS procedure and program logic, the following terms are defined:

1. Primary area is the area in the bowl of first choice for track assignment to a block,
2. Secondary area is the area in the bowl of second choice for track assignment to a block,
3. Assigned block is the block that is already assigned to a track,
4. Starter block is the block that needs a track assignment or overflow cars for an assigned track,
5. Companion blocks are blocks that should be near each other to minimize trim work,
6. Locked track is the track unavailable for assignment,
7. Clear track is the track that has no cars and is unassigned to a block,
8. Idle track is the track that is already assigned to another block but has sufficient room in time and in space to accommodate a second block without mixing the two blocks, and
9. Rehump track is the track for cars to be rehumped later.

To minimize trim-end work, each block is assigned a primary area and a secondary area. For example, blocks to depart from the east departure yard are assigned to a primary and a secondary area on the east side of the classification yard; this eliminates the inefficiencies of a crossover move from one side of the classification yard to the other side of the departure yard. Furthermore, the blocks that are to make the same train should be assigned to the same area; this eliminates conflict between trim engines building different trains. Also, blocks that are in sequence on the same train are designated companion blocks and should be placed on adjacent tracks if possible to minimize the pull time of both blocks.

To maximize track utilization, the number of cars in a starter block is used to determine its track assignment--clear track, idle track, or rehump track. In particular, a block that does not have

Figure 1. Simplified planning worksheet.

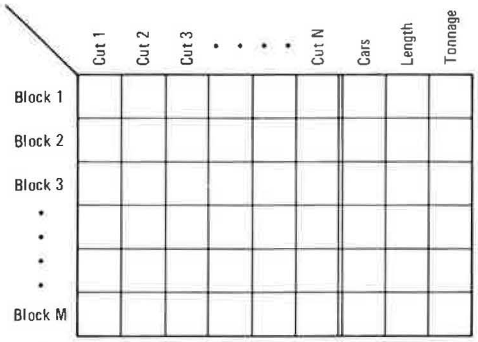
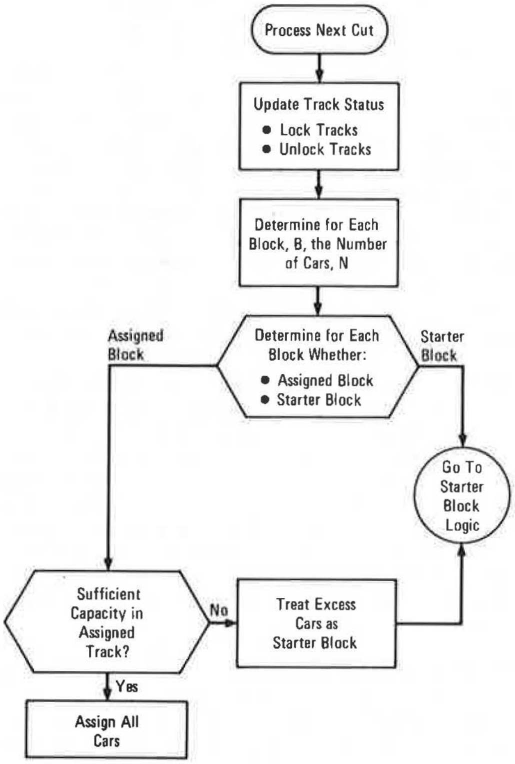


Figure 2. Overall assignment logic.

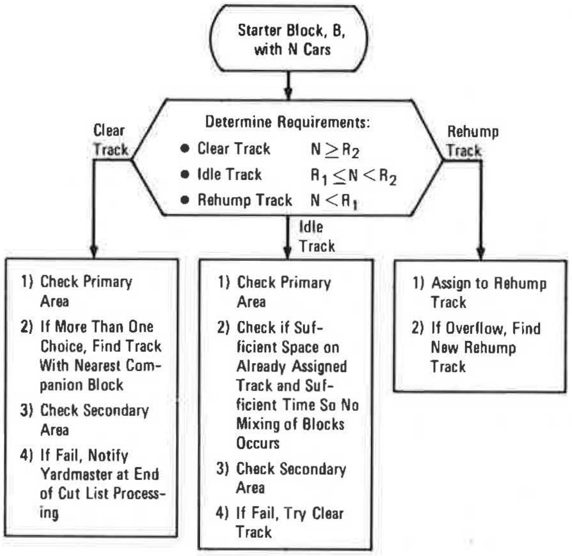


enough cars to be assigned to a clear track but has too many cars to be assigned to a rehump track is assigned to an idle track. In this manner, tracks are assigned to fit the needs of the blocks without wasting track space.

Worksheet Planning Process

Periodically (e.g., at the beginning of each shift and as appropriate thereafter), the yardmaster specifies the sequence of cuts to be humped and TRACS produces a planning worksheet. The worksheet (Figure 1) is essentially a matrix; the blocks to be made in the yard are listed down the side and the sequence of cuts to be humped is listed across the top. The columns of the matrix display for each cut the number of cars for each block. These numbers reflect either cars already in the receiving yard or advance consist information. The rows display for each block the projected future accumulation of cars by cut sequence. The last three columns of the worksheet indicate projected total cars, total length, and total tonnage of incoming cars for each block.

Figure 3. Starter-block logic.



The yardmaster examines the worksheet and determines for each block how many cars to be humped will be grouped together to make the same outbound train; this is called the split determination. The yardmaster specifies to the TRACS program the position of the split in the block count, that is, the hump cut and the car within the cut at which the split is to occur. The group of cars in a block up to the split are treated as a unit for purposes of track assignment. The worksheet process is repeated whenever changes occur in the hump sequence, yard conditions or operations, or incoming traffic conditions.

Track Assignment Logic

Figure 2 shows the overall TRACS assignment logic. When each cut is to be humped, the yardmaster indicates to the TRACS program any changes in track status (i.e., locked tracks or clear tracks). By using the split determination from the worksheet planning process, TRACS determines the appropriate number of cars (N) in each block. Next, each block in the cut is processed in order of size. If the block is an assigned block, the cars are designated to the assigned track.

The starter-block logic is shown in Figure 3. Each block is assigned two threshold numbers, R_1 and R_2, which determine whether the block is to be assigned to a clear track (i.e., $N \geq R_2$), to an idle track (i.e., $R_1 \leq N < R_2$), or to a rehump track (i.e., $N < R_1$). If a block is to be assigned to a clear track, the primary area for the block is searched for a clear track. If more than one choice is found in the primary area, the track with the nearest companion block is found. If no clear track is found in the primary area, the secondary area is searched. If no clear track is found in either the primary or secondary area, the yardmaster is notified so that a decision can be made.

If a block is to be assigned to an idle track (see Figure 3), the primary area is searched first for an idle track and then the secondary area is searched. If searching both areas fails to produce an idle track, a clear track is sought for the block.

If a block is to be assigned to a rehump track, the TRACS program assigns the block to one. If the rehump track is at capacity, the program determines a new track for the excess rehump cars.

ROSEVILLE YARD EVALUATION

Background

The purpose of the Roseville Yard evaluation was to quantify the benefits of using the TRACS program on the basis of operational data from an actual yard. The plan was to gather data for several days at Roseville Yard and then to replay those days off line by using the TRACS program to operate the yard. In this way, the effectiveness of the program could be compared with actual operations.

Roseville Yard is just outside of Sacramento, California, and is the main SP gateway in and out of northern California. The yard has approximately 20 receiving tracks in line to the hump, 49 classification tracks, an in-line west departure yard with 10 tracks, and an in-line east departure yard with 10 tracks. Generally, the yard is segmented into east and west traffic; there is a corresponding division of the receiving, classification, and departure yards. More than 2,000 cars/day can be classified.

Data Collection and Simulation

Data collection began at 12:01 a.m. on June 1, 1981, and continued around the clock until 12:00 midnight on June 6, a period of 6 days.

During the data-collection period, traffic volume was approximately 30-40 percent below yard capacity. The specific operating characteristics of the yard during this period were the following:

1. 1,100 to 1,400 cars classified per day;
2. 16 to 18 inbound trains per day (including run-through trains, which set out blocks);
3. 20 to 21 outbound trains per day (including run-through trains that were filled); and
4. 58 classifications per day.

A chronological log of all hump-engine and hump activity was kept, as was a log of extraneous events (such as malfunctioning switches blocking a bowl track). Copies of the following documents were collected: hump lists (with the yardmaster's notations), pull instructions (with departing train and set time indicated), classification track summary (after every humped cut), inbound line-up reports, receiving-yard reports, and hot sheets (identifying priority cars or traffic).

The data collected from Roseville Yard were used to simulate the use of the TRACS program in yard operations. The actual simulation took 16 working days.

Quantitative Results

A tabulation of the number of empty classification tracks as a function of the time of day for June 3 and 4, 1981, indicated that the TRACS program used slightly more tracks than were actually used on those days.

At first, this result was surprising because we had expected the TRACS program to use fewer tracks and thus create more empty tracks. Closer examination revealed, however, that the TRACS program and procedures performed as designed. Recall that the TRACS program logic attempts to assign a clear (or idle) track or rehump track to a block depending on the projected volume of cars in that block. By using the planning worksheet and examining advance consists and the status of the bowl, we determined that many clear tracks were available for assignment (because the yard was under capacity). Thus, a number of idle and rehump assignments were overridden and assigned to clear tracks. (For a yard at capacity, we would expect more idle-track assignments to create clear tracks for additional assignments.)

Table 1. Cars classified and humped.

	No. of Cars			
	June 3		June 4	
Category	Real	Simulated	Real	Simulated
Classified	1,397	1,582	1,108	1,319
Rehumped	371	208	478	223
Total	1,768	1,790	1,586	1,542

In the actual operations, the yardmasters appeared not to take advantage of the available clear tracks for assignment of small blocks. Thus, they assigned more cars to the rehump (or sluff) tracks for later reswitching. We do not know why the yardmasters did not use the available clear tracks. One reason may be that the clear tracks are traditionally assigned to blocks that on June 3 and 4 had either no traffic or so little traffic that the cars were sent to the sluff track. By using the TRACS program and the associated planning worksheet, the yardmaster can anticipate the need in 8 to 12 hr to reserve or use a clear track for traffic already in the yard and for traffic that will arrive in the yard.

Table 1 shows that on both June 3 and 4, approximately 200 fewer cars were rehumped (reswitched) under the simulation with TRACS than in actual operations. At Roseville Yard, a hump engine must travel down the hump to bring cars back over the hump for rehumping. During this operation, the hump and hump engine are occupied. Thus, use of the program would have permitted classification of approximately 200 more cars per day (Table 1) because the hump and hump engines would have had fewer rehump cars to process.

If fewer cars are rehumped by using the TRACS program, the associated yard-detention times should be shorter. This is because rehumped cars are not classified until after the second humping operation, which in certain cases was once a day. Thus, a rehumped car could spend an extra 24 hr in the yard. The data tabulated below indicate that the use of the TRACS program would have reduced the average car-detention time by approximately 5 hr:

	Car-Detention Time (hr)	
Data	June 3	June 4
Real	26.05	27.75
Simulated	21.59	22.48

Interpretation of Results

The traffic volume at Roseville Yard was considerably reduced during the simulation period. In this environment, the TRACS program attempted to maximize use of tracks by so assigning tracks that the number of cars rehumped was minimized. Minimizing rehumping resulted in the classification of approximately 200 more cars per day and a reduction in average yard-detention time of approximately 5 hr.

If we assume that the 5-hr reduction in yard detention can be translated to a reduction in system transit time, an average SP daily per-diem rate of $6.51 applied to 5 hr of savings for 1,400 cars per day processed by Roseville Yard could, in theory, translate to approximately $700,000 in savings per year in per-diem costs. These numbers are unrealistically optimistic, but if even a small fraction of these savings could be realized in practice, the worth of the TRACS program could more than justify its implementation in a yard.

The impact of TRACS on a yard at or near capacity may be different than that experienced at Roseville Yard, which was considerably under capacity and had substantial rehump traffic. Nevertheless, the results of the Roseville Yard simulation do justify the high expectations for the TRACS program.

CONCLUDING REMARKS

The worth of the concepts underlying the TRACS program has been demonstrated in the Roseville Yard evaluation. Under the sponsorship of the AAR, the program is being installed in SP's Terminal Control Computer (TCC) system. The first yard to use the program will be SP's West Colton Yard; once installed in the TCC, however, the program can readily be made available to other SP yards.

ACKNOWLEDGMENT

We acknowledge the project technical supervision of W.V. Williamson and his successor, W.H. Justus, and the significant technical and conceptual contributions of P.L. Phillips and J.G. Clendenen, both of SP. We also express appreciation to the AAR Freight Car Utilization Program task force members, who represent more than a dozen railroads and who were assigned to monitor the project, and especially to P.W. French of FCUP.

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Publication of this paper sponsored by Committee on Railroad Operations Management.

Labor Productivity in Rail Transport

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Labor productivity is among the central economic issues in the railroad industry. Labor negotiations and federal price-control programs are examples of activities that have involved productivity considerations. Currently, the Interstate Commerce Commission is considering productivity adjustments in the rail cost recovery procedures that were mandated by the Staggers Rail Act of 1980. Historically, productivity has been measured as labor content per ton-mile. Such measures, however, typically have produced productivity gains that appear to be unreasonably large. This may be caused by the changing nature of the ton-mile itself as the railroads increasingly embrace new operating practices such as unit trains, larger freight cars, and so on. An allocation of rail labor inputs among several output measures, including train miles, car miles, and carloads, is proposed. It is shown that rail productivity gains have been modest, at best, and that there has been considerable variation in productivity gains among the major carriers.

