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Foreword

The seven papers in this Record cover recent research in the areas of commuter, regional, and rail transit. Commuter rail transportation, which is in need of more extensive treatment in the literature, is the subject of the first four papers.

In the first paper, by Zavattero and Beal, the characteristics of the parking facilities serving the Metra system, located in the northeastern Illinois region, are described. The study included a field survey of its 208 stations and an assessment of the capacity needs at each of those stations. Strategies are developed to alleviate the deficiencies.

Discussed in the next paper is research performed to develop a modeling capability for the Long Island Rail Road that will make it possible to forecast the impact of changes in parking supply, price, and other commuter rail service characteristics on ridership.

Described in the third paper is a model developed to forecast rail ridership to specific stations of the New Jersey TRANSIT system. This model gives the agency the opportunity to define its market as narrowly as possible. A data base with 20 service and demographic variables was created to validate the model and perform a simple analysis.

Presented in the paper by Musso and Vuchic are the results of research on rapid transit network planning, with a focus on geometric characteristics. For the purpose of analysis, the authors selected several measures of metropolitan transit networks, such as length of system, number of lines, and stations that express the extensiveness of the system. The methodology developed is applied to 10 different cities to illustrate the application of theoretical and empirical materials.

A report in the next paper describes research completed to improve the control of stray current corrosion problems attributed to direct current (DC) powered transit systems. The work draws from numerous sources to address the technical aspects of system structure design, construction maintenance, occupational and public safety, and the institutional concerns of economics and liability.

Examined in the Chow, Nichols, and Benz paper is the ability of New Jersey TRANSIT's Hoboken Terminal to handle the increased numbers of pedestrians anticipated in the year 2000. A microcomputer model of pedestrian flow was developed to examine the impact of the various planned changes. Various alternatives, including automated ticket vending machines, ordered queues, and new window configurations, are proposed to relieve the expected congestion in the waiting room and rail concourse.

Discussed in the last paper is a staging area simulation model developed for the Seattle METRO bus subway. The bus subway uses dual-powered buses that operate on diesel engines above ground and from DC electric traction power from an overhead trolley wire in the tunnel. Lutin, Hornung, and Beck describe the real-time simulation model that features graphic displays of the proposed staging areas. The model also allowed planners to evaluate the performance of bus dispatchers and automatic dispatching.

Evaluating the Accessibility of Commuter Rail Services: Metra Systemwide Parking Inventory/Assessment

DAVID A. ZAVATTERO AND DAVID P. BEAL

Consumer acceptance and use of the rail mode are clearly influenced by the availability, convenience, and cost of commuter parking around each station. Access conditions represent an opportunity to improve rail service quality and to attract or expand ridership. A thorough understanding of available access to each commuter rail station is essential to a comprehensive transit marketing strategy. To this end, Metra, the commuter rail operator in the northeastern Illinois region, conducted a systemwide inventory and assessment of commuter parking capacity, use, and physical condition at its 208 stations. The study included field surveys, data base design and development, and assessment of the capacity needs at each station. More than 860 parking lots serve these stations. These lots provided more than 54,000 commuter parking spaces, which were used by more than 45,000 cars. The systemwide use rate was over 85 percent, with 90 stations experiencing major capacity deficiencies. The focus of this paper is on the characteristics of the parking facilities serving the Metra system and the strategies proposed to alleviate identified deficiencies. Strategies considered included: overselling of commuter parking permits, redesigning existing lots, construction of new lots, development of shared parking opportunities, pricing adjustments to redistribute parking demand, and expansion of feeder bus and other access alternatives. This study constitutes the initial phase in the development by Metra of a comprehensive parking policy that recognizes the importance of station access to rail service quality.

Metra operates the commuter rail system in northeastern Illinois. This system consists of 11 rail lines plus branch lines generally radially oriented toward the Chicago central business district (CBD), as shown in Figure 1. The system carries an average of 125,000 riders daily. The most frequent mode of travel to Metra commuter rail stations is the drive-and-park mode. Clearly, the availability and condition of parking around stations play an important role in consumers' decisions to use commuter rail. In 1986, Metra began a multiphased study of the role of parking in the definition of the commuter rail travel market. The first phase of the Metra Parking Study is the data collection and analysis activity discussed in this paper: the Metra Systemwide Commuter Rail Parking Inventory/Assessment.

The parking inventory/assessment involved field visits to 208 Metra stations. At the 186 stations where commuter parking was determined to exist, 861 parking locations were identified as having 45,631 cars parked in 54,022 spaces.

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The information collected during the inventory/assessment forms the data base for several planned studies of the tripmaking behavior of Metra riders. It will be possible to investigate questions such as: Do riders drive to stations, other than the stations closest to their homes, in order to obtain more readily available or less costly parking? Other questions about the effects of parking capacity use on commuter rail ridership levels can also be addressed.

Included among Metra's goals is the enhancement of access to the rail system. To this end, Metra initiated an annual parking capital-improvement program. The inventory/assessment data base constitutes a systemwide analysis of parking, which will be a key element in the formulation of that annual program.

Another intended use of the parking data is the derivation of a set of parking standards and policies for implementation by Metra. The inventory/assessment revealed a great diversity in the practice of parking provision throughout the Metra service area. Unique combinations of factors such as fees, collection methods, and restrictions were found to exist around each station.

The systemwide parking inventory/assessment was managed by the Metra Office of Planning and Analysis and the Metra Parking Committee, which is an interdepartmental task force charged with monitoring all phases of the Metra Parking Study. Virtually all elements of the inventory/assessment were the responsibility of Metra's consultant, Lester B. Knight and Associates, Inc.

OUTLINE OF INVENTORY/ASSESSMENT ACTIVITIES

This project consisted of five major tasks, of which the first three were field survey activities. These are described as follows:

Facilities Inventory

Field crews visited all Metra stations, and all associated parking locations, in the six-county metropolitan area. Crews conducted an inventory of a broad range of facilities and passenger amenities such as public phones, transit maps, bus stops, kiss-and-ride areas, and so forth.

Capacity and Utilization Survey

Crews performed a utilization count by recording the license plate number of every vehicle present at all commuter parking

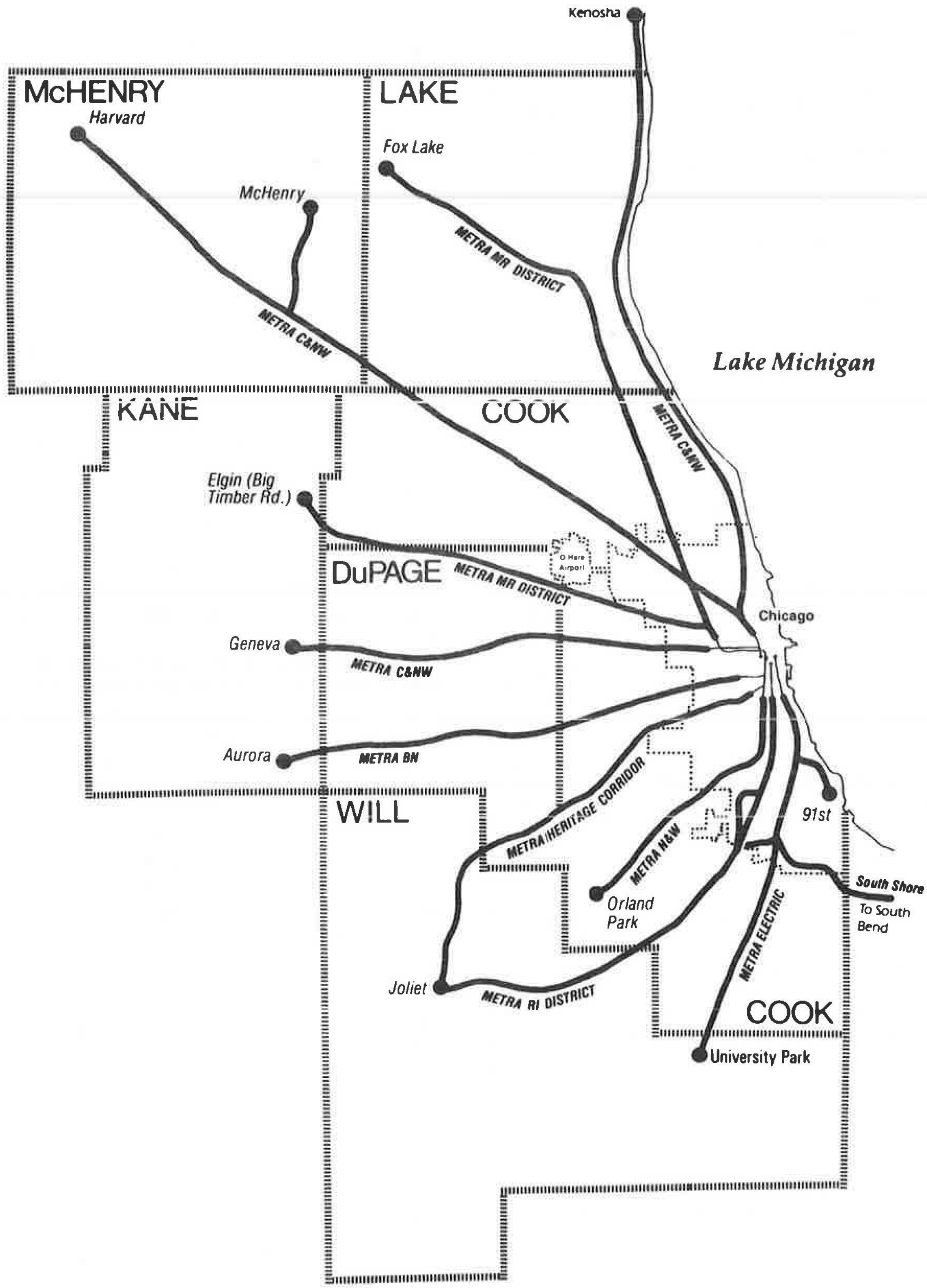


FIGURE 1 Metra commuter rail system.

locations. A count of total capacity was also performed. In unstriped or unpaved locations, crews measured the area to permit capacity to be calculated later.

Physical Conditions Assessment

An assessment of the current physical condition of the parking surface was performed at all publicly owned parking locations outside the public right-of-way. The method selected for rating surfaces was the pavement condition index (PCI).

These field activities provided the base-line data for later phases of the inventory/assessment. These are described as follows:

Data Base Development

Field data were developed in the Metra parking inventory data base. This data base operates on a personal computer and consists of four relatable files. The Village file consists of information on the local government unit in which the station is located. It includes data on the local contact and the commuter parking permit practices of that village. The Station file contains station-specific information gathered during the inventory. This file contains information on passenger amenities available at the station and demographic data for the stations' market areas. The Lot file contains descriptive data associated with each parking location. These include information on the location, capacity, and use of each lot; parking fees; collection methods; lot ownership; and maintenance responsibilities. The Capacity file is derived from the previous files and contains information on the capacity utilization characteristics of each station. The final segment of the data base is a set of consistently formatted maps, one for each station surveyed, which provide geographic information on commuter parking locations for the station concerned.

A user-friendly data management system was developed and implemented in the dBASE language. This software permits the casual user to extract detailed parking information on a municipality, station, or lot through a menu-driven program. For the experienced user, this data base permits detailed analyses of existing parking-ridership patterns and scenario testing for regional demographic forecasts and proposed parking policies.

Inventory/Assessment Reports

The final report summarizes systemwide statistics and identifies parking problems and needs. It identifies specific locations where parking deficiencies are most serious. In addition, current management practices that contribute to deficiencies are identified and possible improvement strategies are proposed for further study. A procedures manual was developed that describes a preferred method and schedule for updating the inventory/assessment. Finally, a user's manual was prepared describing the development of the computer data base and operation of the user-friendly system.

In a related project, Metra has matched the license plates collected during field work to the names and addresses of the automobile owners. These addresses were geo-coded to the quarter section of origin, yielding a station-specific file of commuter rail users that could be converted to map form. Several studies of station market areas are planned using this data.

CHARACTERISTICS OF COMMUTER PARKING

A wide array of parking conditions exists around the 208 stations included in this inventory. This ranges from no available parking at 22 stations to 6 stations where over 1,000 parking spaces are available for commuters. The stations with no available parking are primarily inner city locations with relatively low boardings and surrounded by higher-density development. The larger suburban stations with heavy ridership generally are served by more parking facilities.

Indicated in Figure 2 is the distribution of the 186 stations with parking by the number of spaces provided. The typical

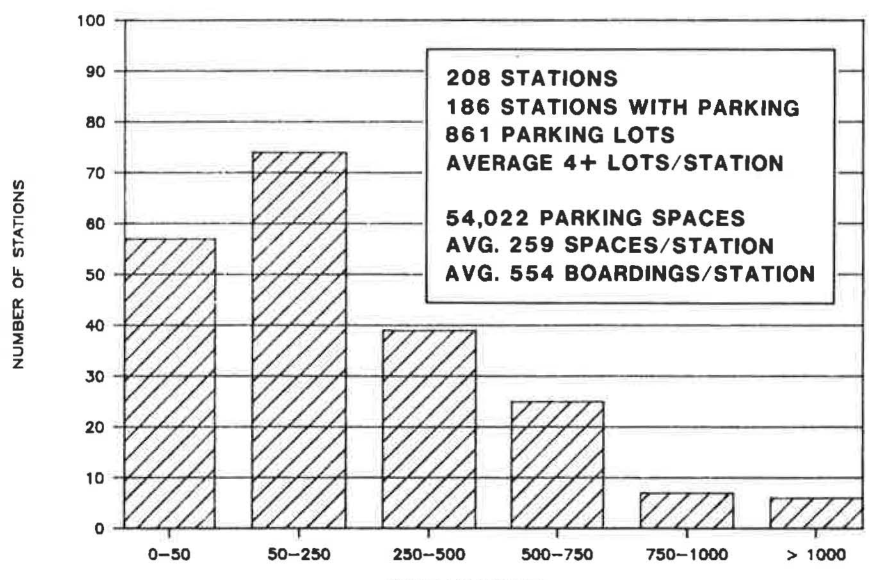


FIGURE 2 Stations by parking availability.

station in the Metra system is served by four parking lots containing a total of 260 spaces. These facilities would serve an average station ridership of 554 boardings. The drive and park mode is clearly the preferred access alternative, with nearly three-fifths of rail commuters arriving at the station by this mode.

As shown in Figure 2, there was a total of 861 parking locations at the 208 stations. These locations provided 54,022 parking spaces. The use of these spaces is summarized in Figure 3. More than 45,631 automobiles were parked in these spaces for a systemwide use rate of 84.5 percent. The average station with parking in the Metra system is used by 245 automobile drivers requiring parking spaces. The distribution of stations by number of spaces used is also shown in Figure 3. More than 1,000 vehicles were parked at four Metra stations.

The 861 locations inventoried included on-street and off-street lots, designated and nondesignated commuter facilities, paved or unimproved surfaces, and so on. Some systemwide statistics are presented in Figures 4 and 5 that characterize the parking locations available to the rail commuter. As shown in Figure 4, some 366 or nearly 43 percent of all parking locations are off-street designated commuter rail parking lots. These are the typical commuter rail parking lots generally located in close proximity to the station itself. About 213 locations or 24.7 percent are on-street designated lots. On-street nondesignated facilities account for 26.0 percent of the commuter parking lots. Off-street nondesignated and off-street joint-use lots accounted

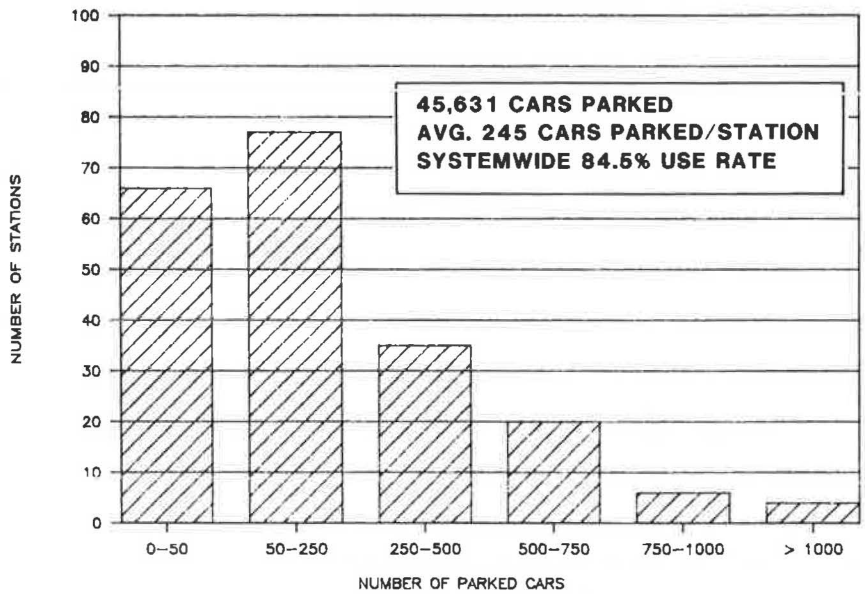


FIGURE 3 Stations by spaces used.

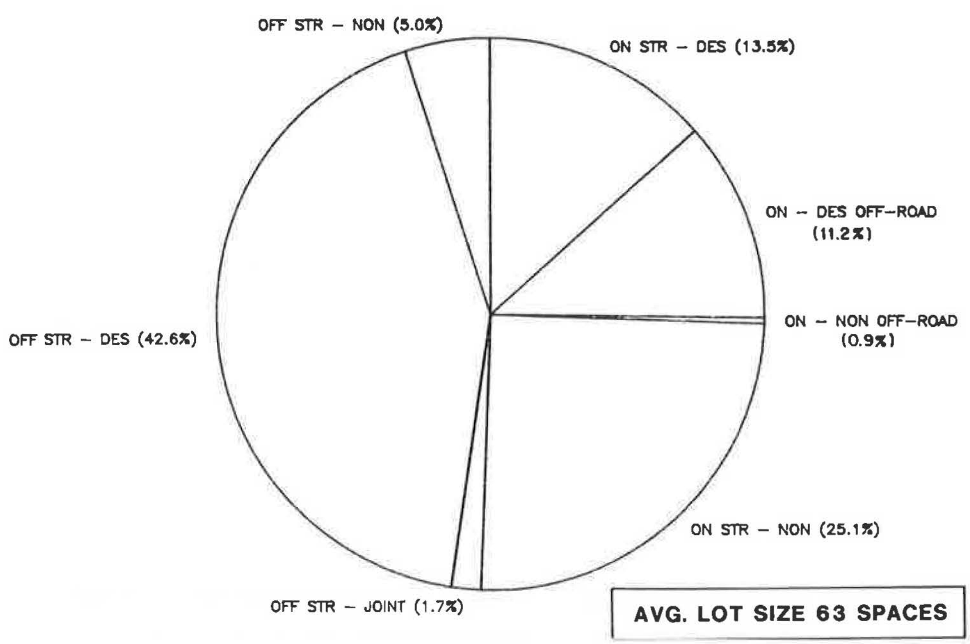


FIGURE 4 Lots by parking category.

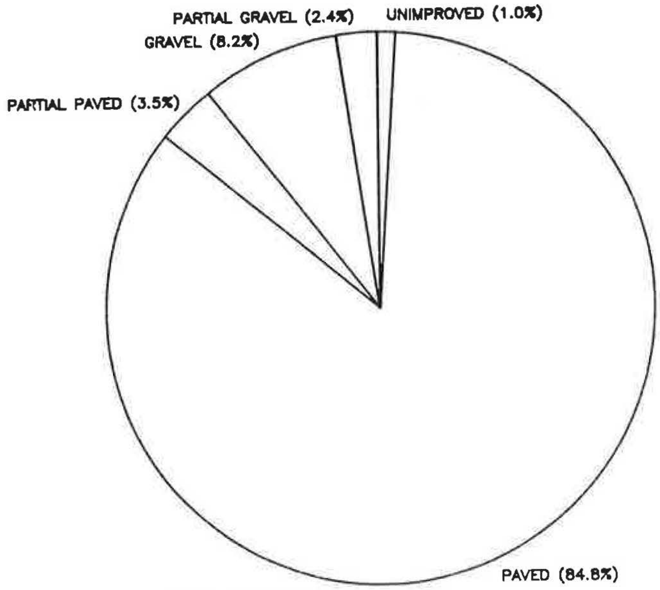


FIGURE 5 Lots by surface type.

for the remaining facilities at 5.0 percent and 1.7 percent, respectively.

More than 84 percent of the locations had paved surfaces, as shown in Figure 5. The rest of the locations ranged from partly paved to unimproved, with 8.2 percent of the locations having gravel or crushed stone surfaces, 3.5 percent having partly paved surfaces, 2.4 percent having partly gravel surfaces, and 1.0 percent having grass or dirt surfaces.

Consumer acceptance and use of the rail mode are clearly influenced by the availability, convenience, and cost of commuter parking around each station. A useful measure of the availability and convenience of parking is the percentage of capacity used. The distribution of stations by percentage of capacity used is shown in Figure 6. More than 95 percent of available parking capacity is used at 58 stations. Between 90 and 95 percent of available spaces are used at another 27 stations. These 85 stations represent potential capacity problems that the improvement strategies discussed later in this paper are intended to solve.

One of the key objectives of the parking inventory was an assessment of the physical condition of all off-street parking locations. The PCI methodology developed by the U.S. Army Corps of Engineers (*1*) was adapted and applied to rate the surface condition of each publicly owned lot. The distribution of surface conditions for each of the more than 500 rated lots is shown in Figure 7. The majority of lots are in good condition or better. Only 78 lots are categorized as being in poor condition or worse. Improvement of these deteriorated surfaces is required to maintain an acceptable quality of parking facilities.

The distribution of lots by a fee-collection method is shown in Figure 8. No fee is charged at some 33 percent of the lots inventoried. Of the lots charging a fee, 27.7 percent collect by prepayment methods including stickers or permits (22.9 percent) and window cards (4.8 percent). Fees at nearly 36 percent of the lots are collected by daily (or day-of-service) methods including 18 percent by collection boards and 17.4 percent by meters. The average fee charged for commuter parking was \$0.62 per day if all lots are included or \$0.77 per day if only those lots charging fees are included.

PRELIMINARY TOOL FOR COMMUTER PARKING PLANNING

A model of commuter parking demand and capacity requirements was made from the data for the 64 stations with available parking and at which the capacity utilization rate was under the 85 percent taken as the capacity deficiency bench mark. Shown in Figure 9 is parking capacity as a function of weekday rail ridership at each station. The following regression equation was developed for use in estimating the typical parking requirements associated with Metra ridership:

Spaces = 37.3 + 0.49 Riders $\quad R^2 = 0.66$

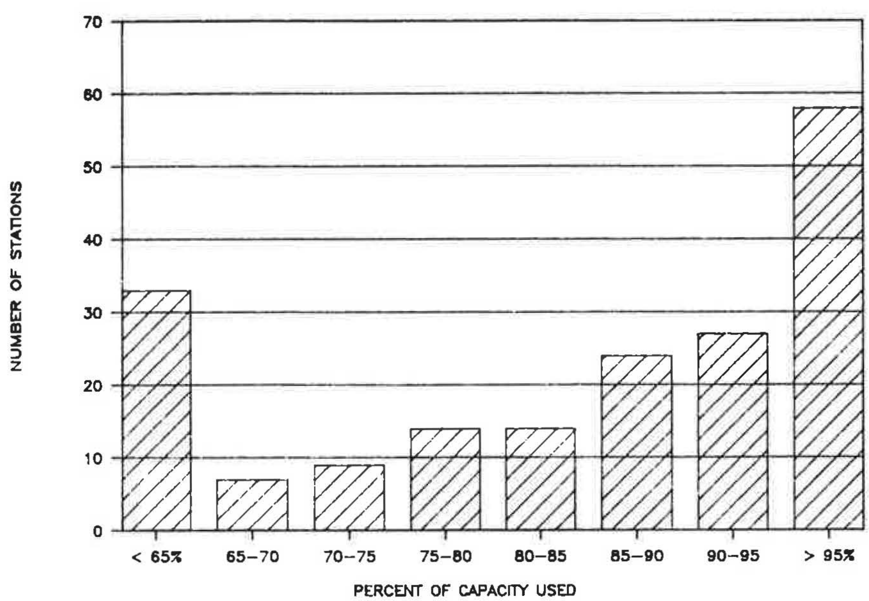


FIGURE 6 Stations by capacity used.

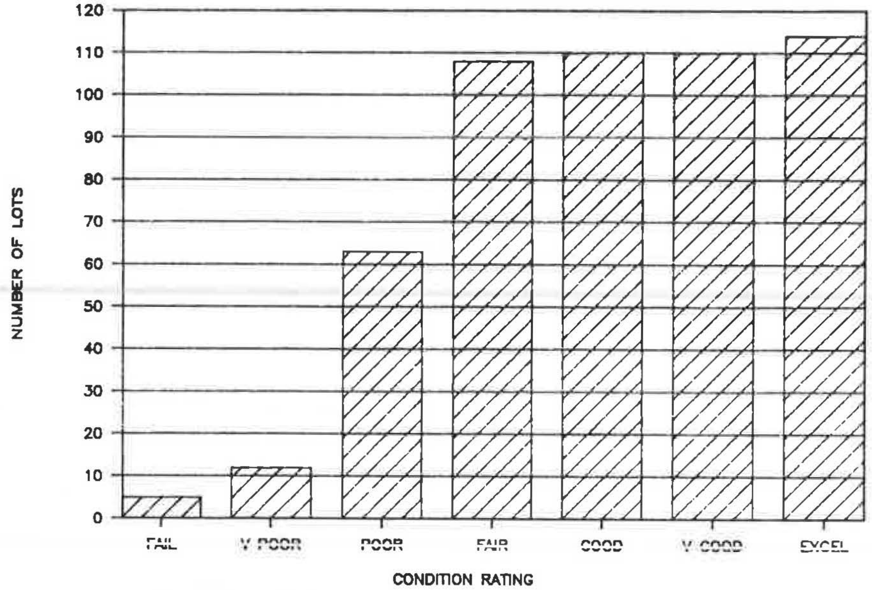
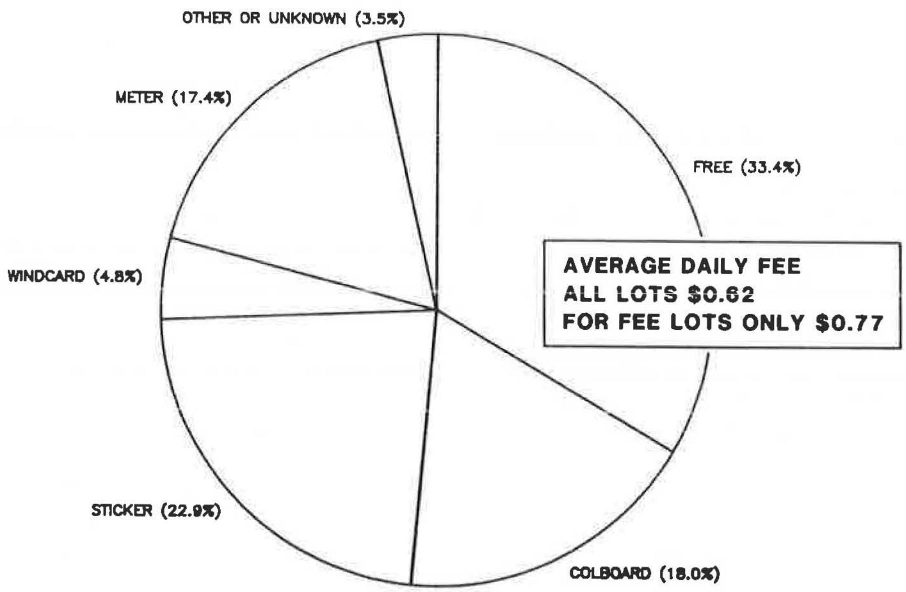


FIGURE 7 Condition of lots.



NOTE: AN INDIVIDUAL LOT MAY HAVE MULTIPLE COLLECTION METHODS.

FIGURE 8 Lots by collection method.

This model indicates that the average Metra station should be served by 38 initial spaces with an additional parking space provided for every two riders boarding at that station. Such a model may be useful in estimating the parking needs of proposed or existing stations. Although development of such a planning tool was beyond the scope of the inventory/assessment, it is clear that the detailed information of the parking data base is well suited to subsequent analysis of this type. The next section offers some parking strategies that may relieve parking problems around particular stations.

COMMUTER PARKING STRATEGIES

Several strategies for increasing the parking available to commuters at specific stations will be considered as a result of the inventory analysis (*2, 3*). The first, which has the lowest implementation cost, is a program of overselling monthly or quarterly permits for commuter parking, taking advantage of the fairly constant commuter-absentee rate. This practice already occurs in a small number of municipalities, giving evidence that actual parking capacity can be oversold by 5 to 20 percent without causing inconvenience to the commuter.

Another low-cost strategy for increasing capacity would be a program of restriping parking lots to down-size additional spaces for compact cars. This method is common in shopping malls and increases capacity significantly. The typical commuter parking location has spaces of uniform size, all large enough to readily accommodate full-sized vehicles. Because rail commuters are typically all-day parkers, with minimum recycling of the stalls, it may also be possible to increase

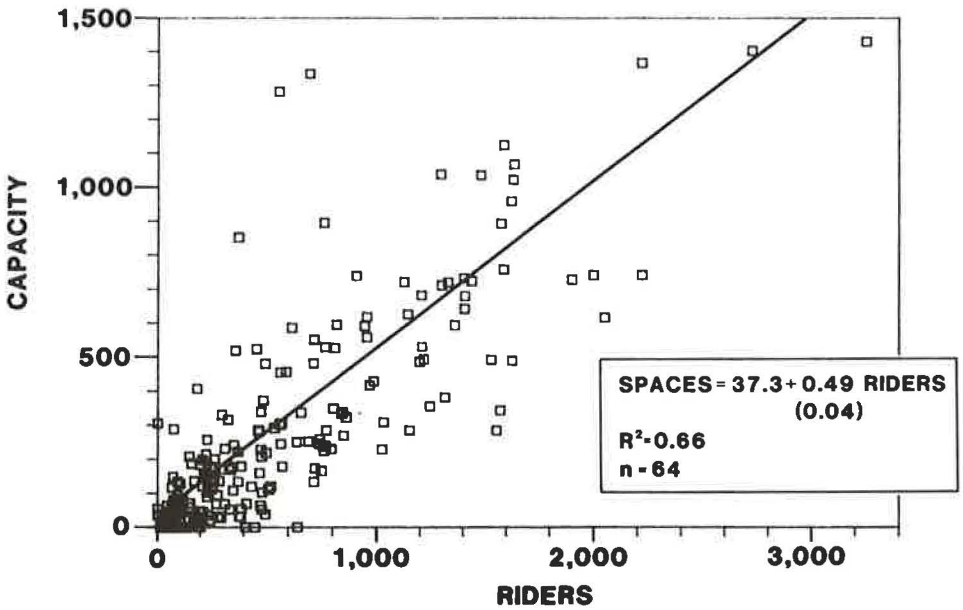


FIGURE 9 Parking capacity versus weekday riders.

capacity by a general down-sizing of stalls to a 9 ft width, for example.

The parking inventory revealed very few instances of commuter parking shared with another activity. Where this exists, it appears to work to the benefit of Metra, the municipality, the sharing establishment, and the commuters. Logically, where shared or jointly developed parking is feasible, the total cost of the parking provision may increase marginally, but the proportional cost for the joint users is lower than if it is not shared. The shared–joint-parking strategy will be the subject of further investigations, and several opportunities for joint parking were identified in the assessment.

The most obvious method of increasing available commuter parking is the construction of new lots. This costly method is also often the most complicated to implement. The areas surrounding Metra's busiest stations, where parking is most frequently in short supply, are the areas most likely to be fully developed. In many cases, the nearest vacant or underused parcel is a great distance from the station. Even where land is available, using it for parking prevents its use for commercial and other high revenue-producing purposes, and is a tax-exempt activity. Not surprisingly, municipalities are not always eager to develop additional parking around their train stations. For these reasons, Metra has vigorously investigated other parking–station-access policy options as alternatives to construction of new parking, though a number of locations for new lot construction were also identified in the assessment.

Metra market studies indicate that many commuters travel to other than the closest rail station to obtain less expensive parking. This behavior exacerbates parking problems when heavily used stations are attractive to commuters from outside a strictly defined market area because of relatively low parking rates. This, of course, means that other stations with excess parking capacity are unattractive to commuters because of comparatively high parking fees. Metra is also investigating the potential impact and the feasibility of establishing a systemwide, uniform parking fee structure to encourage use of stations with available parking capacity.

Stations with severe parking deficiencies are, in some instances, located within a few miles of other stations with equally priced, excess parking. A study of strategies (e.g., revisions to the timetable) will also be undertaken to assess the ability to attract commuters to underused stations.

At many Metra stations, an alternative to drive-and-park station access exists in the form of feeder bus routes. A cooperative, interagency study of improvements to the feeder bus network is currently under way as a logical consequence of this parking inventory/assessment and the commuter origin geocoding project.

The Metra Systemwide Commuter Rail Parking Inventory/Assessment will be the basis for further study. Many questions regarding the role of parking in shaping the northeastern Illinois region's travel patterns were answered through this effort. This phase of the Metra Parking Study was an unusual undertaking in that, by design, it raised additional questions and provided the foundation on which to construct the answers.

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RailRider—A Comprehensive Commuter Rail Forecasting Model

HOWARD L. SLAVIN, ZVI TAREM, ERIC A. ZIERING, AND ROBERT BRICKMAN

Presented in this paper are the results of research performed to develop a modeling capability for the Long Island Rail Road that would make it possible to forecast the impact of changes in parking supply, price, and other commuter rail service characteristics on Long Island Rail Road ridership and on the access mode choice, station choice, and parking lot use of riders. In this project, Caliper Corporation and the Long Island Rail Road developed and implemented a unified network modeling approach that incorporated these travel choices and was applied within a modified stochastic user equilibrium framework. This model was implemented in a user-friendly microcomputer software package to provide easy access to this forecasting capability.

Presented in this paper are the results of research performed to develop a modeling capability for the Long Island Rail Road (LIRR) that would make it possible to forecast the impact of changes in parking supply, price, and other commuter rail service characteristics on LIRR ridership and on the access mode choice, station choice, and parking lot use of LIRR riders. Although it is commonly recognized that parking availability can be a key determinant of rail ridership, quantification of the impact of specific changes in parking supply and price has generally been beyond the reach of current forecasting techniques. Nevertheless, the forecasting problem posed is one that is faced by virtually all urban rail passenger transit systems, both existing and proposed.

The challenging nature of the task stemmed from numerous methodological and empirical difficulties. First, the small-scale changes that were of interest to the LIRR were numerous, were not confined to any particular geographic subarea, and could not necessarily be anticipated. Using subarea study approaches, therefore, was not feasible. Second, the forecasting capability had to be able to deal with major changes in system configuration and operation that are being implemented as part of the LIRR's capital program. This was particularly important with respect to anticipated major changes in the rail network, especially the electrification of the LIRR Main Line through central Long Island, which involved major track reconstruction, the relocation of several commuter stations, and significant improvements in overall level of service. As a result, the model also had to be comprehensive enough to be able to forecast the impact of these changes.

Third, the forecasting model had to account for the multiplicity of travel choices faced by commuters in the Long Island–Manhattan travel market. These choices include whether to ride the LIRR, and, if choosing to do so, station, access mode, and parking lots selected (for LIRR riders who use park access only). Travelers do not consider these decisions separately in a predetermined sequence. The access mode a rail traveler will select depends on the station used; the decision to commute by automobile is often motivated (in the LIRR's case) by unavailability of parking at a traveler's preferred station. This interdependence of travel choices is often ignored or overly simplified in demand forecasting, resulting in unrealistic forecasts.

Fourth, the model had to be able to treat explicitly the capacity constraints and congestion effects that influence rail ridership and parking. To the extent that more travelers want to use travel paths than can be accommodated or to the extent that travel costs increase with travel volume, inconsistent forecasts are likely to be produced. Thus, achievement of consistent supply-demand forecasts was considered essential.