Productivity is a perennial issue in rail transport. It arises in commonplace regulatory proceedings involving rail prices, costs, and inflation impacts. Currently, productivity is the central issue in an Interstate Commerce Commission (ICC) consideration of the propriety of its rail cost recovery index.

Productivity is a deceptively simple concept that becomes complex either when econometricians attempt to formulate equations of measurement or when a simple productivity equation is quantified. The literature is highly theoretical, yet claims of measured change are often cited in the trade journals. The railroad industry is no exception; we are regularly treated to numbers of ties laid per man and coal cars unloaded and, simultaneously, to a literature overloaded with transformation equations and mathematical symbolism--all in disagreement.

In the economic literature, production functions relate outputs and inputs. In measuring productivity, one can hold inputs constant and measure the change in output or hold output constant and measure the change in inputs, but basically the production function is a cost function related to some measure of physical output. Theory attempts to differentiate change related to scale economies from changes due to organizational and technological improvement. Theory can offer many reasons for, and include them in, the theoretical formulation of the production function, but for the practitioner, there is an immediate need for simplicity.

There is another more practical school, which measures single-factor productivity. This is more or less an engineering approach, easier to use in practice. But it is not the measurement of productivity in the theoretical sense. Output per person hour, a single factor, is not the same as productivity of all factors, but it has many advantages. For example, if there is some fixity in other factor input, e.g., capital, or if labor is left constant and a capital change is made, the net effect can be measured. For instance, if a tamping machine replaces labor, there will undoubtedly be a rise in output per person hour, even though total factor productivity may not rise. Such a result would be a function of whether the total cost of the activity were reduced through the capital substitution. The introduction of the tamper can be looked at in two ways, and the way one looks at it influences distributive shares. A rise in output per person hour when all else is held constant can be used to justify a rise in wages, whereas if the wage is held constant, an increase in productivity would measure the marginal productivity of capital or scale economies. The difficulty in the real world is holding all things constant and varying only one factor at a time. Thus the theoretical concept of the production function would be extremely useful to the management of the firm if it could be quantified, but it has its limitation in practice.

The next most difficult concept is that of homogeneity. The production-function approach glosses over the output homogeneity problem. It is assumed that the railroad industry customarily has two products, freight and passenger service, measured as ton-miles and passenger miles. Real output may be very different, however, because passenger service has all but disappeared. But in studying freight alone, a production function may be thought to include highly distinctive technologies, such as unit-train service for coal as distinct from piggyback service.

Another complexity is nontransportation service. A simple example is the effort expended in running the Greenbrier, a railroad-owned hotel and medical facility. How is the labor of the chief executive officer of the Chessie System divided between rail and nonrail activities? More seriously, most railroads build and repair cars, and not only for their own account. An even greater perturbation in any time series would be maintenance of track, which has a high correlation with earnings. Maintenance can be viewed as either an expense or an investment and treating it as an expense may distort factor input.

If we revert to a simple question of the output unit, freight, and associate it with one variable, which is measurable, such as person hours, perhaps we have a relationship that has utility and can be understood. Perhaps analyzing all change as an attribute of one variable is as useful a method as possible as long as it is understood and other measures are used simultaneously to modify or limit conclusions and recommendations.

Thus, in this paper we start from the measurable and it is hoped that as we understand the data employed, we can expand our knowledge, introduce more variables, and simultaneously interpret so as not to ignore effects of other variables.

Our inputs are person hours only. There is disaggregation in that freight is separated from passenger service. We interpret change over time as it is reflected in this one measure.

For outputs, we reject the methodology most often used to analyze rail labor productivity, which relies on a single measure of output--the ton-mile. This measure generally computes a level of rail labor productivity growth that appears to be unrealistically high.

Though distinctions are often blurred, major categories of rail labor input can be associated with a particular output measure. This exercise was undertaken in this study. Analysis of the data in this framework for several railroads and for the sum of all Class 1 railroads shows that labor productivity growth in recent years has been modest at best and that growth has varied widely among the carriers. These conclusions have serious implications for the railroad industry, its customers, and national transportation policy.

IMPORTANCE OF PROPER PRODUCTIVITY MEASUREMENT

Proper productivity measurement is not a trivial matter. This is emphasized by the current debate over the ICC rail cost recovery index and by the experience of the Federal Price Commission in its control of rail price increases in the early 1970s.

Cost Recovery Index

The Staggers Rail Act of 1980 prohibited the use of general rate increases as a vehicle to compensate the rail industry for inflation-generated cost increases. The act directed the ICC to devise an appropriate cost-adjustment procedure to replace the function of the general rate increase.

General rate increases, which had been presented as periodic petitions to the ICC, had been predicated on revenue needs--a euphemism for cost increases generated, presumably, by inflation. Because the general rate increase was cost based, productivity was not an issue outside the railroad industry itself, because gains in productivity were automatically passed through to the shipping public.

In response to the Staggers Act, the ICC initially has adopted a cost recovery index procedure based on price indexes. Because this procedure involves price--not cost--indexes, productivity gains are not automatically passed through to the shipping public. The ICC is considering the petition for productivity adjustments in this calculation.

Price Commission Experience

In the early 1970s, the federal government undertook the control of rapidly growing inflation through wage and price controls. Of interest here is the Price Commission effort, in which permissible price increases by industry were derived as the net of labor cost increases and industry gains in labor productivity.

For its efforts, the Price Commission computed average productivity gains for all industries for the 1961-1971 decade. The railroad industry productivity standard was calculated to be 6.3 percent per year by using the ton-mile measure for rail output. This result was nearly three times the annual gain for the motor carrier industry and twice the national average for all industries.

These results for the railroad industry were not reasonable. Were the railroad industry to have made a sharp gain in productivity relative to its major competitor, the railroads could have reduced relative prices and enhanced their market share and profitability. In fact, it is clear that the railroad industry did not enjoy a competitive advantage relative to motor carriers.

Problems with use of the ton-mile as a measure of railroad output were not addressed by the Price Commission. These problems include the following:

1. Changes in rail traffic mix at the commodity and subcommodity level can distort output measured by ton-miles. The current version of a full-sized automobile--say, a Chrysler New Yorker--weighs considerably less than its predecessors of a few years past. The marginal productivity of rail labor would be affected by the downsizing of this model Chrysler by using the ton-mile measure. There is ample evidence that such examples are not isolated.
2. Just as commodity mix changes can be responsible for lack of homogeneity in the ton-mile measure, mileage itself can cause distortions. This is evident in freight rates that commonly taper with

increasingly long freight hauls. Furthermore, it is known that diversion of rail traffic to motor carrier has been far more dramatic in the shorter-haul sector of the market. These factors indicate a segmentation of the freight transportation market by length of haul.

SELECTED MEASURES FOR EVALUATION

Like professional baseball, the railroad industry is awash in the statistics it generates. For measures of freight output and labor input, the task is to seek suitable data or data that can be altered to suit the task.

Freight Output

The railroad industry produces several categories of reliable data for freight output measurement. The ton-mile was rejected because it was concluded that car miles, train miles, and carloads were more descriptive. This selection rests on the proposition that carloads, train miles, and car miles are the basic units of transportation output processed by the principal classes of railway workers.

Car miles are assigned to measure output for maintenance of way and equipment and for bridge and building workers and their supervisors.

The train mile is used to measure output for such diverse workers as train dispatchers, telegraphers, train and engine workers, and signal and electrical workers. These functions typically deal with freight output in trainload lots (or, alternatively, are assigned to areas based on trainload activity).

Finally, the carload is used to measure output for two groups of employees: (a) clerks and yard-operations workers and (b) executives, general office workers, and support personnel--railway police and the like.

It is appropriate here to point out a problem with the carload measure. Historic carload data are discontinuous for rail merger partners. That is, the sum of premerger carload counts involves double counting of loads interchanged between the merger partners. The double counting is not present in postmerger data. Merger-related efficiencies in the labor functions, which are associated with carloads here, by merger partners will eliminate some duplication in labor input associated with carload output, and this will ameliorate the impact of the discontinuity in carload counts.

Labor Input

As with freight output data, the railroads generate labor input data in quantity. Labor data are taken here from the ICC Wage Statistics Forms A and B: Annual Report of Employees, Service and Compensation. This report includes total person hours worked for 128 classes of employees.

These rail labor data are not ideal for our purpose here. Three significant difficulties were confronted and only one could be dealt with successfully. These were as follows:

1. The 128 categories of employees are not sufficient to distinguish all the myriad occupations of rail workers. Grouping occurs and this is a detrimental productivity measurement.
2. Railroad workers are involved in numerous activities only incidentally related to the transportation function. The building of freight cars and locomotives is one obvious example of this.
3. Both freight- and passenger-related labor are mingled in the data. By using data from the railroads' annual reports to the ICC (Form R-1), it was possible to estimate the passenger-related content of the major categories of labor input. This procedure reduced the U.S. total labor hours by 10.9 percent for 1969 and the effect declined steadily to 6.5 percent for 1981.

ANALYSIS AND RESULTS

Analyses of labor productivity were performed for 11 major railroads and all U.S. railroads for the 1969-1981 period. Because of various mergers, the 11 carriers currently are major partners in 7 rail systems. Data for all U.S. railroads less those for Consolidated Rail Corporation (Conrail) and Penn Central were analyzed also to respond to the legitimate concern that there might be bias in U.S. total data caused by the demise and subsequent reconstruction of the former Penn Central properties.

Productivity for each road was calculated for the four component measures: car miles per maintenance hour, train miles per transportation hour, carloads per clerk and yard-operations hour, and carloads per executive and general-office hour. A joint index for each road year was computed from the four component measures by using freight labor hours as weighing factors.

Analysis of these materials results in four important conclusions: (a) For an individual carrier, the four component productivity values used here can exhibit widely divergent trends; (b) when carriers are compared, productivity varies over a wide range; (c) overall labor productivity growth for the U.S. total has been less than 1 percent per year since 1969; and (d) removing the Conrail-Penn Central data does not materially change the growth trend of U.S. rail productivity.

If we look at the four component productivity measures for each carrier over time, it is seen that the growth patterns differ markedly. This is true even for the most efficient carriers. For example, the Southern Railway System has enjoyed sharp productivity growth in the transportation area but some decline in the clerk and yard-operations sector (Figure 1). Union Pacific, on the other hand, has a strong pattern of growth in the clerk and yard-operations area and modest growth in transportation (Figure 2). Clearly, this disparity in productivity trends is a product of management emphasis, geography, physical plant influences, and other factors. This illustrates the potential for error in rail productivity calculations based on sample data sets.

Output per person hour for each of the four component measures varies widely among the carriers. Figures 3-6 display the range of these data for the carriers studied. The figures show U.S. total data and illustrate the high and low ends of the range of productivity values with appropriate carrier data.

1. For maintenance functions (Figure 3), the U.S. total has a slight upward trend. Southern, among the most efficient carriers, has a slight downward trend from about 140 car miles/hr. Chessie, among the least productive, has a downward trend in the range of 60-80 car miles/hr. Chessie has been active in freight car construction and this clearly causes a downward bias in these data.
2. In the transportation area (Figure 4), U.S. total productivity shows little change at just more than 1 train mile/hr. Southern is a strong performer in both level and growth. Conrail, at the bottom of the range, has had little change in output per person hour through 1981.

Figure 1. Productivity components: Southern Railway.

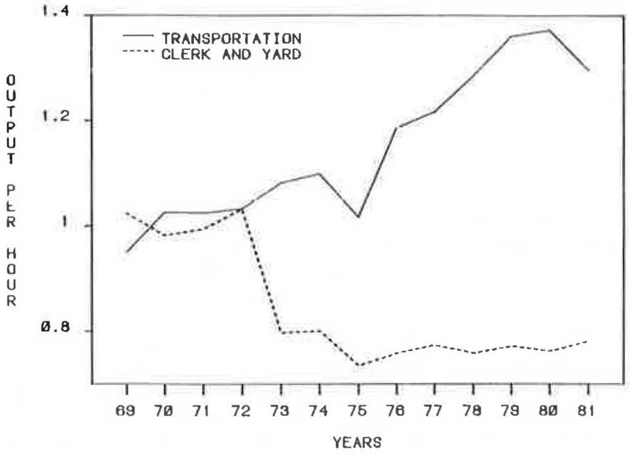


Figure 2. Productivity components: Union Pacific.

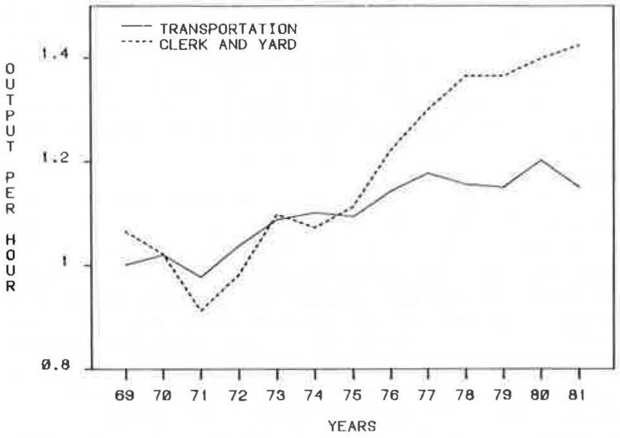


Figure 3. Range of car miles per maintenance hour: U.S. total, Southern Railway, Chessie System.