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TECHNICAL APPROACH

The study approach integrated significant technical efforts in market research, travel demand modeling, network equilibrium analysis, and software development. Existing LIRR data were supplemented by a parking inventory that obtained base data on parking supply and use at the LIRR's 110 commuter stations. An onboard survey containing a stated preference experiment was conducted so that travelers' behavioral responses to changes in parking conditions could be quantified with choice models. Extensive analysis and reconciliation of data from multiple sources were required to obtain base-case aggregate data on passenger use of the LIRR by origin zone and on passenger flows on the various rail network links.

A unified travel-demand forecasting model was developed within the framework of stochastic user equilibrium on a network. In this framework, the various choices open to commuters (including choice of mode, access mode, LIRR station, and parking lot) were jointly analyzed in terms of a supernetwork (*1*) made up of links representing these alternative travel paths. Estimated monetary values of level-of-service attributes from prior- and new-traveler preference models were used as the basis for the perceived generalized costs of rail network links of various types.

A stochastic user equilibrium assignment methodology (*2*), modified to incorporate capacity constraints, was used to assign travelers to the various modes, access modes, LIRR stations, and parking facilities. The equilibrium formulation ensures that consistency is achieved between forecast demand and level of service despite the flow dependence of the latter.

In stochastic user equilibrium, travelers vary in their perceptions of link costs and no user believes that he can unilaterally reduce his disutility of travel by selecting an alternative travel path (*1*). Because perceptions of link costs vary among travelers, stochastic user equilibrium produces much more realistic assignments than does deterministic user equilibrium, in which only the least-cost paths are used. The basic feasibility of the stochastic user equilibrium approach in building an empirical rail demand model had been established in previous internal research and development by Caliper Corporation and in a small-scale application to the problem of forecasting LIRR riders' destination terminal choices under alternative scenarios (*3*).

BACKGROUND RESEARCH

Survey research was conducted with 900 LIRR passengers to measure their preferences with respect to access mode choice. These data were combined with information collected in previous survey research performed for the LIRR. On-board survey research conducted in 1982 (*4*) focused on the choice of commutation station by LIRR riders, and measured the relative importance of fares, travel times, parking availability, and access time. Subsequent research by Caliper Corporation developed improved measures of the value of travel time, and also measured the effects of transfers on travel choice (*3*). On-board survey research conducted in 1985 as part of this study focused on access mode and parking-lot choices.

In these studies, conjoint data collection was used to measure the manner in which current and potential riders trade off selected characteristics of their commutation trip. The data-collection efforts were combined with extensive statistical and econometric analysis using regression, logit, and ordered logit model-estimation techniques. The result of these efforts was an estimate of the dollar values (or marginal rates of substitution) for the various relevant determinants of travel choices. These dollar values were used to determine the appropriate costs on various links of the network, and were as follows:

	Dollar Value/hr
LIRR and other mode travel time and wait time at LIRR stations	4.50
Access time to LIRR stations	5.22
Walk time from lots to LIRR stations	6.00
Egress time from LIRR terminals	2.94
Diesel service penalty	0.48

The diesel service penalty is applied at stations that provide diesel service only, and reflects the inconvenience associated with transferring to an electric train to reach the LIRR's Pennsylvania Station and Brooklyn terminals.

Significant effort was also invested in developing an accurate estimate of base-case patterns of demand on the LIRR and on competing modes. Total ridership by mode was derived using LIRR ridership data and 1980 U.S. Census Journey-to-Work data for Queens, Nassau, and Suffolk counties. Rail ridership by station was derived by reconciling several different sets of counts and survey data collected by the LIRR. Base access mode information was compiled through survey tabulations and through a comprehensive parking inventory that obtained parking supply and use statistics at all 110 LIRR commuter stations.

DEVELOPMENT OF FORECASTING MODEL

The forecasting model generates estimates of the travel choices that will be made by commuters in the Long Island–New York City travel market. These forecasts are based on characteristics of the LIRR system and associated parking facilities. The model encompasses all modes of travel, although all non-LIRR travel modes are aggregated within the model. The LIRR system is modeled in great detail, with individual stations and parking facilities included at the most disaggregate level.

The model is network based, with the region represented as a set of nodes and links that connects them. Travel flows can occur between any two nodes along a sequence of links (a path) connecting them. The movement between any pair of nodes along a link may be associated with some impedance or generalized cost. Nodes, on the other hand, do not have any costs associated with them. The base network consisted of 1,930 links and 846 nodes.

The service territory, which covers Queens, Nassau, and Suffolk counties, was divided into 50 zones. Commutation trips originate at these 50 origin zones and terminate at a single destination zone representing New York City. Commuters have hundreds of alternative paths to follow through the network to complete a trip from their origin to their destination, representing various paths through the LIRR system and alternative paths using non-LIRR modes of travel. Certain links represent facilities with a limited capacity (e.g., parking lots), and on these links the capacity limitation is modeled explicitly.

The model evaluates the various paths available to travelers by estimating the total cost of each path. This cost is computed by summing the costs over all the individual links that make up that path. Based on the total cost of the available paths, the model assigns the demand between any two points in the network to appropriate paths.

Because the model is an equilibrium model, the cost of traversing a link may depend on the volume of travelers using it. Therefore, the model reevaluates the costs of alternative paths on an iterative basis, and reassigns some portion of travelers based on the revised estimate of path costs. In addition, because the model is stochastic, the cost associated with traversing a link is represented as a sample from a distribution of costs. At each iteration, a random component is added to the cost of certain types of links to simulate the stochastic effect.

Each link in the model may, therefore, have up to four types of costs associated with it, as follows:

- Out-of-pocket cost (in dollars);
- Time (in minutes);
- Congestion penalties; and
- A random cost element, which simulates the stochastic nature of link costs.

All time costs are converted into dollar equivalents using the marginal rates of substitution presented earlier. Congestion penalties represent the decrease in level of service associated with higher demand levels. Congestion on LIRR service links reflects lower levels of comfort and decreasing seat availability. Congestion on nonrail links reflects increased highway congestion and discomfort associated with increased subway crowding. The random-cost element represents the variation in link costs and commuter perceptions of link costs described earlier. It is the presence of this random cost element that distinguishes stochastic user equilibrium from deterministic user equilibrium.

The network assignment procedure that was used as the basis for the forecasting model is the stochastic user equilibrium (SUE) assignment procedure described by Sheffi, which uses the method of successive averages (*1*). The mathematical approach presented in that paper is proved to converge at a true SUE solution. The variant used here assumes that the path flows are logit distributed based on the differences in path costs. This formulation leads to a Gumbel distribution of the stochastic link cost component.

Initial implementation of the SUE algorithm identified several practical complications. First and most significant, the original SUE algorithm did not lend itself well to networks in which a large number of links have fixed capacities. This was a severe problem in the LIRR network, because more than 400 links represented parking facilities with fixed capacities. Simulation of fixed link capacities through exponentially increasing congestion penalty functions yielded an unstable model that would require countless iterations before reaching equilibrium.

As an alternative, an attempt was made to use a deterministic user equilibrium approach with fixed capacity constraints. This approach yielded a model that produced unrealistic solutions, in which many of the possible paths through the network (which were known to be used by travelers on the real LIRR network) were not used. This undesirable characteristic of deterministic equilibrium solutions is well known and was, in fact, a principal motivation for the development of the stochastic user equilibrium approach. Other ad hoc procedures for multipath assignment were also considered but rejected based on their unsound theoretical and empirical properties.

As a result, the SUE algorithm was modified to accommodate links with absolute capacity constraints. The modified algorithm performed well, but resulted in an increased computational burden in producing a network assignment. The slower speed of the forecasting model had a significant impact on the level of effort required to calibrate the model.

Calibration was the final step in the development of the forecasting model. In this step, model parameters are adjusted so that the forecasting model accurately reproduces base case conditions. Conceptually, calibration may be thought of as tuning the model to reflect the contribution of variables that influence travel behavior but are not accounted for explicitly. Calibration of the model was greatly complicated by the multiplicity of travel choices and the high degree of interdependence among flows on alternative paths. The mathematical problem of directly solving for the constants is computationally intractable, and an enormous computational burden was involved in informed trial-and-error tests. Ultimately, a semiautomated approach was developed that was extremely effective, although time consuming. Calibration was ultimately achieved to within 1 percent of the base case flows on most links. For links with very small flows, errors of less than one or two riders were achieved. This calibration was dramatically better than that typically achieved in large-scale urban transportation planning studies, in which link volumes may be off by more than 100 percent.

RAILRIDER FORECASTING SOFTWARE

A key element of this study was the incorporation of the forecasting model into a microcomputer software package that made the sophisticated modeling capabilities directly and easily accessible to the LIRR. Many network equilibrium models must be applied by a specially trained analyst who manually develops and codes the transportation network. Changes in fares or in service must be implemented through the time-consuming and laborious process of manually recoding the network representation of the system. Many of these systems produce results in a format that is not immediately accessible and requires considerable post-processing before it can be comprehended. In developing the software, the goal was to eliminate these problems, thereby reducing the likelihood of errors and facilitating use of the system by individuals without specialized training.

The product of the development effort was RailRider, a proprietary microcomputer software product that implements Caliper Corporation's network-based demand forecasting methodology. The RailRider software is a user-friendly, menu-driven microcomputer package that was developed to the standards set by commercial microcomputer software. An on-line context-sensitive Help facility makes operating instructions and technical advice on producing forecasts immediately accessible to the user. No specialized technical knowledge of microcomputers or of the specific equilibrium algorithms used by the model is required to make use of the system. The software runs under MS-DOS on 80286- or 80386-based microcomputers.

The RailRider forecasting system has three major components: a file editor, a forecasting module, and a report generator. Each of these is described as follows. A schematic of the RailRider model appears in Figure 1.

File Editor

The file editor allows the user to edit seven different types of files that contain information on LIRR service, fares, and parking facilities and on overall commutation demand in the Long Island–New York City travel market. The file editor is designed to manage large numbers of input files effectively, and provides the user with the ability to give each file an alphanumeric label to assist in tracking scenario development and forecast generation. The editor functions in a fashion similar to a spreadsheet program, with special functions for adding and deleting records and for producing formatted printed copies of each file. Editing of alphanumeric fields is simplified by the incorporation of pop-up menus, and range checks are automatically performed on all numeric fields.

Shown in Figure 2 is the RailRider software as it offers the user a choice of files to edit. Note that each file is accompanied by its descriptive label. The RailRider display is shown in Figure 3 in the process of editing the 1986 Base Case Fare Zone file.

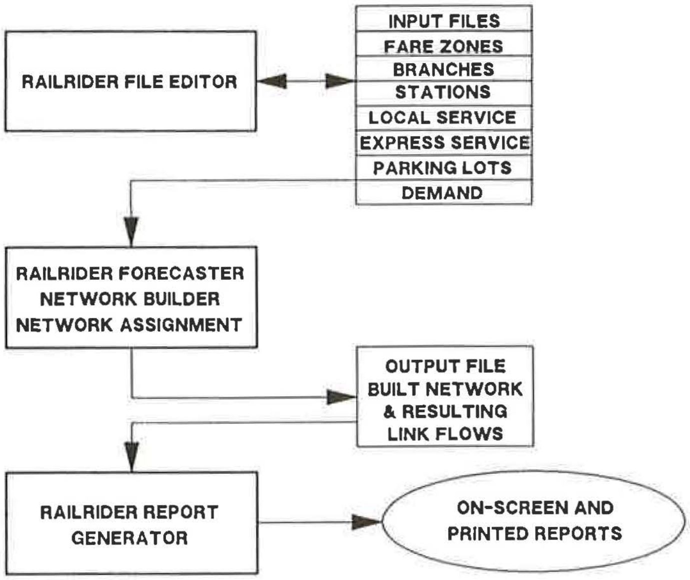

FIGURE 1 Schematic of RailRider model.

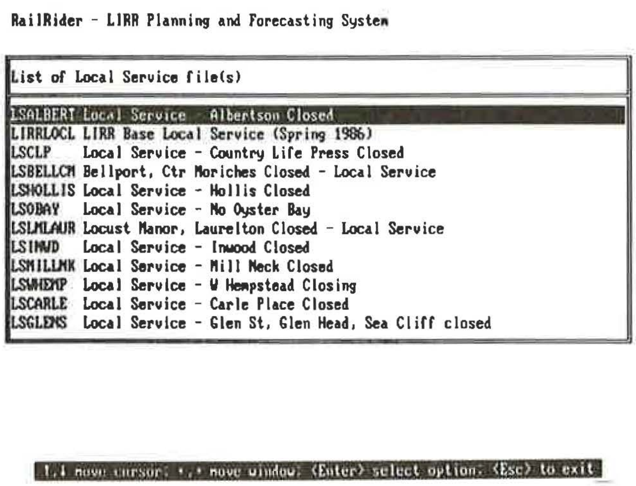

FIGURE 2 Sample RailRider file menu.

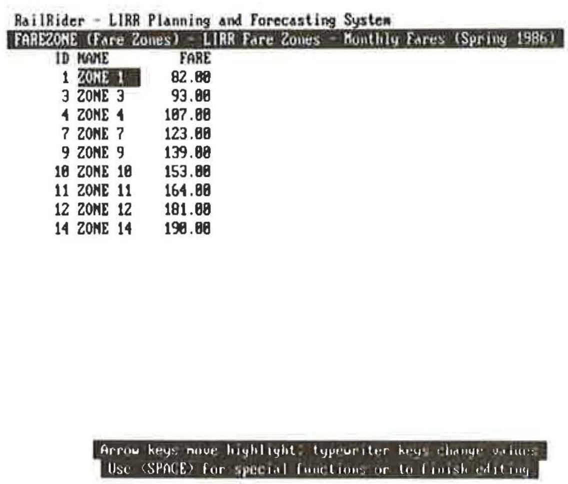

FIGURE 3 RailRider file editor.

Forecasting Module

The forecasting module has two major components: a network builder, and the assignment routine. The network builder is a powerful program module that translates 19 types of input files into an internal representation of an appropriate network. The network builder by itself is an innovation in the application of network forecasting methods to transportation problems because it permits the user to specify the structure and parameters of a network by editing easily understandable files. The network builder also saves time and reduces errors in developing analysis scenarios.

Networks that are used in transportation analysis typically differ from the physical networks that they represent. Invariably, they include additional nodes and links that represent internal connectivity among system components but have no physical parallel. Individual LIRR stations, for example, must be represented in the internal network as two distinct nodes with a link between them. To model accurately the parking restrictions that apply to lots at LIRR stations, RailRider must construct an internal subnetwork of dummy nodes and links that connect origin zones with individual parking facilities.

In traditional transportation network forecasting applications, users are required to manually construct the internal network. RailRider's network builder makes it possible for the user to edit a set of simple input files, each organized in a manner familiar to the user, and to have these files automatically converted into the complex internal representation required to produce an accurate forecast.

The other major component of the forecasting module is the assignment routine itself. As described earlier, the assignment routine is a stochastic user equilibrium assignment algorithm that has been modified to accommodate fixed-capacity constraints.

Report Generator

The report generator takes the results of an assignment and produces a variety of on-screen and printed reports. The information that can be abstracted from a RailRider network forecast is extensive, and the report generator is designed to allow the user to compile desired results efficiently and quickly, and with appropriate documentation.

When the forecasting module completes an assignment, it produces an output file that contains all the information required to produce and fully document sets of on-screen and printed reports.

The output file contains the names, dates, creation times, and descriptions of all the input files that were used to generate that particular forecast, the date and time that the output file was created, and a user-defined label that describes the run. The output file also contains a reproduction of the internal network representation, all of the text labels required for producing output reports, and the resulting network flows. As a result, reports can be produced from the output file without requiring that the original input files also be available. This alleviates a host of file-management problems.

The following reports are produced by the report generator:

- Summary reports
  - System summary report
  - Origin zone summary report
  - County and town summary report
  - Branch summary report
- Branch detail reports
  - Branch passenger loading reports
  - Branch parking summary reports
- Station detail reports
  - Station parking detail reports

All reports come in both on-screen and printed formats, with the printed versions supplying slightly more detail than their on-screen counterparts. On-screen reports are selected through a series of simple on-screen menus. For printed reports, the user can select any combination through on-screen menus, specifying the branches and stations for which detailed reports are required. All printed reports are automatically accompanied by a header page that describes the run and the input files that were used in preparing the forecast. Several of the on-screen reports produced by RailRider are shown in Figures 4, 5, and 6.

RailRider - LIRR Planning System Branch Summary Report

	Total	-----Volume by------ -----Access Mode----		-----Parking Utilization----		
Branch Name	Volume	Park	Other	Slots	Cars	%
PORT WASHINGTON	17,350	4,477	12,873	4,592	3,731	81.3%
OYSTER BAY	2,544	1,215	1,330	1,607	1,025	63.8%
PORT JEFFERSON	25,522	16,428	9,094	14,908	13,911	93.3%
RONKONKOMA	6,390	3,896	2,494	4,793	3,247	67.7%
HEMPSTEAD	7,094	2,674	4,421	3,073	2,228	72.5%
WEST HEMPSTEAD	1,729	470	1,259	480	392	81.7%
MONTAUK	3,426	2,807	618	3,639	2,423	66.6%
BABYLON	32,036	16,730	15,306	14,905	13,942	93.0%
LONG BEACH	7,255	3,124	4,131	3,039	2,603	85.7%
FAR ROCKAWAY	8,560	3,402	5,158	4,387	2,835	64.6%
CITY TERMINAL	826	82	744	68	68	100.0%
LIRR Total	112,733	55,305	57,428	55,573	46,406	83.5%

↑ System Summary ↓-County Summary (Space)-Report List

FIGURE 4 Sample RailRider branch summary report.

RailRider - LIRR Planning System Branch Loading Report - PORT JEFFERSON Branch

	-Arriving Trains--		---Boardings by--- ---Access Mode----		-Departing Trains-	
Station	Seats	Riders	Park	Non-Park	Seats	Riders
PORT JEFFERSON	0	0	616	79	7,200	696
STONY BROOK	7,200	696	479	13	7,200	1,187
ST JAMES	7,200	1,187	302	75	7,200	1,564
SMITHTOWN	7,200	1,564	761	114	7,200	2,439
KINGS PARK	7,200	2,439	841	298	7,200	3,570
NORTHPORT	7,200	3,570	1,083	388	7,200	5,049
GREENLAWN	7,200	5,049	384	183	7,200	5,617
HUNTINGTON	3,400	822	3,909	644	14,000	5,375
COLD SPRING HARBOR	13,920	4,229	1,003	193	13,920	5,426
SYOSSET	13,920	5,426	1,026	947	13,920	7,399
HICKSVILLE	14,160	3,439	3,687	4,055	20,400	11,181
WESTBURY	15,840	6,075	940	645	15,840	7,660
CARLE PLACE	9,120	3,584	0	366	9,120	3,950
MINEOLA	17,280	7,425	632	795	16,800	8,052
MERILLON AVE	8,280	2,056	153	249	8,280	3,258
NEW HYDE PARK	8,280	3,258	612	50	8,280	3,920

↑-OYSTER BAY ↓-RONKONKOMA ↔ Parking Report (Space) Branch List

FIGURE 5 Sample RailRider branch loading report.

RailRider - LIRR Planning System Branch Parking Report - PORT JEFFERSON Branch

	-All Parking Lots-			---Unrestricted---			----Restricted----		
Station	Slots	Cars	%	Slots	Cars	%	Slots	Cars	%
PORT JEFFERSON	637	587	92%	555	510	92%	82	77	94%
STONY BROOK	516	456	88%	516	456	88%	0	0	--%
ST JAMES	275	252	92%	128	122	95%	147	130	88%
SMITHTOWN	761	725	95%	461	437	95%	300	288	96%
KINGS PARK	737	701	95%	125	119	95%	612	581	95%
NORTHPORT	1,078	902	84%	177	133	75%	901	770	85%
GREENLAWN	343	328	93%	30	30	100%	313	290	93%
HUNTINGTON	3,323	3,257	98%	1,365	1,364	100%	1,957	1,893	97%
COLD SPRING HARBOR	836	836	100%	52	52	100%	784	784	100%
SYOSSET	978	855	87%	0	0	--%	978	855	87%
HICKSVILLE	3,345	3,073	92%	2,159	1,965	91%	1,185	1,107	93%
WESTBURY	823	783	95%	597	557	93%	226	226	100%
CARLE PLACE	0	0	--%	0	0	--%	0	0	--%
MINEOLA	530	527	99%	222	222	100%	308	304	99%
MERILLON AVE	140	128	91%	105	103	98%	35	25	71%
NEW HYDE PARK	584	510	87%	584	510	87%	0	0	--%
Branch Total	14,908	13,911	93%	7,070	6,580	93%	7,838	7,331	94%

↑-OYSTER BAY ↓-RONKONKOMA ↔-Loading Report (Space)-Branch List

FIGURE 6 Sample RailRider branch parking report.

The practical benefit of the report generator lies in the fact that a user can produce a forecast and examine some of the "top-line" results on the screen, and then return to that forecast several days (or weeks or months) later and generate more detailed reports. Even if the input files used to generate the forecast have been edited or deleted, the complete forecast results are still accessible.

RailRider also generates graphic output of forecast results, showing bar charts of demand-by-access mode at each station along each branch. A reproduction of the RailRider graphic display appears in Figure 7.

RailRider User Interface

The RailRider software is designed with a sophisticated user interface that simplifies the use of the various program modules. The entire system is menu driven, with on-screen menus and prompts to help the user select an appropriate course of action. All user keystrokes are automatically screened to prevent illegal entries, and all numeric inputs are checked to ensure that they are within a valid numeric range.

RailRider has an integrated, context-sensitive Help facility, similar to that provided in many microcomputer software products. At any point in the program, pressing the Help key

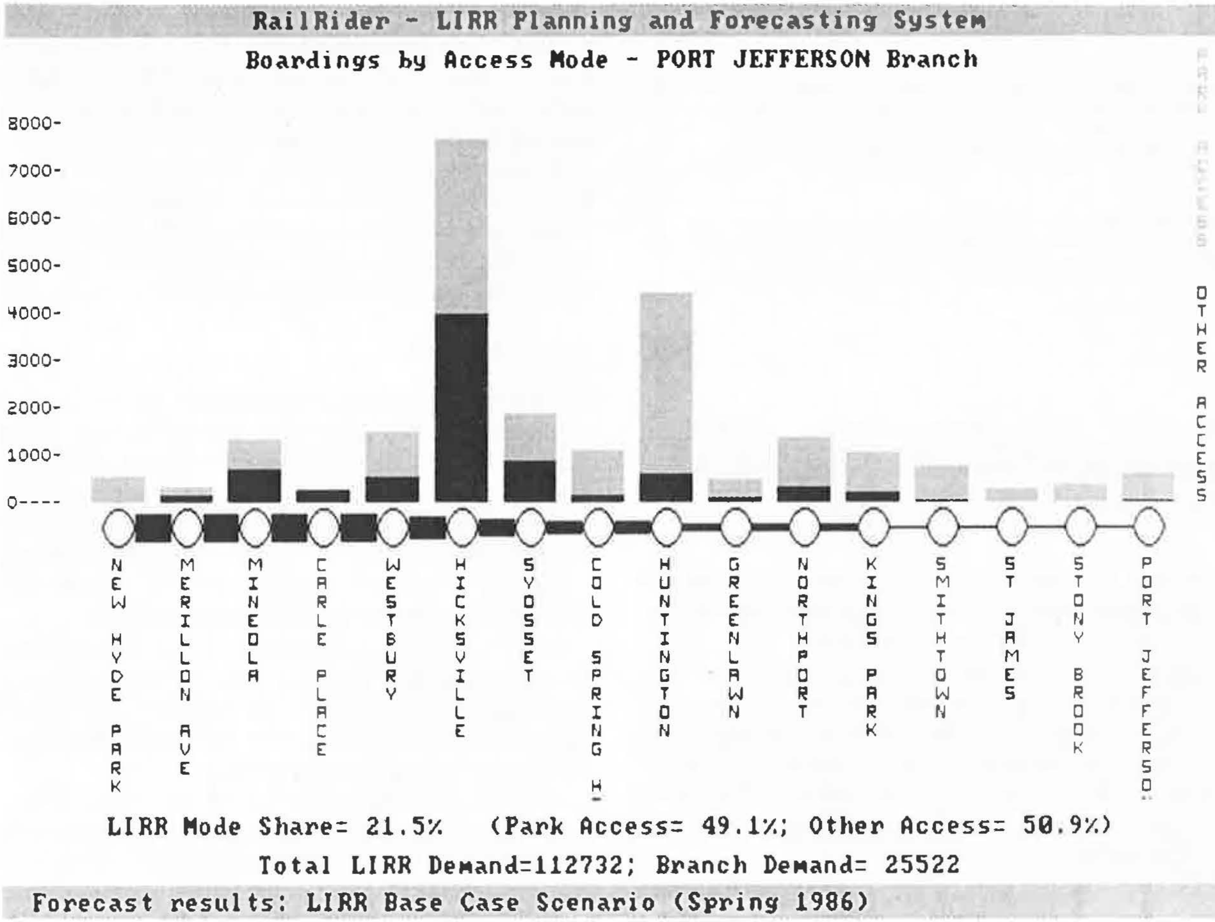

FIGURE 7 Sample RailRider graphic display.

accesses the on-line Help Manual, which contains over 50 screens of information on how to use the RailRider system. The on-line Help facility can be used, for example, while editing a file to clarify the definition of a particular data file, or while in the report generator to remind the user of the contents of a particular type of report. Shown in Figures 8 and 9 are various screens from the RailRider help system.

Because of this advanced interface, model users do not need to have extensive microcomputer experience to use the RailRider forecasting models, although rudimentary familiarity with MS-DOS and the microcomputer keyboard can be helpful.

Using RailRider

The RailRider forecasting software produces demand forecasts based on a particular scenario, which consists of a designated set of seven input files. These files are as follows:

- Fare zone files, which contain monthly ticket prices in each fare zone;
- Branch files, which provide information about service on LIRR branches;
- Station files, which provide information about the characteristics of individual stations;
- Parking lot files, which contain data on parking capacities, restrictions, and prices;
- Local service files, which indicate local service connections on each branch;
- Express service files, which indicate skip-stop, express, or flyer connections between nonadjacent stations; and
- Demand files, which contain information on the total size of the Long Island to New York travel market.

There may be several files of each of these types available to the user. For example, there may be a base fare file and two

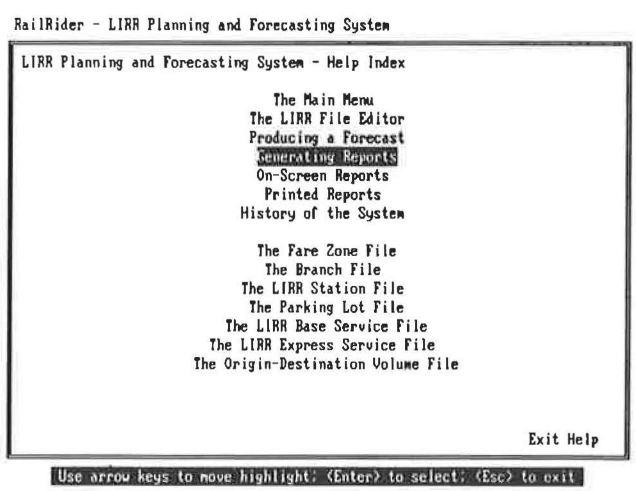

FIGURE 8 RailRider on-line help index.

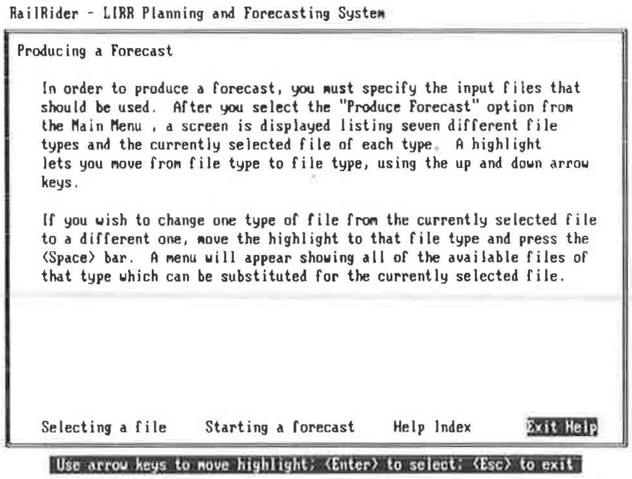

FIGURE 9 Sample RailRider help screen.

other fare files that represent fare increases of 3.5 and 7.0 percent. Additional input files of each type can be created by the user using the RailRider file editor module.

To create a scenario, the user must specify one file of each type to be used as input to the model. Because the input files can be used in a variety of combinations, a large number of scenarios can be generated from a limited number of input file types. With two files of each type, for example, 93 different scenarios can be created by mixing and matching the files in all their possible combinations.

After the user specifies a single file of each type, RailRider processes the input files, generates the appropriate internal representation of the network, produces the demand forecast, and creates the output file. All of these actions are performed automatically, without requiring user intervention.

After a forecast is complete, the user has complete freedom to access the results using only the RailRider report generator module.

TESTING AND APPLICATION OF RAILRIDER

Test runs of the RailRider model in its final calibrated form provide substantial evidence that the model performs well. It yields results that are consistent with expectations and external measurements. The fare elasticity exhibited by the model is between −0.13 and −0.18, depending on the level of fare change. These values are consistent with previous measurements. The model exhibits a travel time elasticity of −0.20 for changes of 10 percent or less. This is lower than normal for the transit industry but reasonable based on the LIRR's large mode share and the relatively long travel times experienced by Long Island commuters.

To test the capabilities of the RailRider model, forecasts were developed for 15 different scenarios specified by the LIRR. Most of these were hypothetical and did not represent actual service changes currently being considered by the LIRR. One of these scenarios, however, was a simulation of the electrification of the LIRR's Main Line, an ongoing capital improvement project scheduled for completion in the fall of 1987. Application of the RailRider model to this major system change was considered a critical test of the model's ability to produce reasonable, consistent, and internally valid forecasts of demand. Under this and all other tests, the RailRider model produced forecasts that were consistent with prior expectations and rational in light of the LIRR's understanding of the composition and behavioral characteristics of its ridership.

External validation, however, is a much more appropriate test for a forecasting model. The ongoing capital program projects and related changes to the LIRR system will in the future provide ample opportunity to validate the RailRider model forecasts against real-world behavior.

CONCLUSIONS

The RailRider forecasting model breaks ground in the implementation of a new generation of travel-demand forecasting procedures based on theoretical advances of the last decade. From a methodological perspective, the project demonstrates the feasibility of applying demand models within a stochastic user equilibrium framework to a problem of sufficient scale and complexity to warrant consideration of this approach for solving significant transportation planning problems.

Based on experience in this project, very different and inherently more plausible forecasts come from a modeling framework that deals explicitly with capacity constraints, flow-dependent costs, and supply-demand equilibration than from traditional four-step planning models.

The computer implementation of the model differs from other urban transportation planning models in that whereas the model itself is more complicated, the forecasting system is easier to use, largely because the software was customized for the LIRR system. Although the conceptual approach is transferable and could be applied to other urban transportation properties, the network structure and the behavioral models that are embedded in the model are specific to the LIRR. As a result, the model does not require a large amount of set-up work for a given application, and there is no need for specially trained analysts who are familiar with the arcane set-up procedures of the Urban Transportation Planning System (UTPS) and similar packages.

Significant automation and simplification of the application process was an essential design goal of the project that is believed have been successfully achieved. It is hoped that, through the on-line Help system, the automatic error checking, and the network builder, RailRider will have made progress in reducing or eliminating user errors in the forecasting process.

A concern at the outset of the project was the size of the network equilibrium problem that could be solved on a microcomputer within reasonable running time. Although RailRider strains the limits of current microcomputer performance, taking an hour to run on a fast microcomputer, the performance is still more than competitive with mainframe models, and the microcomputer implementation permits the use of many sophisticated software features that would not otherwise be possible. Also, the continuing speed increases available in low-cost hardware suggest that current limitations on problem size and performance will be short-lived.

Further development activities could increase still more the accuracy and usefulness of RailRider. Better base ridership data could support improved model calibration. Integration of the model with ticket type of choice models would yield a more flexible forecasting capability. Finally, a more explicit representation of alternative commutation modes and incorporation of a more sophisticated mode choice model would improve the quality of the forecasts and expand the capabilities of the model to determine the impact on the LIRR of changes in service or capacity on competing modes.

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Development of a Rail Station Choice Model for NJ TRANSIT

CHERYL ROSEN KASTRENAKES

NJ TRANSIT sought to develop a rail station choice model that would allow the agency to forecast rail ridership to specific stations. This ability would give NJ TRANSIT the opportunity to define its markets as narrowly as possible so that it could best respond to the escalating travel demand occurring in the region. The end result of running the station choice model would be a new boarding-point distribution for each town that would result from either changes in policy variables affecting a given station or from the addition or deletion of stations in a town's "choice set" of stations. A multinomial logit model provided the appropriate framework for analyzing and predicting the station choices of rail users. A data base was created that included each municipality boarding-point pair found in the 1983 ridership origin-destination survey conducted by NJ TRANSIT, the share of riders from each town to each station, and some 20 service and demographic variables. The results of the analysis indicate that station choice is most influenced by the presence of a station in the passenger's town. Access time to the station exerts the next largest influence, followed closely by the frequency of service during the peak hour. Peak travel time and fare on the commuter railroad combined into a generalized cost variable were also significant in determining station choice, but had the smallest effect.

NJ TRANSIT, operator of all commuter rail service and substantial local and commuter express bus services in New Jersey, has been confronted with rapidly escalating travel demand. This increase is caused by sustained and continuing population growth in New Jersey coupled with job growth in Manhattan, a major destination for New Jersey office workers. The mounting pressure this growth has caused on area roads, rail lines, and bus routes suggests the need for careful planning to extend and expand transit services around the state as a means of capturing new travelers, reducing traffic congestion, and supporting the state's economic expansion and vitality.

In response to this challenge, NJ TRANSIT, in partnership with the Port Authority of New York and New Jersey and the New Jersey Department of Transportation, has undertaken a number of studies aimed at identifying the costs and benefits associated with a variety of transit improvements and park-ride expansions (*1*). The key to this work is the analysis of the probable market response to these improvements; that is, shifts of travelers from automobile to transit and among transit modes in relation to the cost of the improvements and how easy they are to implement. Given the large expense associated with even small improvements in commuter rail services, proposals must be critically analyzed to determine whether riders would enjoy a net gain and how they might redistribute themselves among modes, rail lines, and boarding stations in response to new services. NJ TRANSIT needed tools to help predict these responses for the following three types of rail service improvements:

1. New services on existing lines,
2. Extensions of existing lines or construction of new lines in areas not now receiving commuter rail service, and
3. The creation of new stations on overcrowded lines.

Although intuitive analysis of current travel behavior may help predict the impact of such improvements, NJ TRANSIT determined that, given the scope of the projects under consideration, the volatility of New Jersey population growth and travel markets, and the need for a highly structured and objective evaluation process, a statistically valid set of predictive models would provide the only reasonable means of generating traveler response to system changes and subsequent cost performance of project options. Only with such models could reliable estimates of the comparative market value of different projects and their overall cost-effectiveness be understood.

To provide for this market analysis, a mode-shift model was developed that projects traveler response to changes in travel cost, time, or transfers among modes competing in defined corridors. This model helps planners understand the likely mode-shift consequences of a particular rail or bus service improvement.

To drive the mode-split model, however, planners must determine how travelers originating in an area would distribute themselves among boarding stations under the service option to be tested. To mechanically determine this boarding-point distribution for rail system service changes, NJ TRANSIT decided to develop a "station choice" model. This model would incorporate, as appropriate, those factors that determine rail station choice and would provide a means of redistributing travelers, given the proposal for new services available in specified corridors. For example, if travel time from a particular station is reduced, then the number of people using the station will most likely increase. Likewise, if greater frequency is provided from one station than from another, more people will use that station, all else being equal.