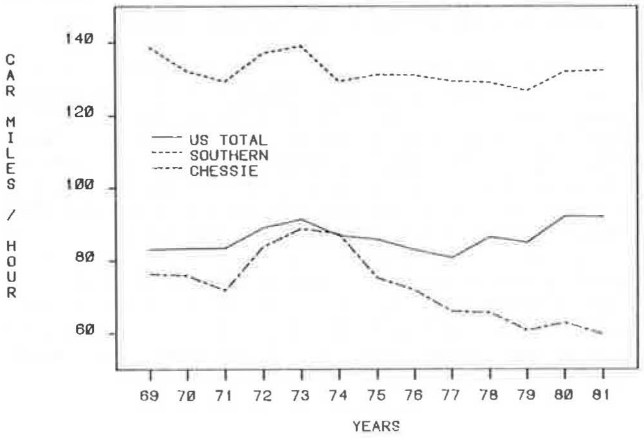


Figure 4. Range of train miles per transportation hour: U.S. total, Southern Railway, Chessie System.

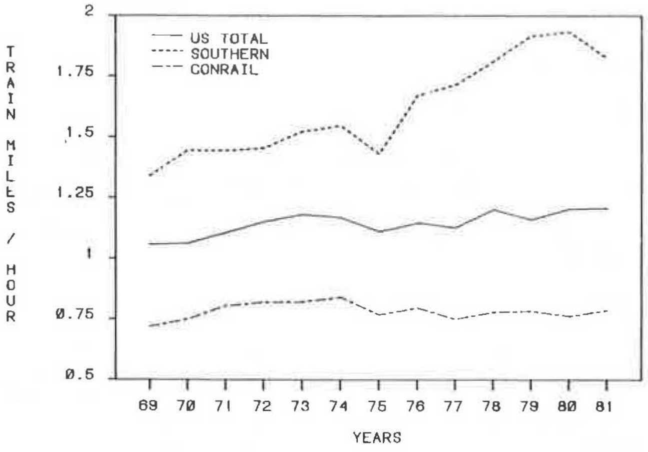


Figure 5. Range of cars per clerk and yard hour: U.S. total, Southern Railway, Union Pacific.

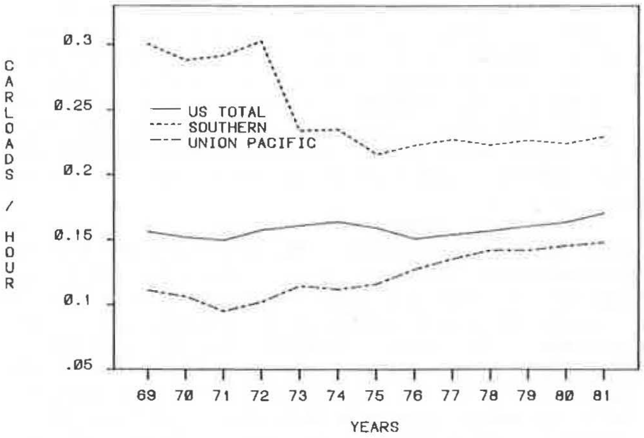


Figure 6. Range of cars per executive and office hour: U.S. total, Southern Railway, Burlington Northern.

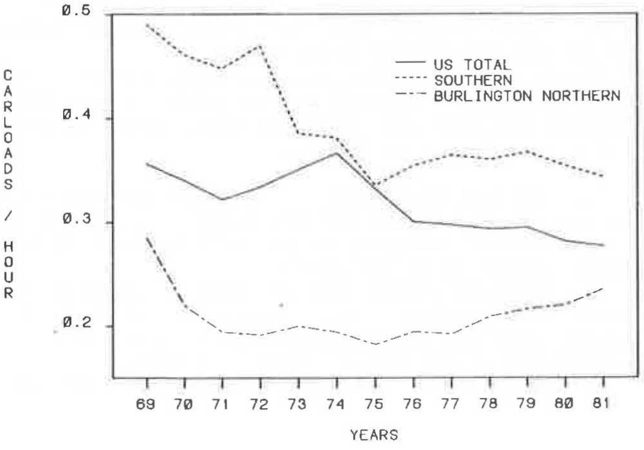
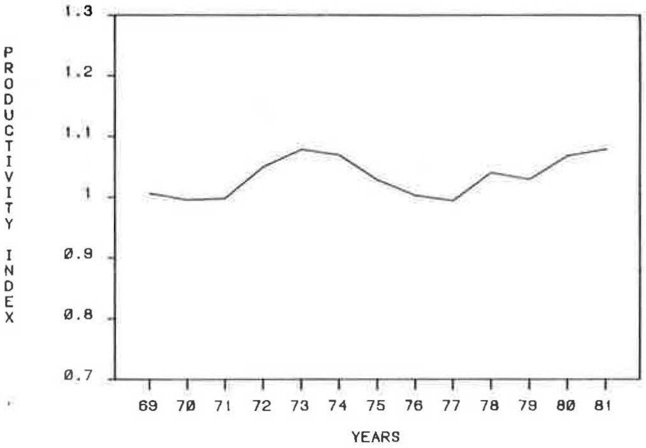


Figure 7. U.S. total rail industry productivity.



3. For clerk and yard operations (Figure 5), U.S. total productivity has a flat trend at just more than 0.15 carload/hr. Southern, again a strong performer, has suffered a steep decline and Union Pacific, a weak performer, has a solid pattern of productivity growth.

4. Executive and general-office output per person hour has declined over the study period (Figure 6). Southern, a strong performer in the early years, has declined sharply and Burlington Northern, at the bottom of the range, has had a solid growth trend since the early 1970s.

Overall labor productivity growth for the rail industry has been less than 0.5 percent/yr for the 1969-1981 period [Figure 7 (1969-1971 = 1.00)]. Rail productivity increased from 1969 to 1973, declined to 1977, and then increased to 1981. By productivity component, the U.S. total has performed as follows from 1969 to 1981 (note the decrease in carloads per executive and general-office hour):

Component	Avg Annual Gain (%)
Car miles per maintenance hour	0.4-0.5
Train miles per transportation hour	0.9-1.0
Carloads per clerk and yard-operations hour	0.5-0.6
Carloads per executive and general office hour	2.0-1.9
Overall productivity growth	0.3-0.4

These data imply that labor productivity in the 1969-1981 period has not made a material contribution to the competitive posture or to the prosperity of the railroad industry.

To add perspective to the overall rail labor productivity found here, it must be compared both with overall U.S. labor productivity as calculated by the Bureau of Labor Statistics (BLS) of the U.S. Department of Labor and with rail labor productivity calculated by the conventional ton-mile method (Figure 8). This comparison shows the following:

1. Growth in labor productivity for all industries has averaged 1.5-1.6 percent annually since 1969. This increase is roughly four times the average annual rail productivity growth computed in this study. Over the 12-yr period of this study, this disparity in average growth rates is cumulatively large.

Figure 8. National total and rail industry productivity.

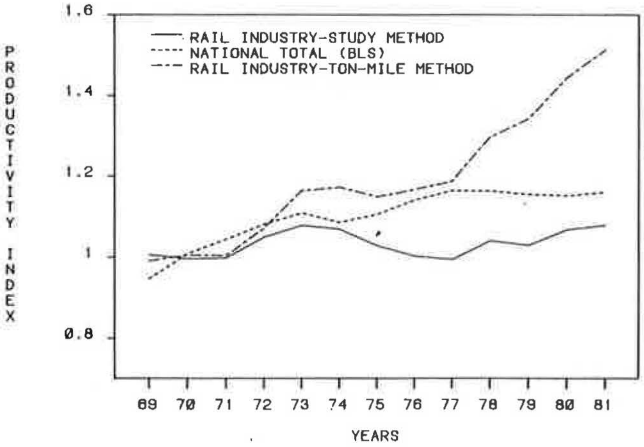
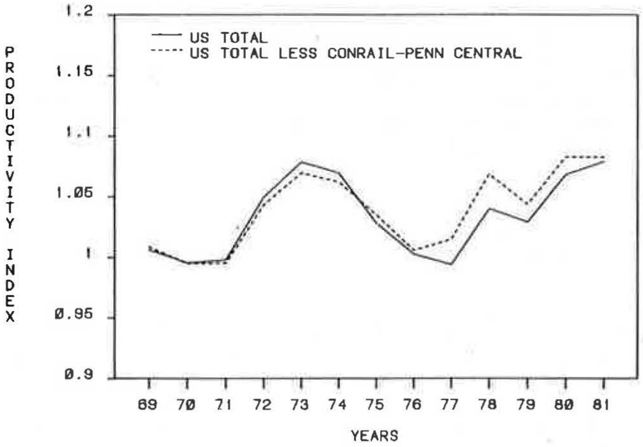


Figure 9. Comparison of U.S. productivity with and without Conrail data.



2. By the ton-mile method, rail productivity has grown 4.0-4.1 percent annually since 1969. This is 2.5 times the growth in productivity for all industries and more than 10 times the growth for the rail industry computed by the methodology of this study.

Because of the Penn Central disaster and the subsequent necessity to rebuild the properties that became the Conrail system, it might be charged that Conrail's presence in the data had a material effect on productivity growth for the rail industry. To respond to this question, Conrail data were removed from the national totals and analyses were repeated. It was found that the productivity growth trend for the United States without Conrail-Penn Central was about 0.2 percentage point/yr higher than that for the U.S. total (Figure 9). This difference is minute on an absolute basis, but since U.S. total productivity growth was small, it is large on a percentage basis. It cannot be charged, however, that Conrail has spoiled the productivity growth record for the railroad industry.

CONCLUSION

We believe that we have demonstrated a simple, understandable methodology for useful labor productivity measurements. These are useful in the sense that a manager can comprehend their message and can react to their implications. The methodology can be a beneficial planning aid, for example, for estimation of productivity gains from capital investment and for verification of results after the investment has been made. Finally, we present our methodology as a general framework for analyses. Our particular choices of output measures, our groupings of labor inputs, and our choice of relationship of certain outputs to certain inputs are unlikely to suit all circumstances or all users. The general framework allows the manager to tailor the features of the model with relatively little effort, however, and this is a major advantage.

ACKNOWLEDGMENT

We gratefully acknowledge the assistance in computer programming and data management provided by Allen A. Carlson.

Publication of this paper sponsored by Committee on Railroad Operations Management.

Minnesota's Railroad Information System

CATHY L. ERICKSON AND ROBERT C. JOHNS

The railroad network in Minnesota has undergone major changes in recent years. Knowing the status of the network and being able to predict future changes and directions depend on having a comprehensive and accessible source of rail information. The implementation of a computerized railroad information system in Minnesota in 1981 is helping to ease the information and decision-making needs of the state's transportation planners. A synopsis is given of the system's computer records, data files, and data elements and of uses of the information.

In the late 1970s, the Minnesota Department of Transportation (Mn/DOT) recognized the need to develop a source of comprehensive and readily accessible information about the state railroad network. Major changes were occurring in the rail system in the state, which made it increasingly important to know the status of the transportation network and to be able to predict future deficiencies. To meet these needs, Minnesota's rail data base was developed in 1981.

Having ready access to information about the state's rail system serves a number of important purposes, among them the annual updating of the state rail plan and providing information for systemwide assessment, eligible branch-line analysis, track inspection, and other surveys arising in rail transportation.

Before a rail data base existed, these needs were satisfied by a time-consuming process. A variety of publications and maps served as sources. Simply finding the right sources was often difficult. Once they were found, understanding the terminology and the format of the data could be difficult.

The data base, which is also called the railroad subsystem, is one of six operational subsystems of Mn/DOT's Transportation Information System (TIS). Roadways, accidents, traffic, bridges, and rail grade crossings are the other five subsystems. Together they are a computerized system of data files and programs for reporting and analyzing transportation data.

SYSTEM DESIGN

At the time that a work program for the development of a data base was being prepared, there were no software packages available for a rail data base. Whatever Mn/DOT would be able to use had to be developed. With no package available, the best development option was a data base that would be similar to the roadway subsystem of TIS, which had been developed for Mn/DOT by Montana State University.

The roadway subsystem is based on mileposts. Computer records describe road sections in terms of surface thickness, number of lanes, and so forth, and physically locate these sections by mileposts. Different points along these sections are also described and located, such as county boundaries or intersections. If further information is needed, subordinate tables or files tied to the physically located data item are supplied. For example, a city table tied to the city number stored in the physical data expands that number so that the city name, population, census year, and so forth, can be accessed.

The rail data base as developed by Montana State University and Mn/DOT follows the same general structure as the roadway subsystem. Railroads originated the milepost concept; their track charts show milepost locations on their lines. Sections of rail lines are described in computer records and located in reference to these mileposts. Points along the lines, such as stations or jurisdictional boundaries, are described and located as well. Another similarity is that subordinate tables or files are used for additional information, such as station details.

Each rail computer record must have a unique identification. This key field format is similar to the roadway key, which consists of a route system code, as for a U.S. or state highway; a route number; and a reference point. The key designed for rail lines consists of a railroad system code, a railroad line number assigned by Mn/DOT, and a reference point calculated in relation to the railroad milepost locations.