Described in this paper is the development of the station choice model, and some insight is given into its value in designing new services that will strengthen transit in New Jersey in support of ongoing growth and development.

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BACKGROUND

NJ TRANSIT's overall modeling project has entailed determining (a) what factors relate to travelers' choice of mode, and (b) when travelers choose rail, how they choose among boarding stations. With this information, NJ TRANSIT has developed predictive models with which to forecast the likely redistribution of travelers, first among modes and second among boarding stations for rail riders. In many cases, the factors affecting choice among modes and among stations have proven similar; however, the macro- versus micro-scale focus of a corridor-level mode-shift model and a local station choice model required that these factors be accorded different weights in the two applications and that some factors be included in one model that are not material to the other.

The end result of running the station choice model is a new boarding-point distribution for each town supplying riders to the rail system (see Figure 1). This distribution is used as both an input to the mode split model and to apportion the mode-split model's output to generate final boarding-point loadings. The station choice model is run to determine the likely percentage distribution of a body of riders generated at the municipality level among those stations that make up the likely set of boarding-point options for those riders. Presumably, as conditions among competing boarding points change, relative appeal changes as well, and riders "vote with their feet" for the better boarding point. The station choice model predicts only the share of riders from an origin point that will use each station in the choice set, not the absolute number of riders that can be handled.

The new shares calculated from the station choice model are used to change the weights of critical variables in the mode choice model—travel time, number of transfers required en route, and travel cost. After the mode choice model has produced the new ridership for each mode that results from these changes, the station choice model input can be used at the output side of the calculation to apportion these travelers back to the boarding points as actual station loadings (see Figure 2). This information in turn can be translated into parking demands, park-ride requirements, platform and corridor pedestrian flows, and, finally, capital (and perhaps operating) costs of the service improvement.

With the ability to forecast ridership at the station level, NJ TRANSIT will be able to fine tune its park-ride program, station rehabilitation program, and operating schedules. Without a station choice model, the decision of how to weight the variables in the mode choice model when testing changes to the system would be left to planning judgment. The model will drastically reduce the time that would otherwise be needed to determine rider distribution and offer a consistent statistical basis to the process. Together, the two models are critical to NJ TRANSIT's ability to objectively appraise the market and cost potential of key transit system proposals: the Kearny Connection, Secaucus Transfer/Connection, West Shore Railroad, Monmouth/Middlesex/Ocean rail and bus options and others (see Figure 3).

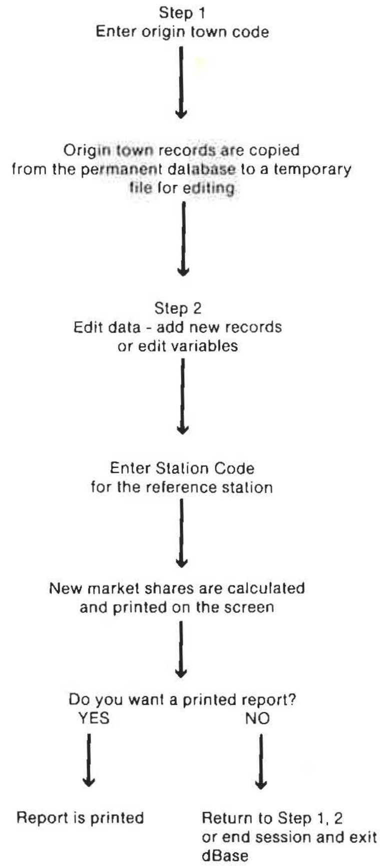

FIGURE 1 Station choice model flowchart.

QUANTITATIVE THEORY

A multinomial logit model provided the appropriate framework for analyzing and predicting the station choices of rail users (2). The standard form of the multinomial logit model is

$$S_i = e^{U_i} \Big/ \sum_{j=1}^{J} e^{U_j}$$

where

S_i = the share of rail users from a given minor civil division (MCD) who board at station i;
U_i = the utility associated with the use of station i by rail users from that MCD. Utility is expressed as a linear function of level-of-service variables; and
J = the number of stations used by rail riders from that MCD.

Because of the availability of regression software for the microcomputer, the logit model was transformed into a form that was linear in parameters and was developed as a regression equation.

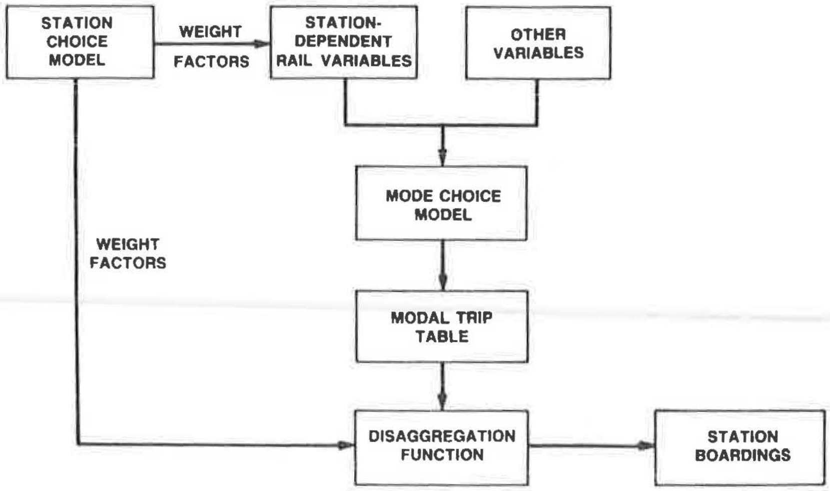

FIGURE 2 Station choice/mode choice flowchart.

VARIABLES AND RESULTS

In 1983, NJ TRANSIT conducted an origin and destination survey of riders on each of its nine commuter rail lines. More than 45,000 survey questionnaires were distributed to 67,000 rail passengers. A total of 26,000 usable surveys were returned, yielding a 58 percent response rate (39 percent of passengers) (*3*). The origin–boarding-point information for this work was obtained from the following questions contained in the survey:

1. Where did you travel from just prior to boarding this train?
2. Is this your residence? Yes or No—I live at ______; and
3. At what station did you board this train?

A data base was created that included each of the municipality–boarding-point pairs found in the 1983 rail survey, the share of riders from each town to each station, and some 20 service and demographic variables.

The variables tested for value in the regression equation included: average access distance, average access time, fare, line-haul distance, density, median household income, transfers, parking availability, parking fees, peak frequency, peak travel time, station location, speed, and cost.

After running regressions with different variable combinations, many of these variables were found to be noncontrolling of rail riders' station choice. The variables that were found to influence station choice were: whether the station was "residential" (i.e., local to the residents selecting it), the access time required to reach the station from the origin municipality, the frequency of rail service from the boarding point, and a generalized cost of the trip from that point. Including these variables as appropriate to their relative strength in driving station choice behavior, the final equation for station choice decisions is

$$\log (S_s/S_r) = 1.5 (\text{res}_s - \text{res}_r) - .027(t_s - t_r) + .383(f_s - f_r) - .005(C_s - C_r)$$

where S_s is the share of rail users from a given MCD who board at the subject station, and S_r is the share of rail users from a given MCD who board at the reference station. The reference station is always the station that receives the smallest share of riders from a given MCD.

The variables driving station choice derived from the regression, in order of importance, are

res = A dummy variable indicating whether a given station is located in a given MCD and acts as a local station in terms of its proximity to the majority of boarders. 1 = Yes, 0 = No;

t = The access time from the origin MCD to the station. Access time was determined by measuring the shortest route from the center of the residential section of the town to the rail station and converting the distance into time;

f = The frequency of service, trains per hour during the morning peak period; and

c = A generalized cost variable calculated as

Fare + (peak travel time/60 × $8.01)

where $8.01 is one-half of the average hourly wage rate. The empirical work for the model is summarized in Table 1.

The results of the regression analysis indicate that station choice is most influenced by the presence of a station in the passenger's town. The lack of correlation between the local station variable and access time highlights the importance of nonquantitative factors in station choice. This variable seems to capture such intangibles as greater awareness of the services available in the passenger's town and perceived security and knowledge of available parking sites. Access time to the station exerts the next largest influence, followed closely by the frequency of service during the peak hour. The generalized cost variable is also significant in determining station choice but has the smallest effect. Peak travel time and fare were highly correlated and could not be used separately in the equation. The variables were also stronger combined in the cost variable than either was independently.

APPLICATIONS

The following material gives some evidence of the station choice model's use to NJ TRANSIT. NJ TRANSIT is, as part

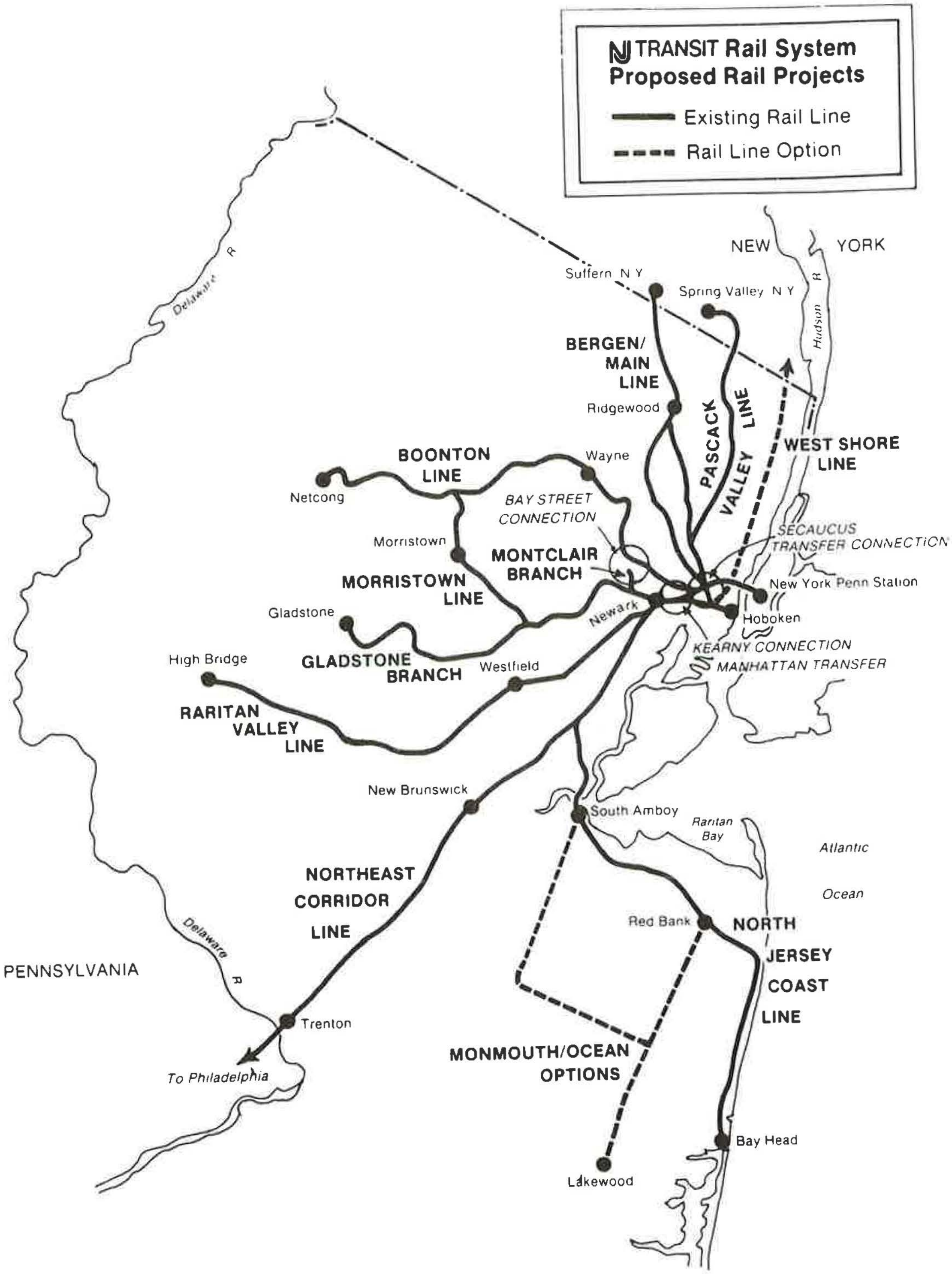

FIGURE 3 Proposed rail projects.

of its overall planning agenda, contemplating the creation of new commuter rail services on branch freight lines that meet current passenger rail lines now in service. One such option in Middlesex County would place new commuter rail service to Newark and Manhattan in an area now served only by buses subject to substantial traffic congestion. Positioned roughly midway between two existing commuter rail services, it is anticipated that the new service will both open up new rail markets and siphon some riders away from each of the parallel routes.

The station choice model was used to test this latter effect as a means of preparing input for the mode choice model and for understanding how travelers might be redistributed if the new service were introduced.

TABLE 1 STATION-CHOICE EQUATION

	Res	Access Time	Frequency	Cost	R^2	F
Parameter estimate	1.5	−.027	.383	−.005	.325	86.6
Standardized estimate	.8	−.493	.434	−.165		
Probability T	.0001	.0001	.0001	.0175		

The results are given in Table 2. The place tested was East Brunswick, a heavily populated town in the center of a major commuter area.

The second column in the table lists the stations that are now used now by East Brunswick commuters and those likely to be used with the introduction of the new rail service. As can be seen by a review of the table, the majority of rail riders originating in East Brunswick (51 percent) use the New Brunswick station to board existing rail services, with lesser proportions using Metropark (16 percent), Metuchen (12 percent), Jersey Avenue (12 percent), and South Amboy (8 percent)—stations located further away. Note that the New Brunswick station is not a resident station but offers the shortest access time from East Brunswick of any of its competitors.

The column Market Share indicates these percentages, with zero as the percentage of East Brunswick rail riders boarding at the three stations that do not currently exist. These other stations are included because they will become available only with the introduction of new rail service and do not exist now.

The last column in the printout, Projected Share, gives the redistribution of East Brunswick rail riders likely to occur with the introduction of new rail service. As can be seen, the new service would not exert a major influence on East Brunswick and would do little to relieve New Brunswick. Because none of the new stations would be local for East Brunswick residents, and none of the existing stations are local, only access time, travel time, and service frequency exert any influence. With New Brunswick still the station with the shortest access time from East Brunswick, it still draws the majority of East Brunswick riders: 42 percent, with the three new stations—Route 18, Cheesequake, and South Brunswick skimming only a handful of the riders from each of the existing stations.

Equivalent tests for each of the municipalities likely to be affected by the new rail service gave widely varying results, depending on the influence of town proximity to the station—the res or local station variable, access time, and the other variables noted previously. The combined weighted average of these township station assignments form the input by which the relative appeal of the new rail service in drawing riders from bus and automobile can be determined by the mode choice model. The station choice model outputs listed in Table 2 are then used to reassign this predicted mode shift back to the station boarding point to guide park-ride analysis and final project costing.

CONCLUSION

The aim of this work has been to determine which factors most influence station choice and to develop a model from these results. The variables with the strongest influence were the presence of a station in the rider's town, access time, peak frequency and travel time, and fare combined into a generalized cost variable.

Unfortunately, some variables that may have proved important were difficult to work with and had to be dropped from the analysis. Parking fee and parking availability are two examples. Parking fee was a significant variable but the coefficient had a positive sign. This implied that as parking fees increase at a station, so would the desire to choose that station. This result is counterintuitive and would distort the model's predictive capabilities. The higher parking fees do not create the demand. In reality, the higher fees are created as a result of a combination of factors that include: (a) high demand for the station because of good service or easy access, or both; (b) a scarcity of parking alternatives or available land to develop parking on the rail system; (c) a heavily congested, and therefore inconvenient, highway system throughout much of the state as NJ TRANSIT's alternative; and (d) high household incomes among the majority of NJ TRANSIT's rail passengers. The same type of situation occurred with the parking-availability variable, where lack of parking availability is because many travelers board there rather than that the lack of parking results in travelers choosing the station.

The results imply that NJ TRANSIT needs to be aware of and responsive to people's need for convenience in their desire both to be near a station and to have frequent service. These results confirm most transportation studies in that a unit of access time and wait time are considered more important to

TABLE 2 STATION CHOICE REPORT

NJ Transit Code	Town	Station Code	Station	Market Share Actual	Market Share Projected
23020	East Brunswick	17	South Amboy	8	6
23020	East Brunswick	903	Jersey Ave.	12	10
23020	East Brunswick	906	Metuchen	12	10
23020	East Brunswick	907	Metropark	16	13
23020	East Brunswick	904	New Brunswick	51	42
23020	East Brunswick	981	Route 18	0	7
23020	East Brunswick	980	Cheesequake	0	6
23020	East Brunswick	913	South Brunswick	0	5

riders than a unit of in-vehicle line-haul time. It should not be inferred, however, that only local rail stations can be successful. It has been proven on the NJ TRANSIT rail system that stations with easy highway access, high quality service, and abundant parking can be successful regional rail stations.

ACKNOWLEDGMENTS

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Characteristics of Metro Networks and Methodology for Their Evaluation

ANTONIO MUSSO AND VUKAN R. VUCHIC

Presented in this paper are the results of research on metro (rapid transit) networks, focusing on their geometric characteristics. The object is to define the most important measures, indicators, and characteristics of geometric forms that can improve the present predominantly empirical methods used in metro network planning and analysis. Several measures of metro network size and form, including length, number of lines, and stations, which express the extensiveness of the system, are selected; they are also needed for derivations of various indicators. A number of selected indicators are then presented. These represent the most effective tool for network comparison because most of them are independent of network size. Several indicators relating metro network to the city size and population express the degree of adequacy of the network to meet the city's needs. Based on experiences from a number of metro systems, characteristics of different types of lines (radial, diametrical, circumferential, and other) are defined. These allow evaluation of network types, such as radial-circumferential versus grid networks. An analysis of metro networks in 10 different cities is presented to illustrate the applications of theoretical and empirical materials; several basic measures and indicators of these networks have been computed and analyzed. The scope of quantitative elements, analyses of types of lines, and descriptions of networks are limited because of space constraints, but they illustrate the methodology that can be used, in a more comprehensive way, for a number of different analyses of metro networks, their designs, or their extensions.