Because of the relatively small size of the rail data base (7,000 miles of railroads versus 128,000 miles of roads) and because many rail characteristics rarely change, once the initial data have been stored, management of the system is relatively simple.

DATA ELEMENTS

Data elements were developed after in-depth investigation of rail user needs. Mn/DOT units that would be the principal users of the data base were consulted about their needs and about potential data elements, codes, and other requirements. Primary among their needs was a data base of sufficient detail to be used for system analysis and eligible-line analysis. As development progressed, regular meetings were held with a representative rail user committee to keep the units informed of the status of the project and to resolve problems or questions as they surfaced. User input was especially important in the later stages in the design of reports.

The primary rail data are physical data, or data that describe the physical network of the Minnesota railroad system. All other data are tied to some physical data element. For example, the location of a station along a line is a physical data item. Tied to that data element are a number of secondary items that further describe the station, such as freight and passenger service, whether it is a trailer-on-flatcar (TOFC) facility, and so forth.

The types of secondary data are station data (tied to station locations), railroad data (tied to operating carriers), and jurisdictional data (tied to jurisdictional boundary locations).

Railroads are sources for many of the data items. This causes two problems. The first is that railroad publications, such as track charts and timetables, differ among railroads. Data items may be represented differently or may be lacking. The second problem is confidentiality, especially when traffic data are involved. Some railroads will release more data than others.

These problems are not insurmountable. With physical data, there is a fair amount of consistency among railroads. Occasionally, different conversions may be required to get a data element into the data-base form. Because one railroad may provide more information than another railroad, there must be an understanding that there may be more data stored for one railroad than perhaps for another.

DATA FILES

Four separate data files have been developed. They are the railway, station, rail-point, and true-mileage files. Each contains a particular kind of information.

The railway file contains all segment data for the subsystem. This includes physical data such as weight of rail and number of tracks; operational data such as densities, trackage rights, and speeds; and jurisdictional data such as city and county. Each railway segment is a length of a rail line in which all data are constant. A segment begins at the location of a reference point and terminates at the reference point that initiates the next segment record. A new record is entered into the file whenever one of the data elements changes along the line.

The station file contains information describing railroad stations in Minnesota, such as the presence of an intermodal facility, interchanges with other railroads, a yard, siding, and so forth. One record exists in the file for each station. The station record itself does not contain location information. Rather, the station is located by a point record in the subsystem's rail-point file.

The rail-point file contains location information for point data in the subsystem. A rail-point record is actually a reference-point location indicating the existence of a station, a rail grade crossing, a bridge, or any other feature (in the verbal description field) along the rail line. These fields (station, grade crossing, and so on) are cross-referenced to the railroad station file and two TIS subsystems, bridges and rail grade crossings.

The true-mileage file defines segment lengths and distances between points in the railroad subsystem. It contains one record for each reference post of every rail line and provides the distance from the beginning of the line to the reference post, i.e., the post location. It is post location that determines the exact physical location of any reference point in the railway or rail-point file. Thus, distances can only be defined from true-mileage data.

Following is a list of data elements in the data base, grouped by file:

1. Railway file

    Railroad system
    Railroad line number
    Reference point
    Ownership of segment
    Abandonment status
    Total density (3 most current years)
    Directional density toward increasing mileposts (3 most current years)
    Directional density toward decreasing mileposts (3 most current years)
    Division
    Subdivision
    FRA line indentification code
    Trackage rights
    FRA track class
    Maximum weight on rail
    Maximum allowable height and corresponding maximum width
    Maximum allowable width and corresponding maximum height
    Number of tracks
    Signal type on track 1, on track 2
    Maximum freight speed toward increasing mileposts on track 1, on track 2
    Maximum freight speed toward decreasing mileposts on track 1, on track 2
    Weight of rail on track 1, on track 2
    State legislative district
    Federal congressional district
    City number
    Population (generated from CITY program)
    Rural or urban code (generated from CITY)
    Population group (generated from CITY)
    Census year of population (generated from CITY)
    County number
    Construction district (generated from COUNTY)
    Regional development commission (generated from COUNTY)
    Functional class
    Verbal description
    Date record added to file or revised

2. Station file

    Railroad system
    Freight station accounting code
    Standard point location code
    Station name
    Freight or passenger service at station
    Intermodal transfer
        TOFC facility at station
        Side-loading device
        Crane only
        Crane and ramp
        Containers handled
        Limited to cars not more than 60 ft long
    Interchanges with other railroads
    Yard at station
    Agent or operator at station
    Length of siding at station
    Date record added to file or revised

3. Rail-point file

    Railroad system
    Railroad line number
    Reference point
    Freight station accounting code
    Railroad grade crossing number
    Bridge number
    Verbal description
    Date record added to file or revised

4. True-mileage file

   Railroad system
   Railroad line number
   Reference post
   True mileage, i.e., location of reference post on line
   Estimated or actual true-mileage code
   Date of true-mileage source
   Date record added to file or revised

DATA-BASE USE

The railroad subsystem allows users to quickly identify lines and their characteristics. The main outputs of the rail data base are inquiries, and the software is specially designed for this type of output. It provides a powerful user-oriented language that allows those unfamiliar with data processing to access information.

The whole of TIS can be accessed by using dialed data communications service that connects the user to the data base by means of the telephone and a terminal. This allows users at off-site locations to submit computer runs and obtain results at places near their own offices. A command structure is provided that allows many users to submit runs without help from computer specialists. For example, the user who wants a listing of all data elements in the railway file for Soo Line Railroad line number 9 would type in the following command:

```
:LIST-RAILWAY-FILE
+ROUTES
RAIL-SYS=SOO, RAIL-LINE=09
```

Specific capabilities of the subsystem are generation of data listings and data summaries, generation of special reports, and data maintenance.

Data listings can be requested from any of the four subsystem files. The user specifies through selection criteria which records are to be included in the listing. For each record selected, all of the data elements stored in the file are shown.

Data summaries are available from the railway and station files. The user can summarize on one, two, or three data elements from the file chosen. Data criteria are applied by the user to select records for inclusion in the summary.

In addition, special reports that combine list and summary capabilities are available from the subsystem.

Data maintenance entails updating the contents of the four data files. Various maintenance commands are used to add, delete, or rewrite records in the files.

The information in the subsystem is used for systemwide assessment, eligible branch-line analysis, track inspection, consultant studies, and other surveys arising in rail transportation. In the area of systemwide assessment, rail planners need to ascertain the status of the entire rail system in order to assess program needs. Use of the data base allows them to determine the percentage of rail lines in the state that are light rail or fall in track classes 1 or 2. This kind of information informs them about the rehabilitation needs of the system and about possible abandonments.

In eligible branch-line analysis, rail lines are identified for possible rehabilitation on the basis of the physical condition of the line as indicated by the track class, on traffic density, and on weight of rail. By using these criteria in the railway file, Mn/DOT rail planners can quickly identify rail segments that are prospective rehabilitation projects.

The data base also provides a foundation for future applications in systems planning, automated mapping, financial and market analysis, and rail and highway accident analysis.

CONCLUSION

Improved retrieval of information was directly related to the development of the data base. With its implementation, updating the state rail plan is easier because of information on traffic densities, TOFC facilities, clearances, and so forth, stored in the computer. Day-to-day questions from Mn/DOT units, other governmental agencies, and also nongovernmental units are quickly answered, especially with the user-oriented TIS commands.

In addition, the ready availability of data improves analysis and decision making. With budgetary cutbacks affecting Mn/DOT, it is increasingly important to know the current status of the transportation network and what deficiencies might occur in the future. Railroads in particular are volatile. Major changes are expected to occur in the rail system serving Minnesota. The rail data base is helping to ease the information and decision-making needs of the state's rail planners.

Publication of this paper sponsored by Committee on State Role in Rail Transport.

Impact of Coal Train Movement on Street Traffic Flows: A Case Study

A. ESSAM RADWAN AND LEE ALEXANDER

The impact of increased train movements through the city of Wilmington, North Carolina, on street traffic flows is evaluated. A comprehensive analysis involved a computer simulation of the city traffic flows based on traffic counts and other street geometric parameters secured by the Wilmington planning department. Sixteen critical railroad and street intersections plus major feeder streets were investigated in detail against three scenarios of train operations. These scenarios took into account train speeds, train lengths, and operating frequencies to transport an estimated 9 million tons of coal annually. Hourly delay figures were derived from the computer simulation runs, and total daily hours of vehicle delays were estimated. It was found that if unit trains are placed on the Belt Line, 453 to 730 vehicle-hr of delay daily will be added to the existing traffic-flow conditions depending on train speeds, lengths, and frequencies tested in the operating scenario. An estimate of public costs due to increased driving times for motorists was made. The result of the traffic simulations indicated a substantial yearly cost in vehicle delays to the public and that the speed of the trains is critical to minimizing delays in the traffic network.

The recent behavior of the international coal market--its steady rise followed by a quick retreat--points to the problem of making predictions on future demands for export products. During the past 2 yr, six firms announced plans to develop coal-shipping facilities along the Cape Fear River in Wilmington, North Carolina; most have cancelled these plans or at best are much more uncertain about following through on the investment.

In the long run, there seems to be no disagreement that the demand for coal will grow far in excess of any other energy commodity. The potential coal market export for Wilmington between now and the turn of the century is probably far less than indicated by prompters of export facilities during the past several years. Determining that market involves a great deal of uncertainty. Two major factors that help to define the city's potential as a location for coal exports are the effectiveness of the transportation system and the availability of coal export sites.

Previous studies conducted by the State Coastal Management Program estimated coal storage and loading capacities at the State Port to have a range of 4 to 9 million tons. Site visits conducted during this research generally confirmed the upper limit of this range.

THE PROBLEM

If the State Port is to be considered for coal export, the Seaboard Coast Line would serve their facilities with 70-car unit trains; each car would have a hauling capacity of 100 tons. In order to serve an export facility of 9 million tons, an average of four trains per day would be required on a 365-day/yr schedule. The Wilmington Belt Line (Figure 1) is a semiclosed loop that crosses many city streets. The introduction of unit trains on the Wilmington Belt Line will substantially increase the amount of rail traffic through the city, which will cause vehicular traffic delays that are not now factors in street traffic flow. It is the main objective of this study to evaluate the impact on vehicle hours of delay of the increased unit-train movements through the city of Wilmington.

DELAY-ESTIMATION METHODOLOGY

The uniqueness of the semiclosed railroad loop of the Belt Line and the fact that some streets extend over a significant portion of the loop width require an analysis with a systemwide approach; this means that the street network of Wilmington is dealt with as one unit, in which a queue buildup on one artery is assumed to delay traffic on other connecting streets.

The immense data analysis of the traffic flow on the street network requires computer simulation methods. The NETSIM network simulation model, formerly called UTCS-1, was adapted and then used for the traffic-flow analysis of this research (1). This program is used widely in urban traffic evaluation studies because it has the capacity to make systemwide evaluations of city traffic flows. Given street designs and traffic counts, the model moves each individual vehicle through the street network based on its type (automobile, bus, or truck), average speed, average discharge headway, average acceptable gap, and so on.

The adaptation of the NETSIM model to Wilmington was accomplished by treating the unit train as a vehicle that always has a green light at all the city's street crossings. Thus, in the case of a 4,000-ft train traveling 10 mph, the train occupies the crossing for 272 sec, which has the same effect as a red light that lasts 4.5 min. Because it takes a unit train traveling 10 mph more than 0.5 hr to cover the Belt Line distance, it can be assumed that no more than one train per hour will be in operation on the Belt Line (also considering the track capacities at the State Port). An increase in train speed to 20 mph does not significantly affect this assumption. Once the train clears the intersection after the 4.5-min delay, the intersection vehicle traffic flow is treated as though it has a green signal for the remaining 55.5 min of the hour.