The planning of metro (rapid transit) networks is usually predominantly empirical. Consideration of local conditions, such as demand characteristics, existence of transportation corridors, requirements for certain station locations, and so on, tend to suppress the analyses of network topology and geometric characteristics. However, even though designers of metro lines and networks may want to use some design guidelines, to perform comparative analyses or to make use of experiences from network operations in other cities, very few of these can be found in the professional literature.

Because of the high cost of metro construction and the permanence of its facilities, it is important to design optimal networks with respect to service for passengers, efficiency of operation, and relationship of the metro system to the city. This is a complex task and it deserves more attention than it has received until now. An attempt is made in this study to provide materials that may assist in the planning and design of metro system networks, lines, and stations.

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PURPOSE, ORGANIZATION, AND SCOPE

Presented in this paper is a systematic set of quantitative elements that defines the network characteristics of metro systems that can be used for their description, evaluation, and comparative analysis. Examples of such evaluations include planning of new or analysis of existing networks, their comparison with networks of other cities, and comparison of alternative network extensions.

The quantitative elements are grouped into five general categories, as follows:

1. Measures of network size and form,
2. Indicators of network topology,
3. Measures of relationship between network and city,
4. Quantity and quality of offered service, and
5. Measures of service use.

The sections covering these five categories are followed by a description of the basic forms of metro lines and their characteristics. Finally, an application of these measures to metro networks in 10 cities is given using many of the elements defined previously.

Many different aspects of metro networks can be analyzed; the emphasis here is on the geometric form and the method of operation of transit lines and networks; that is, on categories 1–3 listed. Categories 4 and 5 are given only as a guideline for analysis focusing on service quality and efficiency of operations.

In this paper, theoretical concepts are selectively used, particularly from graph theory (*1*), focusing on those with practical relevance to actual metro network planning. The paper is also based on experiences from many cities on metro network design, service, and operating characteristics.

As already mentioned, the data needed for network planning and analysis vary with the purpose of the analysis and local conditions in the city studied. The data used for the indicators and analyses presented in this paper are listed in Table 1.

MEASURES AND INDICATORS OF METRO NETWORKS

Network Size and Form

The main elements that express the size and form of a metro network are defined as follows. Corresponding terms from graph theory are given in parentheses.

TABLE 1 BASIC INFORMATION NEEDED FOR METRO NETWORK ANALYSIS

Number	Item	Symbol	Dimension
1	Population of the served area	P	Persons
2	Surface of the served area	S_u	km^2
3	Vehicle-km operated per day	W	veh-km
4	Vehicle or car capacity	C_v	Spaces/veh
5	Vehicles per train [transit unit (TU)]	n_{TU}	veh/TU
6	Operating speed	V_o	km/h
7	Frequency of service	f	TU/h
8	Number of metro passengers per day	P_{ad}	Persons/day
9	Number of metro passengers per year	P_{ay}	Persons/year
10	Average trip length	$\bar{l}p$	km
11	Number of total transit passengers per day	P_t	Persons/day
12	Number of stations on the network	N	Stations
13	Number of stations with park-and-ride	N_p	Stations
14	Schematic map of network with stations	—	—
15	Number of lines and their lengths	n_l, l_i	–, km

a-1 *Number of stations (nodes) on a line i, n_i.*

a-2 *Number of interstation spacings (arcs) on a line i, a_i,* is related to n as follows:

$$a_i = n_i - 1 \quad (1)$$

a-3 *Length of line i, l_i.*

a-4 *Number of multiple stations (jointly used by two or more lines), n_m^k, and lengths of double sections, l_m^k,* in which k designates the number of lines using a station or a spacing. These superscripts must be introduced to avoid double counting in computations of the number of stations, spacings, and origin-destination (OD) pairs. For these computations the number of stations, n_m^k, must be computed as 1 less than the number of lines it serves (i.e., as $k - 1$, while the number of multiple spacings, a_m^k, and their lengths, l_m^k, are used as given). This will be illustrated on cases following *a*-6, *a*-7, and *a*-8.

a-5 *Number of lines in a network, n_l.*

a-6 *Number of stations in a network, N,* is computed as the sum of stations on individual lines minus the multiple stations as follows:

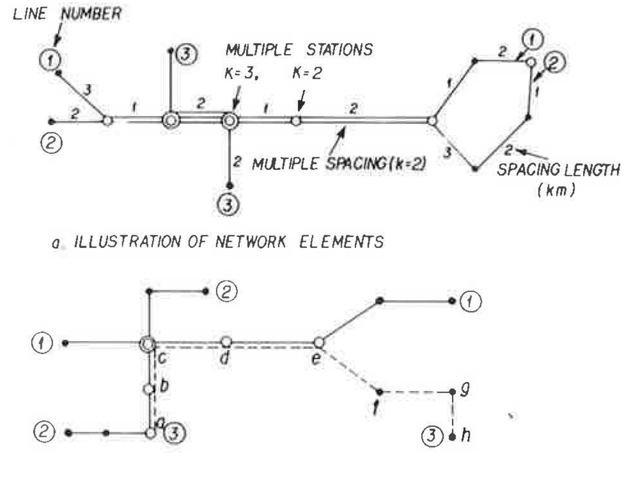
$$N = \sum_{i=1}^{n_i} n_i - \sum_{k=2}^{k_{max}} (k-1) \times n_m^k \quad (2)$$

For example, the network in Figure 1*a* consists of three lines with 8, 9, and 4 stations, respectively:

$n_m^2 = 4$ and $n_m^3 = 2$

thus, the total number of stations (single and multiple) in the network is

$N = 8 + 9 + 4 - (1 \times 4 + 2 \times 2) = 13$ stations



b ELEMENTS FOR COMPUTATION OF OD VALUES

FIGURE 1 Network schematics.

a-7 *Number of station spacings in a network, A,* is computed as the sum of spacings on individual lines minus the multiple spacings, as explained under *a*-4:

$$A = \sum_{i=1}^{n_l} a_i - \sum_{k=2}^{k_{max}} k \times a_m^k \quad (3)$$

This number can also be computed via N:

$$A = N - 1 + C_r \quad (4)$$

where C_r is the number of closed circles in the network. In the case illustrated in Figure 1*a*, the number of spacings (including single and multiple) computed by line is

$A = 7 + 8 + 3 - (1 \times 3 + 2 \times 1) = 13$ spacings

Alternatively, using the number of stations (Equation 4), the number of spacings is

$A = 13 - 1 + 1 = 13$ spacings

a-8 *Length of network, L,* is the sum of line lengths minus the multiple spacings:

$$L = \sum_{i=1}^{n_l} l_i - \sum_{k=2}^{k_{max}} (k-1) \times l_m^k \quad (5)$$

Using the example from Figure 1*a*:

$L = 12 + 14 + 5 - (1 \times 1 + 2 \times 2 + 1 \times 1 + 1 \times 2) = 23$ km

a-9 *Number of circles in a network, C_r.* The number of circles in a network can be computed by Equation 4 as:

$$C_r = A - N + 1 \quad (6)$$

The range of C_r values is $0 < C_r < 2N - 5$.

a-10 *Number of station-to-station travel paths, OD,* consists of direct paths, OD_d, and paths that include one or more transfers, OD_t. In a network with N stations, the number of all possible OD paths is

$$OD = N(N-1)/2 \quad (7)$$

For a line with i stations, the number of OD paths is

$$OD_i = n_i(n_i - 1)/2 \quad (8)$$

and all of them are direct. The total number of direct paths in a network is equal to the sum of OD paths along each line and along each single branch plus the paths on overlapping lines (i.e., those serving jointly sections of different lines):

$$OD_d = \frac{1}{2}\sum_{i=1}^{n_l} n_i(n_i - 1) + \sum_{j=1}^{n_l} n_{mj} \times n_{bj} \quad (9)$$

where

- n_m = the number of joint stations that the "double" line shares with the already counted "basic" line,
- n_b = the number of stations on the branches (single sections) of that line, and
- n_d = the number of lines with joint sections with other lines.

These additional direct OD paths must actually be computed among all line sections that such lines connect. The number of paths that require transfers, OD_t, is computed as the difference between all paths and direct paths:

$$OD_t = OD - OD_d = \frac{1}{2}\left[N(N-1) - \sum_{i=1}^{n_l} n_i(n_i - 1)\right] - \sum_{j=1}^{n_l} n_{mj} \times n_{bj} \quad (10)$$

An example for illustration of the computations of OD values is given in Figure 1*b*. The network shown by solid lines consists of two lines with one joint (transfer) station. Line 1 has 6, and Line 2 has 7 stations. To compute OD values, Equations 2, 7, and the first member of Equation 9 are used:

$N = 6 + 7 - 1 \times 1 = 12$ stations

$OD = \frac{1}{2} \times 12(12 - 1) = 66$ paths

$OD_d = \frac{1}{2}[6(6-1) + 7(7-1)] = 36$ paths

$OD_t = 66 - 36 = 30$ paths

If Line 3, with 8 stations (shown by dashes), is added to this network, the numbers change as follows:

$N = 6 + 7 + 8 - (4 \times 1 + 1 \times 2) = 15$ stations

$OD = \frac{1}{2} \times 15(15 - 1) = 105$ paths

The computation of OD_d now becomes more complex. The first sum in Equation 9 is:

$$(\tfrac{1}{2})\sum_{i=1}^{n_l} n_i(n_i - 1) = (\tfrac{1}{2}) \times (6 \times 5 + 7 \times 6 + 4 \times 3) = 42 \text{ paths}$$

the last member (4×3) representing the branch section *e–h*. The second sum from Equation 9 must include the additional paths between stations: *a–b* and *d–e* (2×2), *a–d* and *f–h* (4×3); thus,

$$\sum_{j=1}^{n_d} n_{mj} \times n_{bj} = 2 \times 2 + 4 \times 3 = 16 \text{ paths}$$

$OD_d = 42 + 16 = 58$ paths

$OD_t = OD - OD_d = 105 - 58 = 47$ paths

The 10 elements expressing size and form of metro network are listed in Table 2.

Network Topology

Various ratios of the previously defined measures of network size can be used as quantitative indicators of network topology. Those particularly useful in metro network planning and analysis are selected here.

b-1 *Average interstation spacing, S,* can be computed for a network as

$$\bar{S} = \frac{L}{N - n_l + \sum_{k=2}^{k_{max}} n_m^k} = \frac{L}{A} \quad (11)$$

Spacings between stations, $\bar{S}$, are usually selected as a compromise between good area coverage (short spacings) and high operating speed (long spacings). Therefore, longer lines tend to have longer spacings: regional rail networks [e.g., San Francisco Bay Area Rapid Transit (BART), and the Munich S-Bahn] have average spacings of 1000–2500 m, compared with the spacings of 500–800 m on typical urban metro systems such as those in Paris, Philadelphia, and Mexico (*2*).

b-2 *Line overlapping index, λ, is computed as*

$$\lambda = \frac{\sum_{i=1}^{n_l} l_i}{L} = 1 + \frac{\sum_{k=2}^{k_{max}} l_m^k}{L} \quad (12)$$

TABLE 2 METRO NETWORK MEASURES AND INDICATORS

Item code	Definition	Symbol	Equation	Range
Network Size and Form				
a-1	Number of stations on line i	n_i		
a-2	Number of interstation spacings (arcs) on line i	a_i	$n_i - i$	
a-3	Length of line i	ℓ_i		
a-4	Number of multiple stations, spacings and their lengths	n_m^k, a_m^k, ℓ_m^k		
a-5	Number of lines in network	n_ℓ		
a-6	Number of stations in network	N	$\sum_{i=1}^{n_\ell} n_i - \sum_{k=2}^{k_{max}} (k-1) n_m^k$	
a-7	Number of interstation spacings	A	$\sum_{i=1}^{n_\ell} a_i - \sum_{k=2}^{k_{max}} k \cdot a_m^k$	
a-8	Length of network	L	$\sum_{i=1}^{n_\ell} \ell_i - \sum_{k=2}^{k_{max}} (k-1) \ell_m^k$	
a-9	Number of circles	C_r	A-N+1	$0 \le C_r \le 2N-5$
a-10	Number of station-to-station	OD	$(1/2) \cdot N(N-1)$	
	travel paths: total - OD, direct	OD_d	$(1/2) \sum_{i=1}^{n_\ell} n_i \cdot (n_i - 1) + \sum_{j=1}^{n_d} n$	
	OD_d, with transfer - OD_t	OD_t	$OD - OD_d$	
Network Topology				
b-1	Average interstation spacing	$\bar{S}$	$\frac{L}{A}$	
b-2	Line overlapping	λ	$1 + \frac{\sum_{k=2}^{k_{max}} \ell_m^k}{L}$;	$\lambda \ge 1$
b-3	Circle availability	α_c	$\frac{C_r}{2N-5}$	$0 \le \alpha_c \le 1$
b-4	Network complexity	β	$\frac{A}{N}$	$\beta \ge 0.5$
b-5	Network connectivity	γ	$\frac{A}{3(N-2)}$;	$0.33 \le \gamma \le 1$ for N < 2
b-6	Directness of service	δ	$\frac{OD_d}{OD}$;	$\frac{2}{A+1} \le \delta \le 1$

Descriptively, this index is the ratio of the sum of line lengths to the network length. Therefore, a network consisting of independently operated lines (e.g., Leningrad, Mexico, or Toronto) has a value of 1.00. The more the lines are interconnected, sharing common sections with other lines and then branching, the greater is the value of λ.

Independent operation of lines is the simplest method from the operational point of view because there is no diverging or merging of trains and no mutual influence among lines (no transfer of delays). Operation of interconnected services (e.g., trunk lines with branches, overlapping routings among line sections, and so on), although more sensitive operationally, has the advantage that it offers more direct trips (without transfers) and, in some cases, allows a better "fitting" of offered capacity to demand, resulting in higher use of transportation work (train- or space-km).

Frequency is another element of service that is affected by the type of line operation. For a given required capacity of service, determined by passenger demand and level of offered service on a particular line section, an independently operated line has an *n* times greater frequency than that existing if the same section were served by *n* lines branching in different directions so that each passenger traveling beyond the joint section could take only every *n*th train.

b-3 *Circle availability*, α_c, represents the ratio of the number of circles (sections of lines making up the closed loops in the network) to the maximum number of circles that, theoretically, the network with the given number of nodes could have:

$$\alpha_c = \frac{C_r}{2N+5} = \frac{A-N+1}{2N-5} \tag{13}$$

The theoretical range of this indicator is $0 \leq \alpha_c \leq 1$. Open networks with lines radiating from the central trunk lines (e.g., Atlanta or Rome) have $\alpha_c = 0$. The greater α_c is, the more options passengers have to travel through the metro network: the complex Paris Metro network has the largest α_c indicator of all cities, 0.11.

b-4 *Network complexity indicator,* β, is the ratio of the number of spacings (arcs) and stations (nodes):

$$\beta = A/N;\ \beta \leq 0.5 \tag{14}$$

This indicator reflects complexity in terms of the number of interstations spacings (arcs) related to the stations (nodes) of the network. Its minimum value of 0.5 is obtained on an elementary line with two stations; as the line is extended, adding more stations and spacings, β asymptotically approaches 1. On closed networks with cross connections, β can exceed the value of 1.

b-5 *Network connectivity,* γ, represents the ratio of the number of arcs existing in a network and the maximum number that could exist for the available number of nodes:

$$\gamma = \frac{A}{3\,(N-2)};\ 0.33\ \gamma \geq 1, \text{ for } N \geq 2 \tag{15}$$

Similarly to the indicator β, the more connections among nodes in the network there are, the greater is the value of γ.

b-6 *Directness of service,* δ, is the indicator that reflects the proportion of OD paths that can be traveled without transfer:

$$\delta = \frac{\mathrm{OD}_d}{\mathrm{OD}_d + \mathrm{OD}_t} = \frac{OD_d}{\mathrm{OD}};\ 0 \geq \delta \geq 1 \tag{16}$$

For a single line, $\delta = 1$; for more complex networks, δ tends to decrease, but operation of interconnected lines increases it.

For an easy review, these indicators of topology are listed in Table 2 with their symbols, equations, and, where applicable, ranges of value.

In Table 3, eight different types of networks are given with their sizes and indicator values to illustrate their computations and the relative magnitudes of different network topologies. In all eight cases, network length is the same but other elements are changed one by one to show how each one of the changes in measure influences different indicators.

Case 1 is a single line with variable interstation spacing lengths and a longer $\overline{S}$ than the others. Case 2 is similar to Case 1, a single line, but with 12 equal spacings. The difference in *b*-1 also causes the changes in *b*-4 and *b*-5. In Case 3, the same network length is reorganized into three lines with one joint (transfer) station. Compared with Case 2, of all the indicators only *b*-6 changes. Case 4 is of the same network as Case 3, but with lines staggered to divide a single triple station into three double stations; also, a circle is created. Case 5, with four lines intersecting at four points, changes only *b*-6. Cases 6 and 7 have the same network topology but have different line operations: in Case 6 there is one line with a "feeder;" in Case 7 there are 2 lines, each connecting the trunk with a branch. The differences are reflected in indicator λ (*b*-2) and in δ (*b*-6). Finally, Case 8 is of the same network as Case 4 but has line overlaps on the entire network; λ (*b*-2) is doubled and δ (*b*-6) is increased, reflecting a greater portion of travel paths without transfers. It should be noted, however, that this increase in direct service is traded for decreased frequency of service on each line. If one branch requires a service frequency of 12 trains/hr, or headways of 5 min, for example, operation from Case 4 will offer such headways; whereas Case 8 will offer only a 15-min headway for each line.

These cases provide a clear illustration of various influences on indicators. In real-world cases much larger differences exist, so that greater variations among network indicators can be found.

Application to Network Analysis

An example of an application of the measures previously presented to an actual metro system is given as follows. In 1980, the Washington Metropolitan Area Transit Authority (Metro) network consisted of three lines: red, blue, and orange, the latter two with substantial joint section; when completed, the network will consist of five lines.

Using the first three lines (in their final full length) as an example, the question can be asked: What additions to the network will be obtained by the construction of the fourth and fifth lines, which will be operated as the yellow and green lines, with a joint section between the two and a joint section between the blue and yellow lines?