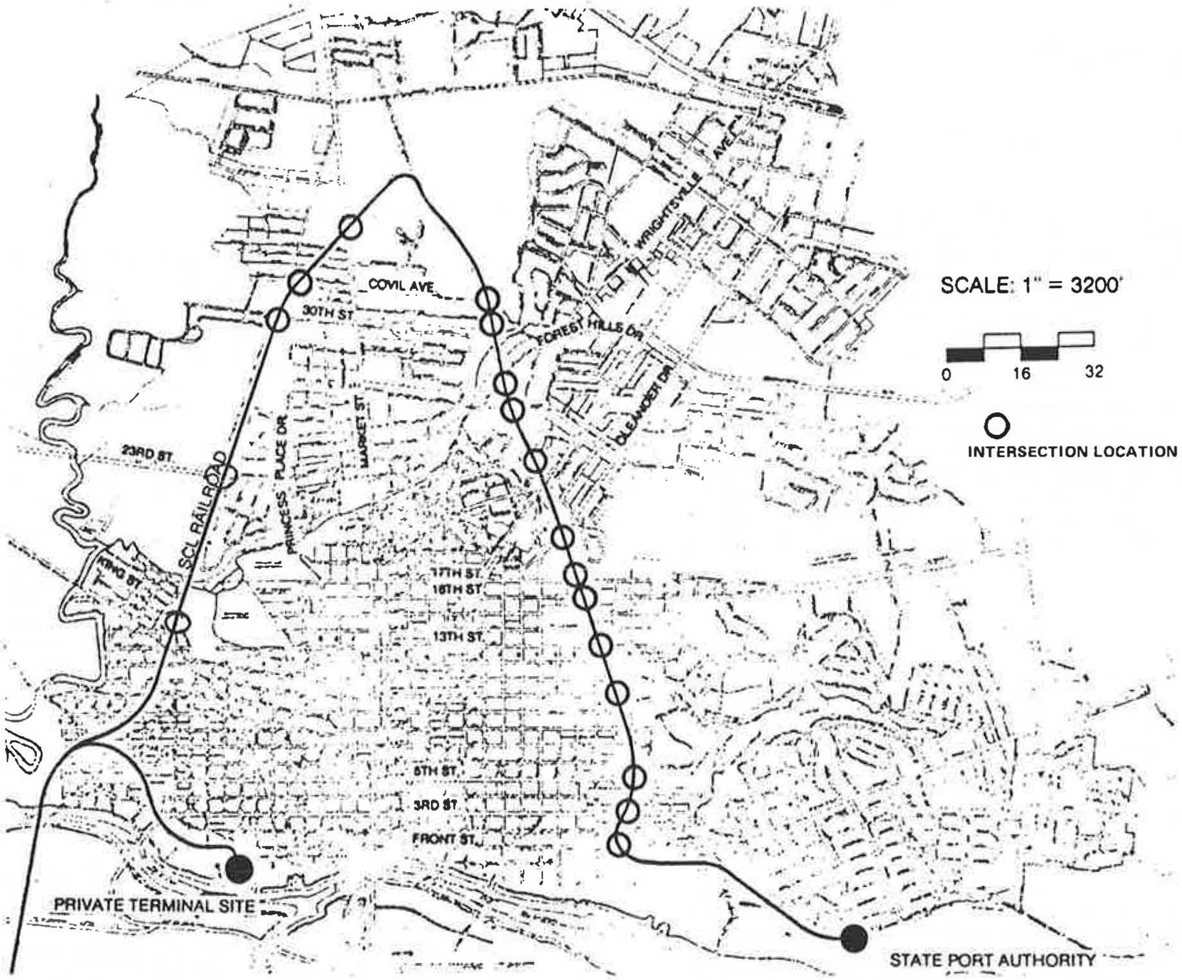
TRAIN CHARACTERISTICS

As mentioned earlier, operating procedures of the Seaboard Coast Line indicate that a 70-car unit train will be used to serve the coal export facility. The total train length, including four diesel engines and an allowance for slack, would be approximately 4,000 ft. Given the physical configuration of the Belt Line loop and assuming necessary track upgrading to accommodate the heavier unit train, it is estimated that speeds are limited to 10 to 20 mph. The use of 70-car trains would require an average of four trains per day to serve a 9-million-ton (annual) coal export facility at the State Port.

STREET TRAFFIC CHARACTERISTICS

The street traffic data used in the NETSIM model concentrate on major arterials in the city identified by the Wilmington Planning Department as the most critical to street traffic flows. These are shown in Figure 1.

Figure 1. Wilmington Belt Line layout.



For each railroad crossing and adjacent street intersections, data were collected by the planning department on approach lengths, number of street lanes, lane configurations, speed limits, signal timings, and turning percentages. Daily traffic counts were made by the planning department for each of the primary streets that cross the Belt Line and for feeder streets.

The traffic counts indicated that the peak hours constituted between 10 and 12 percent of the daily counts. Assuming that the a.m.-peak (7:30 to 8:30) flow and the p.m.-peak (4:30 to 5:30) flow are equal and that each amounts to 11 percent of the average daily traffic (ADT), the remaining 78 percent of the daily traffic will be equal to the sum of the off-peak flows. It was assumed that the vehicular traffic was concentrated between 6:00 a.m. and 10:00 a.m. and between 6:00 p.m. and 10:00 p.m. Therefore, the off-peak period amounts to a total of 14 hr. The average off-peak hour thus constitutes approximately 5.5 percent of the ADT (i.e., one-half of the peak-period flow). The peak hourly flow rates for the 16 major streets at the railroad crossings are shown in Table 1.

OPERATIONAL SCENARIOS

Three operational models were designed to evaluate the impact of unit trains on street traffic flows. The options listed below provide a reasonably comprehensive testing of traffic effects due to number of trains, length, and speed given the physical characteristics of the Belt Line. Each scenario assumes the continued operation of the current 2,000-ft mixed-freight train that travels daily on the Belt Line:

Scenario 1: Daily operation of four 4,000-ft

Table 1. Hourly flow rates during p.m.-peak hour at railroad crossings.

Intersection	Flow Rate (vehicles/hr) Inbound	Outbound
King Street	52	52
23rd Street	616	420
30th Street	250	282
Princess Place Drive	522	347
Market Street	757	1,347
Covil Avenue[a]	93	93
Forest Hills Drive	240	240
Colonial Drive	100	100
Wrightsville Avenue	974	541
Oleander Drive	660	1,340
17th Street[b]	1,002	–
16th Street[b]	–	931
13th Street[b]	220	220
5th Street[b]	130	130
3rd Street	484	616
Front Street	301	502

[a] Peak-hour counts were not available and a fixed percentage of ADT was assumed.

[b] One-way street.

unit trains traveling 10 mph for a total of 10 one-way trips. It is assumed that a single trip will occur during the morning and the evening rush hours.

Scenario 2: Daily operation of one 2,000-ft train (i.e., a split unit train) at a speed of 20 mph during the morning and the evening rush hours. The remaining trips per day will consist of two 2,000-ft trains and three 4,000-ft trains traveling at speeds of 10 mph. This operation will require a total of 12 one-way trips.

Scenario 3: Daily operation of four 4,000-ft trains traveling at speeds of 20 mph for a total of 10 one-way trips. It is assumed that a single trip occurs in the morning and in the evening rush hours.

DELAY RESULTS

The total vehicular delay, average delay per vehicle, and changes in total delay were provided from the NETSIM runs for 16 streets crossed by the railroad track. The results are shown in Tables 2, 3, and 4 for each scenario of train operations.

The analysis was extended to an evaluation of the effects of the operating scenarios on nine other critical intersections connected to the major streets that cross the railroad. The vehicular flow rates, total delay, and average delay per vehicle for those intersections are shown in Table 5. The intersection of Market Street and 30th Street and the intersection of 16th Street and Dawson Street were found to be two bottlenecks in the system under the existing conditions. The introduction of a unit train on the Belt Line would substantially worsen traffic flows at these intersections.

To evaluate what would happen to traffic delays if train speeds were increased, an incremental analysis was conducted between scenarios 1 and 3 as shown in Table 6. The results indicated that for most intersections, even a 10-mph increase in train speeds would result in significant decreases in traffic delays.

The results of the off-peak traffic simulation delays are shown in Tables 7 and 8. A comparison between the increase in total delay for the p.m.-peak (Tables 2, 3, and 4) and the off-peak hours (Table 7) shows that the peak delay will be much greater than would be expected solely on the basis of differences in traffic volumes during the two travel periods.

The delay impacts for scenario 1 and scenario 3 are the same for off-peak traffic flows because train lengths and speeds for these scenarios were varied only during the peak traffic hours. The incremental total delay results for off-peak traffic due to the strategy of increasing train speeds are shown in Table 8. It is important to point out that most of the observed percentages of decrease in total delay due to the strategy of increasing speed from 10 mph to 20 mph are higher for the off-peak hours than for the peak hours. This finding may be

Table 2. Changes in vehicular delays with scenario 1 during p.m.-peak hour at railroad crossings.

	Existing Conditions		Scenario 1[a]		
Intersection	Total Delay (vehicle-min)	Avg Delay per Vehicle (sec)	Total Delay (vehicle-min)	Avg Delay per Vehicle (sec)	Increase in Total Delay (vehicle-min)
King Street	1.80	1.00	17.37	9.65	15.57
23rd Street	401.90	19.36	893.80	43.07	491.90
30th Street	18.40	2.33	161.00	20.42	142.60
Princess Place Drive	72.00	4.86	223.80	15.12	151.80
Market Street	242.40	8.31	902.00	30.94	659.60
Covil Avenue	17.40	5.49	44.90	14.17	27.50
Forest Hills Drive	43.70	4.61	206.40	21.06	162.70
Colonial Drive	10.40	2.66	43.70	11.20	33.30
Wrightsville Avenue	84.60	3.55	450.20	18.91	365.60
Oleander Drive	213.30	6.40	859.20	25.78	645.90
17th Street	15.40	0.88	222.60	12.72	207.20
16th Street	42.00	3.82	192.10	17.51	150.10
13th Street	25.50	3.11	129.60	15.83	104.10
5th Street	10.40	2.73	72.30	18.22	61.90
3rd Street	8.30	0.45	166.80	9.21	158.50
Front Street	27.90	2.10	178.70	13.48	150.80

[a] A 4,000-ft train traveling 10 mph.

Table 3. Changes in vehicular delays with scenario 2 during p.m.-peak hour at railroad crossings.

	Existing Conditions		Scenario 2[a]		
Intersection	Total Delay (vehicle-min)	Avg Delay per Vehicle (sec)	Total Delay (vehicle-min)	Avg Delay per Vehicle (sec)	Increase in Total Delay (vehicle-min)
King Street	1.80	1.00	3.60	2.00	1.80
23rd Street	401.90	19.36	540.20	26.00	138.30
30th Street	18.40	2.33	78.70	10.13	60.30
Princess Place Drive	72.00	4.86	109.30	7.49	37.30
Market Street	242.40	8.31	431.90	14.63	189.50
Covil Avenue	17.40	5.49	21.20	6.50	3.80
Forest Hills Drive	43.70	4.61	83.10	8.82	39.40
Colonial Drive	10.40	2.66	16.00	4.19	5.60
Wrightsville Avenue	84.60	3.55	123.70	5.23	39.10
Oleander Drive	213.30	6.40	401.90	12.04	188.60
17th Street	15.40	0.88	32.20	1.84	16.80
16th Street	42.00	3.82	50.70	4.71	8.70
13th Street	25.50	3.11	33.00	4.03	7.50
5th Street	10.40	2.73	16.70	4.21	6.30
3rd Street	8.30	0.45	42.20	2.32	31.80
Front Street	27.90	2.10	60.10	4.52	32.20

[a] A 2,000-ft train traveling 20 mph only during the peak hour.

Table 4. Changes in vehicular delays with scenario 3 during p.m.-peak hour at railroad crossings.

	Existing Conditions		Scenario 3[a]		
Intersection	Total Delay (vehicle-min)	Avg Delay per Vehicle (sec)	Total Delay (vehicle-min)	Avg Delay per Vehicle (sec)	Increases in Total Delay (vehicle-min)
King Street	1.80	1.00	4.23	2.35	2.43
23rd Street	401.90	19.36	589.80	28.42	187.90
30th Street	18.40	2.33	91.60	11.61	73.20
Princess Place Drive	72.00	4.86	161.90	10.93	89.90
Market Street	242.40	8.31	587.70	20.16	345.30
Covil Avenue	17.40	5.49	29.20	9.22	11.80
Forest Hills Drive	43.70	4.61	118.60	12.52	74.90
Colonial Drive	10.40	2.66	17.50	4.48	7.10
Wrightsville Avenue	84.60	3.55	194.20	8.15	109.60
Oleander Drive	213.30	6.40	521.60	15.63	308.30
17th Street	15.40	0.88	76.80	4.38	61.40
16th Street	42.00	3.82	79.20	7.22	37.20
13th Street	25.50	3.11	58.40	7.13	32.90
5th Street	10.40	2.73	34.40	9.05	24.00
3rd Street	8.30	0.45	135.50	7.48	127.20
Front Street	27.90	2.10	129.10	9.74	101.20

[a] A 4,000-ft train traveling 20 mph.

Table 5. Vehicular delays for p.m.-peak hour at critical intersections on both sides of railroad crossings.

	Existing Conditions			Scenario 1			Scenario 2			Scenario 3		
Intersection	Flow Rate (vehicles/hr)	Total Delay (vehicle-min)	Avg Delay (sec)	Flow Rate (vehicles/hr)	Total Delay (vehicle-min)	Avg Delay (sec)	Flow Rate (vehicles/hr)	Total Delay (vehicle-min)	Avg Delay (sec)	Flow Rate (vehicles/hr)	Total Delay (vehicle-min)	Avg Delay (sec)
Princess Place and 23rd Street	1,952	3,094.70	95.12	1,920	4,544.30	142.00	1,977	3,297.80	100.00	1,951	4,782.40	147.07
Princess Place and 30th Street	1,300	516.10	23.28	1,290	522.70	24.31	1,319	524.00	23.83	1,322	542.70	24.63
Market Street and 30th Street	2,038	7,098.40	208.98	1,867	22,097.0	710.13	1,977	15,562.30	708.00	1,973	16,466.6	500.75
Forest Hills Drive and Colonial Drive	701	81.70	6.99	702	209.86	17.93	693	164.90	14.27	701	171.6	14.64
Wrightsville Avenue and Colonial Drive	1,606	173.30	6.47	1,603	299.60	11.21	1,604	257.30	9.62	1,605	289.10	10.80
Oleander Drive and Columbus Circle	2,025	258.10	7.65	2,020	629.40	18.64	2,093	468.70	13.80	2,050	593.70	17.40
Oleander Drive and Dawson Street	939	55.90	3.57	946	305.72	19.40	941	80.20	5.61	961	122.60	7.65
17th Street and Marsteller Street	1,047	87.00	4.98	1,056	398.10	22.61	1,047	346.30	19.04	1,046	326.20	18.71
16th Street and Dawson Street	1,536	4,514.40	176.34	1,509	12,472.10	495.90	1,510	12,283.40	488.08	1,568	11,466.40	438.76

Table 6. Incremental delay results for p.m.-peak hour at major railroad crossings due to increased train speed.

Intersection	Decrease in Total Delay due to Train Speed Increase[a] (vehicle-min)	Percentage of Decrease in Total Delay
King Street	13.14	75.65
23rd Street	304.00	34.00
30th Street	69.40	43.10
Princess Place Drive	61.90	27.65
Market Street	314.30	34.84
Covil Avenue	15.70	34.96
Forest Hills Drive	87.80	42.53
Colonial Drive	26.20	59.95
Wrightsville Avenue	256.00	56.86
Oleander Drive	337.60	39.29
17th Street	145.80	65.49
16th Street	112.90	58.77
13th Street	71.20	54.93
5th Street	37.90	52.42
3rd Street	31.30	18.76
Front Street	49.60	27.75

[a] Total vehicular delay of scenario 1 minus total vehicular delay of scenario 3.

attributed to the differences in size of queues during the peak and off-peak hours.

To evaluate the three operational scenarios, it was found necessary to estimate the total vehicle delays on a networkwide basis and to combine the peak-hour and off-peak-hour results to produce daily delay results. The total traffic network delay statistics for the peak and off-peak hours were generated by the NETSIM computer model. These are shown in Table 9. The results of these calculations are much higher than the sum of the individual intersection values shown in Tables 2, 3, 4, and 7 because the delay due to vehicle acceleration on the links leaving the intersections was not accounted for in those tables. To estimate the average daily delay in vehicle hours, it was assumed that train arrivals to the Belt Line follow a Poisson probability distribution. The calculations of the average daily delays for the three scenarios are shown below. The average total delay is calculated for the high level of forecast train traffic (five trains):

Table 7. Change in total vehicle delays with three scenarios for off-peak hours at railroad crossings.

Intersection[a]	Existing Conditions (vehicle-min)	Scenario 1 (vehicle-min)		Scenario 2 (vehicle-min)		Scenario 3 (vehicle-min)	
		Total Delay	Increase in Total Delay	Total Delay	Increase in Total Delay	Total Delay	Increase in Total Delay
23rd Street	153.40	334.50	181.10	334.50	181.10	210.40	57.00
30th Street	9.40	68.90	59.50	68.90	59.50	31.70	22.30
Princess Place Drive	33.00	116.70	83.70	116.70	83.70	56.30	23.30
Market Street	119.60	494.80	375.20	494.80	375.20	235.10	115.50
Covil Avenue	10.90	33.20	22.30	33.20	22.30	13.00	2.10
Forest Hills Drive	20.50	86.30	65.80	86.30	65.80	44.40	23.90
Colonial Drive	5.40	25.40	20.00	25.40	20.00	9.10	3.70
Wrightsville Avenue	34.90	175.20	140.30	175.20	140.30	86.60	33.70
Oleander Drive	90.60	378.70	268.10	378.70	268.10	194.50	103.90
17th Street	4.10	131.20	127.10	131.20	127.10	36.00	31.90
16th Street	32.30	134.70	102.40	134.70	102.40	58.80	26.50
13th Street	11.60	65.10	53.50	65.10	53.50	23.50	11.90
5th Street	5.60	21.10	15.50	21.10	12.00	6.40	6.40
3rd Street	3.60	103.90	100.30	103.90	100.30	57.20	56.30
Front Street	13.20	107.00	93.80	107.00	93.80	60.20	47.00

[a] There was a negligible off-peak impact for King Street.

5 trains/day = 10 one-way trips/day,
16 hr of vehicular traffic daily,
Average number of trains per hour = m = 10/16 = 0.625.

The Poisson probability distribution is

$P(X) = e^{-m}m^{X}/X!$

$P(X \geq 1) = 0.4647$ = probability that one or more trains will arrive in any given hour.

Scenario 1

Change in peak-hour delay = +30,595.1 vehicle-min,
Change in off-peak delay = +2,361.2 vehicle-min,
Average delay per day = (30,595.1) (2) (0.4647) + (2,361.2) (14) (0.4647) = 43,800 vehicle-min/day = 730.00 vehicle-hr/day.

Table 8. Incremental total delay results for off-peak hours at major railroad crossings due to increased train speed.

Intersection[a]	Decrease in Total Delay due to Train Speed Increase[b] (vehicle-min)	Percentage of Decrease in Total Delay
23rd Street	124.10	37.10
30th Street	37.20	53.99
Princess Place Drive	60.40	51.75
Market Street	259.70	52.48
Covil Avenue	20.20	60.84
Forest Hills Drive	41.90	48.55
Colonial Drive	16.30	64.17
Wrightsville Avenue	106.60	60.84
Oleander Drive	177.50	48.64
17th Street	95.20	75.56
16th Street	75.90	56.34
13th Street	41.60	63.90
5th Street	9.10	43.12
3rd Street	46.70	44.94
Front Street	46.80	45.60

[a] Negligible off-peak impact at King Street.
[b] Total vehicular delay of scenario 1 minus total vehicular delay of scenario 3.

Scenario 2

12 one-way trips/day, $P(X \geq 1) = 0.5276$,
Average delay per day = (18,365.7) (2) (0.5276) + (2,495.7) (14) (0.5276) = 37,816 vehicle-min/day = 630.26 vehicle-hr/day.

Scenario 3

Average delay per day = (21,068.4) (2) (0.4647) + (1,170.1) (14) (0.4647) = 27,192 vehicle-min/day = 453.20 vehicle-hr/day.

TRAVEL-DELAY COSTS

The loss in travel time due to vehicle delays will generate both direct and indirect public costs. Various measures to translate delays into tangible dollar amounts have been used in transportation studies; however, because people value their time differently, it is impossible to assign a value that precisely accounts for each person's delay costs.

A literature review was performed to determine an appropriate value of time (VOT) to convert travel-time delay to an economic cost. The assumed VOT was $6.00/passenger hour of delay. This value was obtained by adjusting the $2.70/passenger-hour value estimated by Stover, Adkins, and Goodknight (2) by using the appropriate consumer-price-index factor, and the adjusted value was found to be $4.38. A vehicle-occupancy factor of 1.37 was used to account for average passenger loads (as developed from city traffic surveys) (3). Annual delay costs were calculated for a period of 250 working days in any given year. The estimated annual costs amounted to $1,095,000, $945,390, and $679,800 for scenarios 1, 2, and 3, respectively.

The totals indicate that unit-train operations will result in substantial public driving-time costs on a yearly basis. Given these costs, if plans are developed that lead to coal export operations at the State Port, it is clearly in the city's interest that track speeds be increased to more than the estimated 10-mph minimum.

Table 9. Total network delay for p.m.-peak hour and single off-peak hour during train movements.

Time Period	Existing Conditions (vehicle-min)	Scenario 1 (vehicle-min)		Scenario 2 (vehicle-min)		Scenario 3 (vehicle-min)	
		Total	Change	Total	Change	Total	Change
P.M. peak	23,712.1	54,307.2	30,595.1	42,077.8	18,365.7	44,780.5	21,068.4
Off peak	2,854.1	5,215.3	2,361.2	5,349.8	2,495.7	4,024.2	1,170.1

SUMMARY AND FINDINGS

The introduction of unit trains on the Wilmington Belt Line will substantially increase the amount of rail traffic through the city, which will cause traffic delays that are not now factors in street traffic flow. Currently, there is only a single train per day that travels the entire Belt Line loop. Four additional trains, each roughly two to three times the length of the current single train, will be required to move coal tonnage for a 9-million-ton facility at the State Port.

Computer simulation was used to estimate hourly vehicular delay at the 16 major intersections between streets and the railroad in Wilmington during peak hours and off-peak hours. Nine intersections between streets were also evaluated for the same time periods. Average daily delays for three operational scenarios were calculated, and their corresponding annual costs were determined. The major findings of this case study are listed below:

1. The length of the Belt Line, its single-track construction, and the loop configuration and consequent speed restrictions allow under the worst conditions the possibility of no more than one train during the morning and one during the evening rush hour.
2. The intersections of Market Street and 30th Street and 16th Street and Dawson Street will be the areas most severely affected in terms of vehicle delays.
3. On a daily basis, during the Monday through Friday work week, unit-train operations can be expected to cause total traffic delays ranging from 453 to 730 vehicle-hr, depending on train speeds, lengths, and frequencies.
4. The public cost of the delays is assumed to involve, at a minimum, a value for the driver's time and an increased vehicle operating expense due to engine idling. For purposes of analysis, a $6.00/hr value is used for driving time, and it is recognized that individual values of time may vary substantially. Given this value, the annual increase in driving-time costs can be expected to range from $679,800 to $1,095,000. Public costs due to engine idling during delays can be expected to range from $84,839 to $136,656.
5. The higher ranges of potential public costs will result if unit trains are operated at 10-mph averages. An increase to 20-mph average speed for the trains on the Belt Line will reduce street traffic delays by approximately 40 percent.

POLICY RECOMMENDATIONS

If unit trains are placed in service, the city should encourage the Seaboard Coast Line to make improvements necessary to increase average operating speeds to 20 mph. Any increment over 10 mph should not be overlooked in its importance to reducing street traffic delays. The city also should work with the railroad toward avoiding train movements during street rush hours.

ACKNOWLEDGMENT

We wish to express appreciation to the Coastal Energy Impact Program (CEIP), which financed this study through a grant provided by the North Carolina Coastal Management Program. This CEIP grant was part of a grant from the National Oceanographic and Atmospheric Administration.

We also wish to express appreciation to Mark Ahrendsen and Arcelia Wicker of the Planning Department of the City of Wilmington for their assistance in obtaining the traffic and street design data for this research.

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Publication of this paper sponsored by Committee on State Role in Rail Transport.

Railroad Car Distribution Performance: Conceptual Framework and Underlying Mathematical Relationships

CARL D. MARTLAND AND MARK McCORD

Car distribution performance, which can be measured in terms of car days, car miles, or other measures, depends on many factors. The mathematical relationships underlying car distribution performance are presented, including equations for analyzing situations in which cars are in surplus or shortage situations. Improving performance requires a coordinated effort involving many organizations and railroad departments, not simply changes in the way that car distribution decisions are made. A framework for structuring this coordination is given.

The railroad freight car distribution process involves moving empty cars from an unloading point to the next loading point. Car distributors assign specific empty cars to specific customers and issue orders for the operating department to move the cars to their designated customers. Car distribution performance is normally measured in terms of resource consumption, productivity, and service levels, as outlined below:

1. Resource consumption
   a. Empty-car miles by type of equipment, region, or time period
   b. Empty-car days by type of equipment, region, or time period
   c. Cost of empty movements and storage
2. Productivity or efficiency of fleet of cars
   a. Ratio of empty-car miles to loaded or total car miles
   b. Empty-car miles per load originated
   c. Empty-car miles per empty-car day
   d. Empty-car days per load originated or per load handled (including loads handled by a railroad that originated on another railroad)
3. Service provided to group of customers by fleet of cars
   a. Unfilled cars orders (i.e., the number of requests for empty cars that could not be filled by customers)
   b. Number of cars rejected by customers as unsuitable for loading

Financial measures can be developed by attributing costs to these measures. A central thesis of this paper is that car distribution performance cannot be solely attributed to the decisions of car distributors. Indeed, car distribution performance is intimately related to other car management functions (especially fleet sizing) as well as to marketing and operating practices and to institutional relationships among railroads.

Car distribution is an extremely complex activity. Any measures of car distribution performance, therefore, must be regarded only as indicators of the general performance of a complex system. To improve car distribution performance, it is necessary to understand not just the performance measures but also the relationships among fleet size, the demand for freight cars, and the car distribution process. It is especially important to understand that the size of the fleet can be a dominant factor in car distribution performance.

The size of the desirable fleet can be determined for any traffic projection by assuming efficient utilization of the cars in the fleet. The desirable fleet balances the costs of overutilization and underutilization. When the fleet is overutilized, profitability suffers because some loads are not handled in the ideal car, and others cannot be handled at all. Adding cars to the fleet would reduce this problem and increase profitability. When the fleet is underutilized, either many cars are idle or improvements in use of the existing fleet would offer a cheaper means of expanding capacity than would the purchase of new cars.

In this paper, a framework is proposed that places the components of railroad car distribution in a unified environment. The need for such a framework became evident during an investigation and evaluation of a plethora of proposals for improving car distribution performance. [More than 60 alternatives for improving car distribution performance were identified and evaluated (1). A more complete discussion of car distribution, including case studies of practices on three railroads, may be found elsewhere (2).] The framework was also useful for assessing the increasing number of modeling efforts that attempt to optimize specific (and sometimes not explicitly defined) portions of car distribution performance. By describing the total environment, it is possible to describe proposed changes in common terms and to determine which levers the increasingly sophisticated analytical tools are pulling.

The unifying framework is provided by portraying the car distribution problem, in its most general sense, as a system control problem. Then, by presenting the underlying mathematical identities that shape the system, one can see, without further complicating assumptions, the most basic limits on the problem--limits that any action must acknowledge. The framework is intentionally general. No black-box model is developed that estimates, for a set of input parameters, a set of performance measures. Rather, it is shown how to link specific proposals for improving or modeling performance to the overall environment of freight car management.