Shown in Figure 2 is the initial network of red, blue, and orange lines, with the additional yellow and green lines indicated by dashes. The elements and indicators (from *a* and *b* categories) that change with this addition (given in Table 4) show that the number of stations increases by 30 percent and the network length increases by 41 percent. Because of the interconnections among lines, however, network complexity increases even more substantially: whereas the old network had no circles, the new one has three and the number of OD pairs increases by 70 percent. Most topology indicators, expressing network complexity (*b*-2 through *b*-5), also increase, reflecting a more complete network with more diversified services.

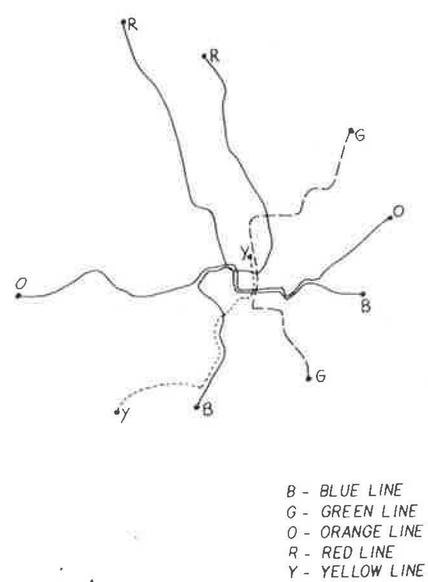


FIGURE 2 Washington Metro network without and with Yellow and Green lines.

TABLE 3 DIFFERENT NETWORK TOPOLOGIES, SHOWING THEIR MEASURES AND INDICATORS

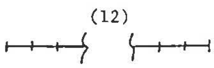
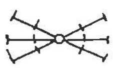
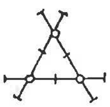
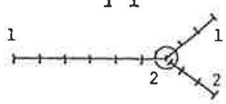
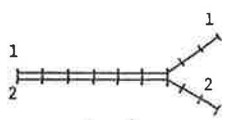
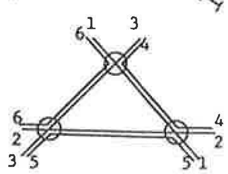
No.	Topology	a-1 n_i	a-2 a_i	a-3 ℓ_i	a-4 n^k_m, a^k_m, ℓ^k_m	a-5 n_ℓ	a-6 N	a-7 A	a-8 L	a-9 C_r	a-10 OD, OD_d, OD_t	b-1 $\bar{S}$	b-2 λ	b-3 α	b-4 β	b-5 γ	b-6 δ
1		4	3	12	0 0 0	1	4	3	12	0	6 6 0	4	1.0	0	0.75	0.50	1.00
2		13	12	12	0 0 0	3	13	12	12	0	78 78 0	1	1.0	0	0.92	0.36	1.00
3		5 5 5	4 4 4	4 4 4	1 0 0	3	13	12	12	0	78 30 48	1	1.0	0	0.92	0.36	0.38
4		5 5 5	4 4 4	4 4 4	3 0 0	3	12	12	12	1	66 30 36	1	1.0	0.05	1.00	0.40	0.45
5		4 4 4 4	3 3 3 3	3 3 3 3	4 0 0	4	12	12	12	1	66 24 42	1	1.0	0.05	1.00	0.40	0.36
6		10 4	9 3	9 3	1 0 0	2	13	12	12	0	78 51 27	1	1.0	0	0.92	0.36	0.65
7		10 10	9 9	9 9	7 6 6	2	13	12	12	0	78 69 9	1	1.5	0	0.92	0.36	0.88
8		5 5 5 5 5 5	4 4 4 4 4 4	4 4 4 4 4 4	18 12 12	6	12	12	12	1	66 45 21	1	2.0	0.05	1.00	0.40	0.68

TABLE 4 WASHINGTON METRO NETWORK MEASURES AND INDICATORS WITHOUT AND WITH THE YELLOW AND GREEN LINES

Item Code	Item	Symbol	Without Yellow and Green Lines	With Yellow and Green Lines	Percent Change
a-5	Number of lines in network	*n*	3	5	+67
a-6	Number of stations in network	*N*	63	82	+30
a-7	Number of station spacings in network	*A*	62	84	+35
a-8	Length of network (km)	*L*	115	162	+41
a-9	Number of circles	*C*	0	3	+∞
a-10	Number of station-to-station travel paths (origin-destination)	OD	1,953	3,321	+70
b-1	Average interstation spacing (km)	$\bar{S}$	1.85	1.93	+4
b-2	Line overlapping	λ	1.19	1.24	+4
b-3	Circle availability	α_c	0	0.02	+∞
b-4	Network complexity	β	0.99	1.02	+3
b-5	Network connectivity	γ	0.34	0.35	+3

METRO NETWORK AND THE CITY

Relationship of Metro Network to City

An important aspect of metro network evaluation is its relationship to the city: its size and the number of stations in relation to the city size, population, and the role of the metro among other transportation modes.

Among the numerous measures and indicators, some of which most directly reflect the relationship between a metro network (with the primary emphasis on its geometric form) and the city it serves, several are selected and defined; these are listed in Table 5.

c-1 *Density of Metro Network, L_a,* is the ratio of the network length to the area of the city. This indicator reflects the extensiveness of a network with respect to the area it serves, primarily center city; for regional networks this indicator is sometimes imprecise because of the difficulty in delineating the "served area" of the region. The indicator is defined as

$$L_a = \frac{L}{S_u} \text{ (km/km}^2\text{)} \qquad (17)$$

where S_u is the area of the city or of the served area, as applicable.

c-2 *Network extensiveness per population, L_p,* expresses the ratio of network length to the population of the served area:

$$L_p = \frac{L}{P} \text{ (km/persons)} \qquad (18)$$

Comparing cities with similar populations, the greater value of L_p indicates a more extensive network and, generally, a more important role in the metro system.

The service that a metro network offers to the urban area and the various forms of access to its stations are more conveniently measured by the three indicators defined as follows; the first one affects access by walking (pedestrian access); the latter two measure the convenience of access to the metro network by street transit and automobile, respectively.

TABLE 5 METRO NETWORK CHARACTERISTICS INDICATORS

Item code	Definition	Symbol	Equation
	RELATIONSHIP TO THE CITY		
c-1	Density of metro network	L_a	$\frac{L}{S_u}$
c-2	Network extensiveness per population (10^6)	L_p	$\frac{L}{P}$
c-3	Area coverage	N_a	$\frac{N\,S_i}{S_u}$
c-4	Street transit integration ratio	η_t	$\frac{n_s^t}{n_s}$
c-5	Auto across integration ratio	n_a	$\frac{Np}{N}$
	SERVICE MEASURES AND UTILIZATION INDICATORS		
d-1	Operating speed weighted by veh-km per time (day)	V_{cv}	$\frac{\sum_{i=1}^{n\ell} W_i \cdot V_{oi}}{\sum_{i=1}^{n\ell} W_i}$
d-2	Frequency of service during peaks weighted by stations	f_w	$\frac{\sum_{i=1}^{n\ell} f_i\, n_i}{\sum_{i=1}^{n\ell} n_i}$
d-3	Highest design line capacity in network	C	$f_{i\,max} \cdot n_{TU}\, C_v$
d-4	Max scheduled line capacity	C_s	$Max\ f_i \cdot n_{TU} \cdot C_v$
d-5	Space-km offered per day	S_d	$W \cdot C_v$
e-1	Line capacity utilization coef.	η_c	$\frac{C_s}{C}$
e-2	Riding habit (annual trips per capita)	R	$\frac{P_{ay}}{P}$
e-3	Passengers per year per network length	R_L	$\frac{P_{ay}}{L}$
e-4	Passenger-km per day	P_w	$P_{ad} \cdot \bar{\ell}_p$
e-5	Passenger-km per day over space-km per day	$\bar{\alpha}$	$\frac{P_{ad}}{S_d}$
e-6	Metro daily passengers as % of transit daily passengers	P_m	$\frac{P_{ad}}{P_t}$

c-3 *Area coverage,* N_a, is the percentage of the urban area (S_u) that is within walking distance of metro stations:

$$N_a = \frac{n\,S_i}{S_u} \times 100\ (\%) \tag{19}$$

where S_i is the area around the metro station with a radius of 400 m (sometimes a 500-m radius is used as the standard).

Area coverage is the most important measure of the availability of metro services within the entire served area; this indicator is therefore used extensively in the planning of metro lines and networks.

c-4 *Street transit integration ratio,* n_t, is the ratio of street transit lines that have transfers to metro network, n^t_s, to all street transit lines, n_s:

$$n^t{}_s = \frac{n^t_s}{n^t_s} \times 100\ (\%) \tag{20}$$

This indicator expresses the relative geometric and functional role of the metro network within the city's total public transport network.

c-5 *Auto access integration ratio,* n_a, is the percentage of stations that have park-and-ride (P+R) facilities (N_p as a percentage of N):

$$n_a = \frac{N_p}{N} \times 100\ (\%) \tag{21}$$

Measures of Service and Use

Most analyses of metro networks, even those that focus on geometric characteristics, involve some consideration of overall service offered by the metro system and its use. These analyses are usually rather general and are based on a few global measures and indicators such as those given in Table 5. For more detailed analyses of transit system performance, there is extensive literature available (*3–6*).

Service measures, designated as items *d*-1 to *d*-5 in Table 5, include the most important components of level of service (speed and frequency) and of system performance (design and scheduled capacities, and performed work) (*7*). It is important to use speed weighted by vehicle-km per time, to reflect the service on the entire network. For the same reason, frequency is weighted by stations.

Utilization indicators, given as items *e*-1 to *e*-6, include use of offered services, which influences the economic efficiency of operations and can be strongly linked to the design of metro lines and the topology of its network. Other utilization indicators express intensity of metro system use in absolute terms in relation to total transit use in the city. Both groups are also related to the extensiveness and topology of a metro network and the role it plays in the city.

GEOMETRY OF METRO LINES AND NETWORKS

Types of Lines

Geometric forms and their location in the city give transit lines certain functional and operational characteristics. Although some lines have irregular form, many can be classified into several basic types. The most common types are defined in the following paragraphs; their characteristics, based on theoretical analyses and experiences from many cities, are also briefly outlined [see also further review (*8, 9*)].

- Radial lines, following alignments from center city outward, usually trace the directions of heavy passenger demand, which gradually decreases toward the suburbs. This decreasing demand can be matched either by turning some trains back at an intermediate station or by branching the line into several directions and thus distributing its capacity and increasing area coverage in the suburbs. Because they serve many commuters, radial lines often have sharp peaking of ridership volumes.

The main advantage of radial lines, and the dominant reason for their extensive use in many cities, is that they tend to serve the heaviest travel corridors in the city; their disadvantages are that they often have limited distribution in center city and that their inner terminals may be constrained in space (expensive construction), making their operations difficult.

- Diametrical lines connect two different suburbs and pass through city center. They are often equivalent to two radial lines connected in the center. Because they are connected, diametrical lines do not have the two disadvantages of radial lines previously listed—their terminal operations take place in suburbs.

Diametrical lines should be planned with two major considerations in mind. First, their two parts from center city should have similar maximum passenger volumes to ensure good use of offered capacity; and second, it is desirable that they connect suburbs between which there is demand for travel.

- Tangential lines serve noncentrally oriented travel, usually in very active areas of the "ring" around center city.
- Circumferential lines are similarly located, serving tangential trips but in a circular form. When such lines are closed in a circle, they represent ring or circle lines; these exist in several metro networks with some variation in the methods of train routing: metros in London, Moscow, and Tokyo [Japanese Railways (JR)] have circle lines, whereas those in Paris and Hamburg have two circumferential lines that form a circle.

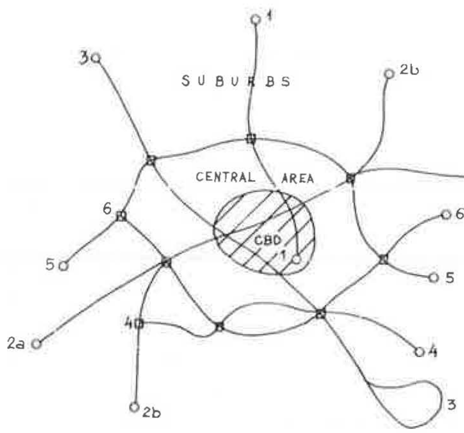
Circle lines usually play an important role in the metro network. In addition to serving tangential trips they connect radial lines, shortening trips among them; their trips are thus distributed to various points in the city. Because of their multiple purpose, circle lines often have rather even passenger loadings along their length and during different periods of day. This results in high use of capacity and makes their operations economical.

Circle lines have some operational problems. First and most serious is the absence of terminal times, which prevents recovery of delays and reduces their reliability; and second, their speed can be changed only in certain increments because of the fixed ratio between headway and cycle time. For these reasons, some transit operators avoid using ring lines.

- Trunk lines with branches are often used in metro systems and even more commonly in regional rail networks. This type of line, which is functionally effective, has the problem of handling short headways when the branches merge into the joint section. Capacity and service frequency are therefore limited by the operation on the trunk line.

Many metro networks have two branches, which do not have the major problems of short headways, but some have three (San Francisco BART) and four branches (Oslo); whereas regional rail networks have up to six or seven branches, but have longer headways than are typical of metro systems (Munich, Philadelphia).

- Irregular lines are those that do not have any regular geometric form. The most common geometric forms of transit lines, including those already described, are illustrated in Figure 3.



LINE	TYPE
1	RADIAL
2	DIAMETRICAL WITH BRANCHES
3	DIAMETRICAL WITH LOOP
4	TANGENTIAL (CROSSTOWN)
5, 6	CIRCUMFERENTIAL FORMING A CIRCLE
□	INTERCHANGE STATION

FIGURE 3 Types of transit lines (*8*).

Types of Networks

A number of metro networks can be classified into different geometric forms. These are defined as follows (*8, 9*):

- Radial networks consist of radial and diametrical lines meeting or intersecting in city center. They are sometimes supplemented by a circumferential or ring line. These networks concentrate on center city and tend to have high peaks because of the large number of commuters they carry. Examples of radial rail transit networks are found in Moscow, San Francisco (BART and Muni Metro), and Munich (S-Bahn).
- Rectangular or grid networks consist of parallel and rectangular lines, usually following a grid street pattern (Toronto, Mexico). These networks provide better area coverage and less focus on a single point than radial networks; on the other hand, much of the radial travel is rather indirect.
- Modified grid is the network form in which lines of different types (radial, tangential, circumferential, branches, and so on) are used in irregular form to obtain an evenly distributed network providing extensive central city area coverage. The most typical examples of this network are the Paris Metro, Tokyo rapid transit, and the Munich U-Bahn networks.

EXAMPLES OF NETWORK EVALUATIONS

Comparison of Quantitative Measures for Different Cities

Metro networks in several cities are briefly analyzed here to illustrate the use of the quantitative measures and characteristics of geometric forms presented.

Ten rather complete metro networks have been selected and the items from categories *a*, *b*, and *c* most relevant for their comparison have been computed. These values, presented in Table 6, must be considered with caution because a number of relevant local conditions could not be included in it. For example, in London the Underground is the only network in the central area, whereas in Paris the Metro is supplemented by three major regional lines; in Hamburg the U-Bahn is nearly duplicated by an urban S-Bahn system, and in Tokyo the case is similar: although the rapid transit (metro) system in Tokyo carries close to 6 million passengers a day, total ridership on all rail systems in the region is about 26 million.

Some arbitrary decisions had to be made in defining the networks and line lengths. In Hamburg, for example, the two branches on the north are not considered to be separate lines, whereas in San Francisco all branches are considered to be separate lines. In London the definition of lines and branches is particularly complex (e.g., Should the Metropolitan Line be considered a set of five lines? In this study it is considered one).

In spite of these difficulties, Table 6 yields some interesting observations about the relationship among these quantitative values and the characteristics of different networks. A few are discussed in the following paragraphs.

Network size is expressed most directly by the number of lines (*a*-5) and network length (*a*-8): Paris, Tokyo, and London are leading examples. Extensiveness and diversity of trip opportunities are mostly related to the number of stations (*a*-6), whereas the density of area coverage can be observed through the density and area coverage indices (*c*-2 and *c*-3): Paris has the fourth largest network, but by density it stands well ahead of all the others.

Diversity of connections in the network is expressed by several items: number of circles (*a*-9) and circle availability indicator α_c (*b*-3), and by complexity and connectivity indicators (*b*-4 and *b*-5): The Paris network leads again, followed by the London network. For smaller and simpler networks (e.g., Baltimore, Lisbon, and Rome) these indicators would be smaller.

The San Francisco network, although rather extensive, has no circles (*a*-9, *b*-3). This is typical for regional networks that offer primarily long trips into the city. Line overlapping coefficient λ (*b*-2), however, shows that the San Francisco network offers the most direct trips by extensive overlapping; the Munich and Washington, D.C., networks, with branching diametrical lines, follow in this respect.

Average station spacings (*b*-1), showing the urban or regional character of the networks, vary from 0.66 km in Paris to 3.47 km in San Francisco. They tend to be greater for regional rail and for U.S. cities because of their large spread and automobile access.

TABLE 6 MEASURES AND INDICATORS OF SELECTED METRO NETWORKS

Item code	Symbol	CITY									
		Chicago	Hamburg	London	Milan	Munich	Osaka	Paris	S. Franc.	Tokyo	Washington
a-5	n_ℓ	7	3	9	2	5	6	15	4	11	4
a-6	N	144	80	247	51	48	77	240	34	173	61
a-7	A	144	85	274	51	49	84	292	33	181	62
a-8	L	161	89	386	40	41	94	158	114	197	113
a-9	C_r	1	6	28	1	2	8	53	0	9	2
a-10	OD	10296	3160	30381	1275	1128	2926	28680	561	14878	1830
b-1	$\bar{S}$	1.12	1.05	1.41	0.78	0.83	1.22	0.66	3.47	1.09	1.82
b-2	λ	1.11	1.00	1.01	1.00	1.48	1.00	1.03	1.86	1.10	1.24
b-3	α_c	0.01	0.04	0.10	0.01	0.02	0.05	0.11	0	0.03	0.02
b-4	β	1.00	1.06	1.11	1.00	1.02	1.09	1.22	0.97	1.05	1.02
b-5	γ	0.34	0.36	0.37	0.35	0.35	0.37	0.41	0.34	0.35	0.39
c-1	L_a	0.28	0.12	0.24	0.13	0.13	0.45	1.50	0.06	0.34	0.71
c-2	L_p	53.60	54.60	57.60	24.90	31.70	37.20	68.70	35.90	23.60	45.20
c-3	N_a	0.13	0.05	0.08	0.16	0.08	0.18	1.15	0.01	0.]5	0.19

The New York City rapid transit system is conspicuously missing from this analysis. The main reason for this absence is because of its great complexity and the difficulty in analyzing its numerous interconnections, overlapping lines, treatment of express-local services, multiple track lines, and so on. A special study of the city's network geometry would be interesting, but it could not be included in this work.