CAR DISTRIBUTION AS A CONTROL PROBLEM

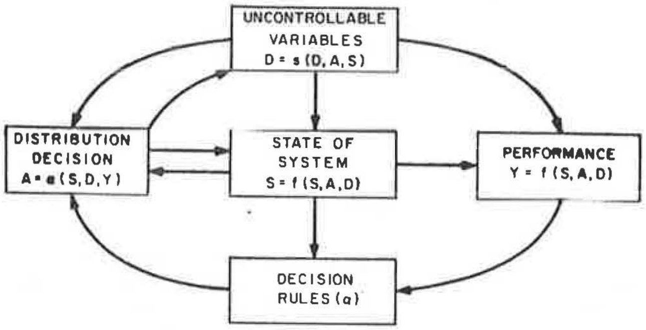
Car distribution as used here involves moving empty cars from one region and status to another region and status. The possible statuses of empty cars include moving to an assigned distribution point, awaiting distribution, awaiting repairs, and being stored. The control-problem (CP) model is shown in Figure 1 and can be stated as follows:

$$CP = [T, S, (A,D), Y, f(a,p), g]$$

where

T = number of days in period and t_k is kth day;
S_k = vector describing location and status of all cars at time k;
A_k = particular decision applied to system on day k (which cars should be assigned to what status at what location at time k + 1);

Figure 1. Car distribution as a control problem.



D_k = input to system at time k concerning demand for cars, institutional constraints, weather, bad orders, and other variables not under direct control of person making decision A_k;

Y_k = vector of performance measures for day k that could include empty-car miles, empty-car days, unfilled orders, and other measures;

f_k = function that determines state of system at k + 1 given state at k, distribution decision A_k, and uncontrollable input D_k;

a_k = rule or policy on day k that determines decision A_k as function of S_k and D_k (this may be formally or informally stated by railroad);

p = function that determines D as function of state of system S and decisions A (for example, how will demand for cars vary with state of system and decisions that allocate empties to shippers); and

g = function that relates performance to state of system S, decisions A, and uncontrollable input D.

The objective of the car distribution problem is to optimize performance Y over the time period T. This problem is complicated by the large numbers of freight cars and statuses of freight cars (i.e., the complexity of S); the numerous options available to decision makers; the uncertainty inherent in f, a, p, and g; and the intricacy of the market for freight transportation and the rules governing car distribution, both of which are included in D. We clarify this model by looking at its various components.

As the basis for any control system, one must be able to identify the state of the system at any time (S_k). In car distribution, the state of the system is given by the location of each car and its status. This is the same information that is kept by most railroads as part of their computer information system. To simplify matters, the state of the system need not consider every car individually but can refer to the number of cars in each status in each region.

The next major part of the control process is the statement of objectives that describe the desired state of the system. The goal of the car distribution function is to improve car distribution performance (Y), which can be a single performance measure or a vector of measures. Some possible measures include total empty-car miles, empty-car days, and various ratios relating empty-car miles and days to loads originated or terminated. Other measures relate to the availability of cars when desired by shippers and the quality of cars. Each of these performance measures can be obtained by analysis of computerized car movement records or, in principle, from network models.

Control variables are the means by which an organization seeks to change the state of the system to be more in line with the objectives. In car distribution, these control variables can be grouped into a number of categories:

1. Car distribution decisions by which empty cars are routed from unloading points to loading points,
2. Operating decisions by which cars actually move along these routes,
3. Marketing decisions by which a particular mix of traffic is solicited,
4. Fleet acquisition decisions by which railroads and other organizations expand and replace their car fleets, and
5. Investment decisions by which railroads and customers build, replace, or downgrade fixed facilities.

Note that these variables are controlled by different groups within the railroads and in some instances by other organizations. Only the first group of these variables is controllable by car distributors. Therefore, if one wishes to model the problem from their perspective, these decisions are included in A, and the rest must be modeled in the environment as uncontrollable variables. From the perspective of car management (as opposed to car distribution), however, all of the potential control variables must be considered.

The environment consists of factors that, for one reason or another, are not controllable. The cyclical patterns of business activity, the location of raw materials and markets, the maximum speed of rail freight trains, and the weather are certainly uncontrollable within the context of car distribution. The rules and regulations governing the movement of cars, the operating practices of railroads and their customers, and the physical facilities of the rail system are relatively uncontrollable except over a period of several years or longer.

It should be emphasized that this is but a conceptual model of the car distribution problem. It would be difficult to solve this problem with any degree of generality. There have been recent attempts to optimize parts of this car distribution problem, however.

Turnquist and Jordan (3) looked at a limited system over a short time period (T). They acknowledge uncertainty in the functions that generate future supplies and demands, part of D_k, but assume that the mean and variance of these inputs are known for each day. They also allow for uncertainty in the state transition function due to uncertain travel times between yards. A subset of the possible performance measures is selected and put into a single dimension by combining revenue from filling orders with costs attributed to holding unused cars, failing to fill orders, and repositioning empty cars. The uncertainty is factored out by considering the expected value of this financial performance distribution. The output is a set of distribution decisions (A_k) that maximizes the expected performance measure.

Turnquist and Jordan have made headway in showing the effect, measured by their specific definition of Y, of uncertainty in the state transition function (f) and some of the input (D). They did not test alternative decision rules of the type used by a railroad. To address this problem, Mendiratta (4) and Mendiratta and Turnquist (5) separated the system-level decisions concerning empty-car movements from the terminal-level decisions concerning empty-car inventories. They conclude that their model can be used as a policy evaluation tool by railroad central management and an operational tool for the daily distribution of empty cars by terminal personnel.

It should not be forgotten that these models, useful in highlighting the effects of certain parameters of the car distribution environment, assume that most of the parameters are held fixed. When car distribution performance is viewed from the broad perspective of Figure 1, it is evident that the above studies investigate only portions of the first of the five major approaches to improving car distribution performance:

1. Try to improve the car distribution function itself by establishing better policies (a) and monitoring car distribution decisions (A) to make sure they are consistent with these policies.
2. Improve the information systems so that decision makers have better data on the state (S) and performance (Y) of the system and can learn more about the transformation functions (f and g).
3. Modify the institutional framework, traffic patterns, and other factors represented by D and p. Although the environment may be outside the control of car distributors, other railroad officials and other organizations can make changes.
4. Change the composition or ownership of the fleet, which will influence S and therefore the decisions made and the resulting performance.
5. Improve the technology or operating policy of the rail system, which would change the transformation functions (f and g).

Controlling car distribution, therefore, is a complicated problem involving coordination among various groups within each railroad as well as among railroads, shippers, and other organizations. Underlying all of the above approaches and overriding any type of coordination, however, are basic relationships among fleet size, traffic volume, traffic mix, and physical utilization. The relationships, which are presented next, are important because they are based on identities concerning the car cycle that both determine and limit the possible performance effects of any change in the car distribution environment.

OVERVIEW OF CAR CYCLE

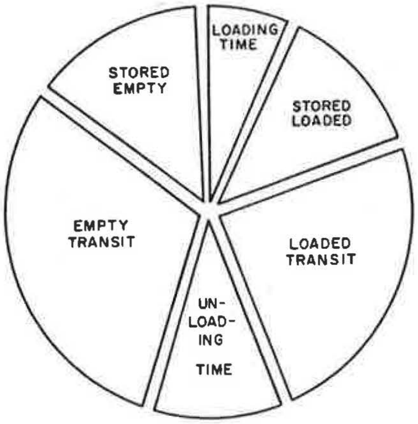
The car cycle is the total time between successive loadings of a particular car, i.e., a period of time that begins when the car is placed for loading and ends when it is next placed for loading. If we define a set of mutually exclusive statuses that cover all possible situations, the car cycle equals the sum of the time spent in each status between two successive loadings. [The first comprehensive, published analysis of freight car cycles was by Reebie Associates (6).]

One can divide this car cycle into components at different levels of detail, but it is instructive to begin at a fairly coarse level and to subdivide only those components that call for more detailed analysis. The first level (Figure 2) divides the car cycle time into six major components:

$$\begin{aligned}\text{Car cycle time} = {} & \text{loading time} + \text{loaded storage time} \\ & + \text{loaded transit time} + \text{unloading time} \\ & + \text{empty-transit time} + \text{empty-storage time}\end{aligned} \quad (1)$$

All of these components can be divided further in a manner that depends on what is to be analyzed. Because the average of a sum is equal to the sum of the averages, we can obtain the next component:

Figure 2. Basic components of car cycle.



$$\begin{aligned}\text{Average car cycle time} = {} & \text{average time in loading} \\ & + \text{average time in loaded storage} \\ & + \text{average time in loaded transit} \\ & + \text{average time in unloading} \\ & + \text{average time in empty transit} \\ & + \text{average time in empty storage}\end{aligned} \quad (2)$$

But for any period of time, the average car cycle time can also be calculated as follows:

$$\begin{aligned}\text{Average car cycle time} = {} & (\text{car days available in period})/ \\ & (\text{number of cycles in period})\end{aligned} \quad (3)$$

By equating Equations 2 and 3 and writing the average times in Equation 2 as the number of car days in each component divided by the number of cycles in the period (equal to the number of loads handled), we obtain

$$\begin{aligned}\text{Car days available} = {} & \text{car days in loading} + \text{car days in loaded storage} \\ & + \text{car days in loaded transit} + \text{car days in unloading} \\ & + \text{car days in empty storage} \\ & + \text{car days in empty transit}\end{aligned} \quad (4)$$

Equation 4 suggests an additional approach to studying car distribution. The car days available during any period are determined by the fleet size and the length of the time period:

$$\text{Car days available} = (\text{fleet size}) \times (\text{length of time}) \quad (5)$$

For this reason, the car days available is a useful accounting measure.

The basic unit of this accounting framework is the elapsed time spent by a single car in a particular status. Because a car is always in one and only one status, the summation of these basic units will be the total car days available for the fleet under consideration (Equation 5). We can aggregate these units in many ways, e.g., by car type, by status (as in Equation 4), by time period, or by cycle. However we choose to do this, the result is still determined by Equation 5. The interrelated measures for car days available, cars handled, and average cycle times will be shown to be useful in analyzing the car distribution problem.

STANDARDS FOR CYCLE-TIME COMPONENTS

If standard times for each component can be developed, they can be combined to find a standard time for the car cycle. Such a standard would be directly relevant for fleet management because, in combination with demand projections, it would provide an estimate of car days required in the future. In this section it is shown how standards can be derived from both theory and empirical evidence. The intent is not to show how to define particular standards but to emphasize that standards for each cycle component can be combined to obtain a standard for the entire cycle. In addition, the discussion assumes a basic familiarity with the use of standards in railroad management control systems.

In all of the following functional relations, only the main variables are identified. The parts of the cycle needed to carry a load are the loading, loaded transit, and unloading components. The loading and unloading portions depend basically on the number and types of loads and the loading and unloading procedures used. This can be expressed as follows:

$$\text{Average loading time} = f\,(\text{number of loads, type of loads, loading procedure}) \qquad (6)$$

For example, if the average loading time remains constant, the total time will be as follows:

$$\text{Loading time} = (\text{average loading time}) \times (\text{number of loads}) \qquad (7)$$

A similar equation can be developed for unloading time. [The Boston and Maine Corporation uses such a standard in its weekly operating and service plan performance report (7, p. D-19).] The average loaded transit time would depend on the network, the traffic mix, and the operating plan. Models that have been developed to determine standard transit times include, for example, the Massachusetts Institute of Technology (MIT) Service Planning Model (8). Basically, the total number of car days in loaded transit for a period of analysis could be considered a weighted average of the standard trip times thus calculated.

Even though the empty and storage components of the cycle are unnecessary to carry the load, some such time will normally be required. Once the car has been unloaded, it must either await loading (empty storage) at the same location or be moved (empty transit) to another point for reloading. Also, variations in demand or in fleet size will cause periodic surpluses of equipment, which leads to empty time. Finally, customers will not always be able (or desire) to unload a car precisely when it arrives, which leads to loaded storage.

Although empty time is not necessary to carry a load, it is nonetheless inevitable. How much empty time is reasonable is a difficult question because of the many alternatives for moving empty cars to reloading points and because of the variability in demand for freight cars.

By identifying the various causes of the empty time and estimating how much empty time each cause implies in the car cycle, the levers that must be adjusted to reduce the empty portion of the cycle can be identified. It is proposed here that the reasons for empty time can be classified into four broad categories. Despite some overlap among the categories, they are distinct enough to present an interesting classification.

One of the basic causes of empty time is that the fleet is at times simply too large for the traffic. Because freight cars last many years, the fleet cannot be quickly reduced if demand slackens. When total car days available is nearly constant, the average cycle time increases as the number of loads declines (see Equation 3). If the average time for the customer and loaded components remains constant, empty time must increase. This effect of fleet size is evident in times of slack activity and will be discussed in the section on surpluses below. In this case it is not the quantity of empty time but its distribution between transit and storage that is important. Because demand is low, more cars will spend more time empty, but they do not necessarily have to be moving (9).

In times of heavy business (see section on shortages below), the quantity of empty time is more important because it can be the cause of car shortages and lost business (10). Empty time persists despite the demand for cars because of spatial and temporal imbalances in loading and unloading patterns, institutional restrictions on the use of empty cars, and operating policies on an individual railroad.

Although the total number of cars loaded equals the total number of cars unloaded, the demand for loads is not uniform in time or in space. From a spatial perspective, one region may be a net originator of loads, whereas another is a net terminator of loads. In this case of spatial imbalances, empty cars will have to be sent from the terminating region to the originating region. From a temporal perspective, loads may originate only some time after the car to carry the load has been unloaded or arrived empty. In this case of temporal imbalance, empty cars will be stored in a yard. Various techniques have been proposed for routing empty cars to minimize the costs of spatial and temporal imbalance. Philip identified 16 car distribution planning models, 7 of which were actually implemented and used. Nevertheless, he concluded (2, p. 34): "Models to support car distribution decisionmaking have not found widespread application in the industry, despite the numerous attempts to describe how such models might be useful, and several attempts to do so."

Over and above the inevitable empty time caused by the spatial and temporal distribution of the demand is the empty time caused by institutional regulations (11). Regulations may prohibit or restrict the loading of cars in certain areas and encourage empty cross-haul, which can be defined as the simultaneous movement of empties in both directions between two regions.

Even in the absence of institutional regulations, there would be more empty time than absolutely necessary due to spatial and temporal imbalances because of the car distribution practices of individual railroads. [The Freight Car Utilization Program (FCUP), administered by the Association of American Railroads (AAR) and supported by FRA, has published numerous reports addressing the management of empty-car distribution. For an annotated bibliography, see AAR Report R-453 (12).] These practices may increase empty time for a variety of reasons. Insufficient information systems would force decisions to be made without valuable data. Poor management structure could preclude efficient operations. A lack of training of distribution personnel could be another reason. Another cause related to distribution practices is that of competing objectives. Empty time must be balanced with the costs of managing cars, repositioning cars, and failing to provide cars when desired by shippers.

In summary, the causes for empty time can be grouped into four broad categories:

1. Excessive fleet size,
2. Spatial and temporal imbalances in demand,
3. Institutional restrictions, and
4. Operating policies.

Given these causes for empty time, a standard for empty time can, at least in theory, be estimated:

$$\text{Empty transit standard} = f\,(\text{traffic volume, fleet size, spatial imbalance, temporal imbalances, institutional regulations, operating policy}) \quad (8)$$

In short, standards can be developed for each component of the car cycle. By summing the average standards for each component, one can define a standard for the average cycle time:

$$C^* = \text{standard cycle time} = \Sigma_{\text{comp}}\ (\text{standard time, component i}) \quad (9)$$

where comp stands for components of car cycle. The standard cycle time can be used in various ways. The next section shows how C* can be used to study fleet sizing issues with a number of equations developed for understanding car shortages and surpluses. C* also provides a link to the control theory and network models described above. Finally, C* provides a link among the analysis of car distribution decisions, operating plans, traffic flows, and fleet sizing, all of which affect empty time and empty mileage.

FLEET SIZING, SURPLUSES, AND SHORTAGES

The object of this section is to sketch the relations among the standard cycle time C*, the actual cycle C, investment decisions, the time period of analysis, and marketing practices. Investment decisions affect the fleet size. The time period of the analysis influences the measured imbalances in traffic flow by smoothing out or accentuating the random and cyclical variations in demand. Marketing practices and the general business environment affect the number of loads carried.

For simplicity, the following notation will be used:

F = fleet size, assumed to be constant over period of analysis;
T = number of days in period of analysis;
C = actual average car cycle time (i.e., the cycle time realized during the period of analysis);
C* = standard average car cycle time (i.e., the cycle time calculated from Equation 9);
L_o = number of loads carried during the period; and
L_d = number of loads demanded during the period, which may exceed L_o.

From the definition of car days available in a period, we have

$$\text{Car days available} = (F)(T) \quad (10)$$

Based on the standards, the number of days needed to fill all of the orders in the period would simply be the product of the standard average car cycle and the number of loads demanded in the period:

$$\text{Car days required} = (C^*)(L_d) \quad (11)$$

The differences between the car days available and the car days required will be defined to be the surplus car days for the period. The extent of such a surplus is determined by the relationships defined above:

$$\begin{aligned}\text{Surplus car days} &= (\text{car days available}) - (\text{car days required})\\ &= [(F)(T)] - [(C^*)(L_d)] \quad (12)\end{aligned}$$

If this difference is greater than zero, the period will be called one of surplus. If the difference is negative, a period of shortage ensues. These two cases will be investigated separately.

A surplus represents idle capacity. Some cars, which require investment and maintenance and therefore accrue costs, cannot be used to move shipments that generate revenue. As a result, the actual cycle time C rises above the standard cycle time C*:

$$\begin{aligned}C - C^* &= [(F)(T)]/[(L_d)] - C^*\\ &= \text{surplus car days}/L_d \quad (13)\end{aligned}$$

This increase is required by the definitions of C, C*, and the assumption of a fixed fleet, which is reasonable for periods of analysis much shorter than the average life of a freight car. During surplus conditions, therefore, the average cycle time will remain higher than the standard until the fleet (F) can be reduced to a more desirable size or until traffic (L_d) rises to the expected level. From the perspective of the entire fleet, the increase in the cycle time is, in short, inevitable when the fleet is too large for the traffic.

It is useful to consider where the extra time shows up in the car cycle. One or more of the six major components of the car cycle (Equation 1) must increase. If customer practices and traffic mix are not affected by the surplus, we would expect the standards for loading time, unloading time, loaded transit, and loaded storage time to remain the same. The extra time would therefore be absorbed either in the empty storage or the empty transit components of the cycle. If the fleet were controlled by a single organization, the need to store a portion of the fleet would be evident. The oldest or least-reliable cars would be obvious candidates for storage (13), but it might also be desirable to slow down the repair of cars or to undertake a rebuilding program.

The number of cars to store or to take out of service in other ways (F_s) can be determined from Equations 5 and 12:

$$(\text{Average number of cars stored})\,(T) = (F_s)\,(T) = (\text{surplus car days})$$

$$\begin{aligned}F_s &= [(F)(T)] - \{[(C^*)(L_d)]/(T)\}\\ &= F - (C^*L_d/T) \quad (14)\end{aligned}$$

$$F_s = F - F^* \quad (15)$$

where F* is the fleet size that would make the surplus equal zero. Because the number of cars stored could vary during the period because of variations in demand, Equations 14 and 15 deal with the average number of cars stored.

If cars are not stored during a surplus, other components of the cycle must increase. To reduce expenditures, the railroads might reduce the number of trains operated as well as the number of yard-crew assignments. This could increase the standards for both the loaded and empty transit portions of the cycle, which reflects the fact that the opportunity cost of the marginal car day has dropped substantially to zero. Railroads might also offer customers greater leeway in the use of cars for temporary storage. If the surplus continues even after these measures have been taken, surpluses of empty cars will become increasingly evident at numerous locations. To what extent these cars sit in yards and to what extent they shuttle back and forth among yards depends greatly on the industry rules and procedures governing the use of foreign cars (i.e., cars belonging to a railroad other than the one using them) and the management objectives and practices of the railroad where the car is unloaded. A single-fleet manager would reduce unnecessary empty movements to avoid the associated costs for fuel, crews, and maintenance. A number of interrelated railroads, however, might well attempt to shift the burden of the surplus to other carriers; such suboptimal behavior could easily increase the cost of car distribution despite the inevitability of the empty time that the railroads individually seek to avoid.

Shortages can also be investigated by using the basic equality of Equation 12. When there are fewer car days available than required to handle the loads demanded, a shortage of capacity exists, and all of the loads demanded cannot be carried in the period of analysis. The amount of shortage is shown by the following:

$$\text{Shortage of car days} = [(C^*)(L_d)] - [(F)(T)] \quad (16)$$

As with surpluses, the extent of the shortage is defined in terms of the standard rather than the average cycle. Equation 16 defines the relative impact that innovations affecting the variables can have on the extent of the shortage. Whereas the costs of surpluses are those of idle capacity, the costs of shortages are unfilled orders and delays to shippers.

When there is a shortage, railroads either change their operating practices to reduce components of cycle time below their standards or are unable to provide cars for loading by shippers. Because the car days available is assumed constant (FT) for the period, the number of loads originated (L_o) will drop below the number of loads demanded (L_d). For the period, our identities give us

$$F(T) = C(L_o) \quad (17)$$

and therefore

$$\text{Shortage of car days} = C^*(L_d) - C(L_o) \quad (18)$$

If the actual cycle equals the standard cycle, we can easily calculate the number of unfilled orders (U):

$$\begin{aligned} U = (L_d - L_o) &= \text{shortage}/C^* \\ &= L_d - [F(T)/C^*] \end{aligned} \quad (19)$$

By the end of the period, if all orders are eventually to be filled (i.e., no loads are lost because of delays), the average delay in waiting for a car can be found by relating the unfilled orders to the average daily demand, which is L_d/T:

$$\text{Average delay} = U/(L_d/T) = UT/(L_d) \quad (20)$$

The mathematics becomes more complicated if we attempt to consider the possibility that shippers unable to obtain cars will either decide not to ship or use another mode. Because computer models have been developed to handle such situations, there is no need to pursue such issues in this paper (14).

What happens where there is a shortage? From Equation 17, we see that the actual cycle time multiplied by the actual loads handled must equal the available car days. The longer the cycle time, therefore, the fewer the cars that are originated and the greater the delays to shippers. Clearly, during such periods, reductions in the cycle time can reduce the delays in placing cars for loading, which may provide an immediate benefit by keeping shippers from diverting traffic to other modes and a long-term benefit by keeping shippers happy.

There is evidence that the car service rules used by the U.S. rail industry promote increases rather than decreases in the car cycle (15). When certain types of cars are in short supply, owners may restrict the ability of railroads terminating these cars to reload them. This causes additional empty mileage and increases the empty-car days required to reposition the cars. Hence the capacity of the fleet is reduced precisely when capacity is most in demand. The justification of this system of car service rules is that the owners deserve first priority in loading cars when shortages occur because they incur the risk of having surplus cars when demand is low. Alternative means of distributing empty cars, however, may achieve the same protection for owners with much lower requirements for empty movements. [For example, the clearinghouse railroads have pooled their general-purpose boxcars and use a linear program to determine the required movements of empty cars from one clearinghouse road to another. FCUP has recommended a new approach to freight car management that would extend the clearinghouse concepts (16).]

SUMMARY AND CONCLUSIONS

Car distribution involves moving empty cars from an unloading point to an appropriate reloading point. Car distribution performance can be measured in terms of empty time, empty mileage, the cost of car distribution, and the quality of service (availability of suitable cars when desired by shippers). Car distribution performance is a function of

1. Fleet size relative to the average demand,
2. Spatial imbalances in demand,
3. Temporal imbalances in demand,
4. Institutional restrictions on the use of cars, and
5. Operating policies.

The car days required for a particular traffic volume can be estimated as the product of the number of loads and the standard car cycle, which consists of the following standard amounts of time:

1. To load car,
2. To move car to unloading point (loaded transit),
3. To unload car,
4. To move car to loading point (empty transit),
5. For loaded storage, and
6. For empty storage (including repairs, cleaning, and idle time).

The car days required varies substantially because of the variations in demand, operating policy, and weather. The total number of car days available in any time period is the product of the average fleet size and the number of days in the period. Because cars have long lives, this number is fairly constant for the fleet as a whole. The variability in the number of car days required plus the invariability in car days available combine to complicate management of car utilization in general and car distribution in particular. When requirements are substantially different from the available car days, the result is a noticeable surplus of equipment or delays in placing cars for loading by shippers.

During surpluses, a single-fleet manager would seek to minimize distribution costs, possibly by storing the oldest or least-reliable equipment. During shortages, a single-fleet manager would seek to reduce the time required for each component of the cycle time, including the time required for car distribution, in order to reduce delays in placing cars for loading.

When car distribution and freight car management involve many railroads and other organizations, however, the industrywide response to surpluses and shortages may be less than optimal. Instead of trying to share the surpluses and shortages in an equitable manner, railroads have an incentive to use the applicable rules so as to shift the burden to other railroads or organizations. Hence, studies of these rules and management practices may identify ways to improve car distribution performance. Many such studies have been conducted by AAR through its various committees and FCUP.

In the long run, car distribution performance can be affected by many activities not commonly perceived as car distribution activities (17):

1. Marketing policies (pricing, sales efforts, etc.) that affect the traffic volume, the traffic mix, and the imbalances in traffic flows;
2. Investments (and disinvestments) by railroads and shippers that affect the structure of the rail network and the location of shippers and receivers on that network;
3. Ownership of the fleet, because different sets of rules and objectives apply to different owners; and
4. Degree of standardization of the fleet, because the larger the group of cars being managed, the less important the random variations in traffic volume and the various types of imbalances.

The equations presented in this paper provide the analytic framework necessary to categorize and evaluate the many alternatives available for improving freight car distribution performance. Because performance varies with the actions of many groups and organizations, a coordinated approach will be necessary to achieve substantial improvements. The mathematical relationships provide a logical basis for this coordination.

ACKNOWLEDGMENT

This paper was prepared with support from the University Grant Program of the U.S. Department of Transportation. It does not, however, necessarily represent the views of DOT or any other government agency.

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Publication of this paper sponsored by Committee on Railroad Operations Management.