Overall Evaluations of Several Networks

Five of the cities listed in Table 6 and their types of lines and networks are discussed as follows:

1. London Underground: The oldest metro system in the world, it is also the most extensive. It has radial lines extending far into the suburbs, reaching areas served by the British Railways lines. Thus it has an urban or regional character.

The network consists of nine separate lines, but most of them have a number of branches. Duplication of some lines, with the Circle Line sharing tracks with two other lines on its entire length, further increases network connectivity. The Circle Line plays a major role in connecting all metro lines as well as most British Railways terminals in the city.

Because of its long interstation spacings, the London Underground does not provide a very dense area coverage even in the central city, leaving the considerable task of serving local travel to buses.

2. Munich U-Bahn: Like the Washington Metro, it is still under construction. When completed, it will serve a smaller area than that served by the Washington Metro because its region is already covered by the extensive S-Bahn network. Thus the U-Bahn is limited to central city but designed to give a rather complete area coverage. The network consists of three diametrical lines, each (with one exception) having two branches on each side so that there is a total of 11 branches. The interconnected operation of lines and the rather short interstation spacings are aimed at offering convenient routing for many OD paths.

3. Paris Metro: This network consists of 15 lines, which include diametrical, radial, tangential, and circumferential examples, all interconnected in a "modified grid"—a dense network with complete area coverage and good service for OD paths among virtually all points in the central city. One or two transfers are often required because most lines are operated independently.

4. San Francisco BART: Although considered to be rapid transit, this is a regional system. In addition to the indicators given, data not presented in this study show that BART has a relatively low number of passengers per km of line but a long average trip length, which brings up the issue of its passenger-km/space-km ratio.

The San Francisco BART, by its topology, represents a set of joint diametrical lines which, truncated on their west side when the plans for its two western branches (San Mateo and Marin Counties) were dropped from the plan in the 1950s, are unbalanced toward the east; there it has three branches. Covergence of these three lines and the superposition of the tangential Richmond–Fremont line require a sophisticated control of train operations—which BART has.

5. Washington Metro: This system is being built relatively late with the task of serving both the city and its region. It has three diametrical trunk alignments in the center, used by 5 lines that then radiate as nine branches far into the suburbs. Although center-city coverage and radial lines serving the suburbs do not offer such extensive area coverage as do some older

systems (rapid transit and regional rail networks in New York or Chicago, or the regional rail system in Philadelphia, for example), the Washington Metro will provide (by 1993) a relatively extensive service with a total length of only 162 km serving a very large region.

The metro networks from 10 cities, including those discussed previously, are listed with their basic characteristics in Table 7.

This review of the basic characteristics of metro networks shows that (a) the network geometry, type of operation (independent versus interconnected lines), interstation spacings, and other design elements are related to the role the metro system plays in the city; (b) urban networks differ from regional ones; and (c) the backbone network relies heavily on street transit and represents the skeleton of the transit network, whereas metro as the basic system carries most of the trips itself without the extensive support of street transit lines.

Selection of Evaluation Items for Specific Analysis

To further illustrate the potential use of the materials presented for the planning and design of metro networks, several typical applications are defined as follows:

1. Evaluation of an existing network: comparison with other peer cities to estimate its adequacy;
2. Change from trunk-feeder into trunk-branch operation (or vice versa): evaluation of the impact on services and operations;
3. Addition of a new line to the network: estimation of its impact;
4. Selection from among several alternative network extensions;
5. Planning a new metro network.

Table 8 lists the most useful quantitative and other items for each one of these types of analyses.

SUMMARY AND CONCLUSIONS

The geometric form of metro (rapid transit) networks and lines can have a major impact on services for passengers and the efficiency of the system's operation (*10, 11*). It is therefore important to base network design on analyses of different geometric alternatives, to compare features with those of other (preferably similar) cities and to use their operational experiences.

Although there are almost 80 metro systems in the world today (*12, 13*), research and literature on the geometry of their networks is limited and planning of new systems is often performed empirically.

In an attempt to advance the knowledge and understanding of metro networks, a set of items is presented in this paper that can be used in network design. First, the measures of network size and form that are particularly relevant to its geometry are

TABLE 7 METRO NETWORKS OF FIVE CITIES AND THEIR SELECTED CHARACTERISTICS

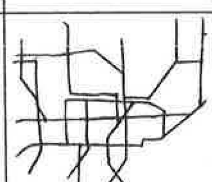
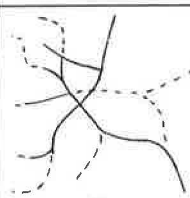
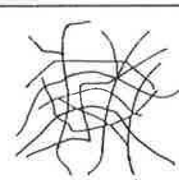
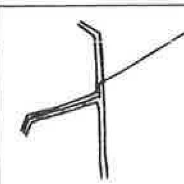
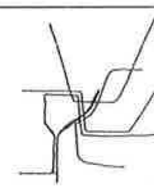
Characteristics / City	London	Munich	Paris	San Francisco	Washington
Network sketch (Not to scale)					
Urban/regional (U) (R)	U - U/R Also large regional	U Also large regional	U Also large regional	(U) R	U/R Also limited regional
Role in the city relation to other modes	All purpose, integrated with regional	All purpose, integrated with tram, bus and regional	All purpose, integrated with regional	Regional, commuting substantial integrated with LRT, bus, P + R	All purpose, integrated with bus, P + R
Extensiveness/ completeness	Very extensive, served area very large	Medium extensiveness, good coverage	Very extensive, total center city area coverage	Connects city to major towns in eastern suburbs	Moderate extensiveness, medium central city coverage
Geometric type	Diametrical lines, circle line	Diametrical lines in a modified grid	Modified grid with many different types of lines	Diametrical lines unbalanced to the east	Diametrical trunk lines with staggered intersections
Branches	Many	Two per line at each end	Very few	Three major branches	Two per line at each end typical
Indep./interconn. operation	A number of lines overlap	Trunk served by two lines	Nearly all independent	High degree of overlap	Trunk served by two lines

TABLE 8 ITEMS TO BE USED FOR DIFFERENT TYPES OF NETWORK ANALYSIS

Item	Symbol	Evaluation of an Existing Network	Change from Trunk-Feeder to Trunk-Branch	Adding a New Line to Network	Selecting from Among Several Alternatives	Planning a New Network
a-5	n	x		x	x	x
a-6	N	x		x	x	x
a-7	A	x		x	x	x
a-8	L	x		x	x	x
a-9	C	x		x	x	x
a-10	OD, OD_d, OD_t	x		x		x
b-1	$\overline{S}$	x		x	x	x
b-2	λ	x	x	x	x	x
b-3	α_c	x		x		x
b-4	β	x		x		x
b-5	λ	x		x	x	x
b-6	δ	x	x	x	x	x
c-1	L_a	x				x
c-2	L_p	x				x
c-3	N_a	x		x	x	x
c-4	η_r	x		x	x	x
c-5	η_a	x		x	x	x
—	Analyze topology	x	x	x	x	x
—	Line geometry	x		x	x	x

presented; then several concepts of graph theory are used to develop a set of network indicators that reflect its complexity, type of operation (relationship among lines), and form. The third group of items includes those relating a network to the city or area it serves; a set of performance and use indicators are also included.

Although it is important to perform quantitative analyses in planning networks and evaluating their alternatives, these must be complemented by other factors such as the designer's experience, knowledge of various network features, and creative imagination. To assist the designers in this respect, a brief review of the characteristics of several basic types of metro lines and networks is presented.

To illustrate the application of the selected theoretical and empirical materials to metro network analysis, indicators have been computed and reviewed for metro networks in several cities and their geometric characteristics briefly described.

The problem of metro network design is so complex that a single paper can only present the basic concepts, their characteristics, and examples of analyses. However, it is expected that the materials presented here will serve as helpful tools for planning and analysis, the content and scope of which may vary depending on specific purpose.

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Attitudes and Practices: Direct Current Transit Systems and Stray Current Corrosion

S. T. McCarthy, M. J. Neatrour, L. M. Krause, J. J. English, and M. M. Abromavage

In 1984, the Transportation Research Board, National Research Council, recognized the need for better control of stray current corrosion problems attributed to direct current powered transit systems. Described in this paper is the work performed as a direct result of that recognition in which the stray current corrosion problem is considered in its entirety. The study is based on information from numerous sources that addresses the technical aspects of system and structure design, construction and maintenance, occupational and public safety, and the institutional concerns of economics and liabilities. The work had three major phases: a literature review, site and mail surveys, and a workshop. Published literature, personal interviews, mail questionnaires, and group evaluations were used to identify the issues, evaluate engineering practices, and suggest a research plan to develop the information needed to control stray current corrosion practically and effectively.

For nearly a century, direct current (DC) powered transit systems have been a boon to urban culture. They have afforded safe, reliable, and efficient mass transportation and have come to be relied on as an integral part of city life. In light of the density and congestion in our cities today, it is not likely that the demand for rapid rail transit will decrease. It is more likely that the need for all types of mass transit, DC rail transit included, will increase in the coming years.

In addition to their obvious benefits, DC transit systems contribute something originally unanticipated to our cities: stray earth currents. These currents are generated by differences in electric potential normally occurring along transit system routes. In their traverse of the earth, from an area of high to low potential, stray currents encounter buried metallic structures. Among others, buried utility pipes and cables, underground storage vessels, and reinforced concrete structures are the most significant and most often noted. Structures are afforded some protection from naturally occurring corrosion where stray current flows from the earth onto them. However, where current flows from high potential structures to the lower potential earth, an electrochemical reaction produces and accelerates corrosion. Although stray current can be considered beneficial, as in instances where it hampers corrosion, it is normally and nearly universally considered a problem.

Stray current induced corrosion, or electrolytic corrosion, like any other type of corrosion, can be the source of severe safety and economic problems if not controlled. Pressurized pipeline rupture, storage vessel leaks, and degradation of structural integrity are possible results. To avoid these possibilities, utility companies and other owners of buried structures must maintain constant vigilance, often spending large sums to locate and replace damaged property. Likewise, transit systems often have to modify their facilities to control the generation of stray currents. Not uncommonly, transit systems bear a large part of the direct and indirect costs of protecting buried structures, even when evidence is questionable that stray currents are destructive in an area.

Historically, stray currents and associated corrosion have been controlled through the cooperative efforts of transit agencies and affected parties. Using a variety of engineering approaches, some aimed at controlling the generation of stray currents, some at controlling the way in which stray currents flow, stray current corrosion problems generally have been managed after the fact. Measures are often implemented only after corrosion problems have been discovered. Resolving corrosion problems at this point is often expensive, with insufficient time to investigate problems thoroughly. Remedies that are "quick fixes" of one problem often cause problems in other areas. Transit agencies and owners of buried structures in those areas are then forced into a game of catch-up; continuously monitoring, modifying, and replacing corrosion controls to maintain a safe and reliable environment.

The reasons for this situation are many: a lack of information on the real costs of corrosion control and corrosion damage, the difficulty of monitoring buried structures and measuring their corrosion rates, the complexities in predicting results of a given corrosion control method in a given situation, and the difficulty of determining the true causes of corrosion. The results, however, are evident. Buried metallic structures in high-density urban areas are at risk. The integrity and longevity expected by their owners are not guaranteed. The safety and reliability expected by and due to the public are inconstant. The ability of transit agencies and owners of buried structures to control problems efficiently and economically are severely hampered. If there is to be improvement, a more complete and widespread

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understanding of DC transit system generated stray currents and their effects is required.

OBJECTIVES AND SCOPE

In 1984, the Transportation Research Board, National Research Council, recognized the need for better control of stray current corrosion problems attributed to DC powered transit systems. The work described here is a direct result of that recognition (*1*). The work, because it is fundamental and intended to encompass all aspects of the stray current corrosion problem, has many objectives. However, all have one of two principal focuses: education or development.

A primary objective of this work was to collect, organize, and make available what is presently known of the effects and the control of stray current corrosion. Although key management personnel may not always be familiar with the significance of the problem, another objective was documenting the severity of the problem and quantifying the economic, legal, and engineering issues in nontechnical terms. As a result, it is hoped that attention will be drawn to the problem and coordination stimulated within and between affected institutions.

Because of the multitude of approaches toward stray current corrosion control and the variability of their usefulness depending on local situations, an objective of the work was to catalog current engineering practices and make recommendations on their effectiveness. There also is a need to clarify aspects of the problem beyond what can be accomplished in this work, and a need to develop more effective means of corrosion control than those that presently exist. Therefore, perhaps the most significant objective of this work was to develop a long-term, all-encompassing program for future research. By this means, it is hoped that the present and future ability to control stray currents and associated corrosion will be enhanced.

METHODOLOGY

The work reported in this paper considers the stray current corrosion problem in its entirety. It draws from numerous sources to address the technical aspects of systems and structures design, construction and maintenance, occupational and public safety, and the institutional concerns of economics and liabilities. The work has three major phases: (a) a literature review, (b) site and mail surveys, and (c) a workshop, as illustrated in Figure 1. Each is described more fully in the following paragraphs, as is a brochure, published following the work on these phases. Detailed descriptions of each phase are contained in the project reports (*1–8*).

An exhaustive search was made of all foreign and domestic literature pertaining to stray current corrosion published since 1900. Abstracts and original papers were obtained for as much of the identified literature as possible. The resulting body of literature was organized and reviewed, and a comprehensive, indexed bibliography created (*2*). Significant issues were identified, and preliminary research priorities were developed. Practices reported in the literature for preventing or reducing structural stray current corrosion were identified and evaluated.

Firsthand information on the present state of the stray current corrosion problem was obtained by visiting five transit agencies. These were: San Francisco Bay Area Rapid Transit District, Toronto Transit Commission, Chicago Transit Authority, Washington Metropolitan Area Transit Authority, and Massachusetts Bay Transportation Authority. Engineers and managers at the transit agencies, local utilities, and other concerned parties were interviewed. The severity of the stray current corrosion problem, key issues and related engineering practices, and research needs were discussed at each agency (*3*).

Questionnaires were distributed to over 300 transit agencies, public utilities, municipalities, and others with an interest in stray current corrosion to augment the information obtained during site visits. Questionnaires covered the same areas addressed in site visits and solicited views on research needs and priorities. Responses were categorized by respondents' affiliation and geographic area (*3*).

A 2-day workshop was conducted in November 1986 to review and evaluate results of these efforts (*4*). Thirty-five participants attended, representing transit agencies, public

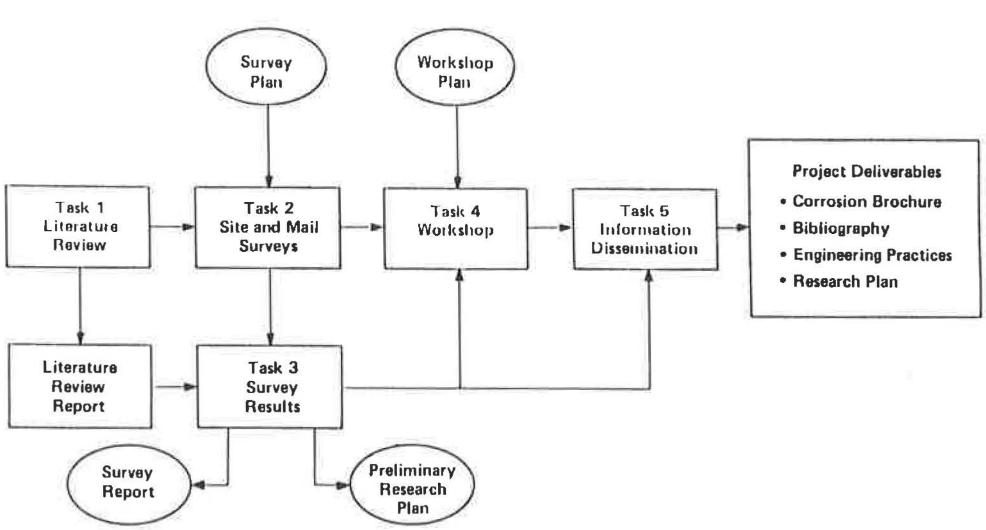

FIGURE 1 Relationship among required plans, tasks, and deliverables for NCTRP Project 48-1.

utilities, municipalities, and corrosion engineering consultants from the United States and Canada. The literature review and site and mail survey results were distributed and reviewed by the entire group. Each member was requested to individually evaluate and make recommendations concerning previously identified engineering practices. Research needs were clarified and documented in working groups. Finally, all members were asked to estimate a 5-yr research budget and to list in order of priority research areas and composite research projects developed by the working groups. The recommendations of the attendees are the basis for the report on engineering practices (*5*) and the development of the research plan (*6*).

Literature Review Findings

Approximately 1,100 potentially relevant references were obtained by searching the foreign and domestic literature. After deleting duplicate and inappropriate references, the total number was reduced to 549, of which 197 are in a foreign language. For many of the latter, English language abstracts are available.

Displayed in Figure 2 is a historical profile of publishing activity. Each bar represents the average number of papers identified for a 3-yr period to better visualize trends. Averages consist of the year at which the bar is displayed and the years immediately preceding and following.

A relatively large number of papers were published at the turn of the century. This probably indicates that the stray current corrosion problem was initially recognized at that time. Many of those reports remain relevant today. Later publications tend to refine the earlier issues and offer a few new techniques. However, the state of the art of stray current corrosion control is substantially the same today as it was in the early 1900s.

Engineering practices addressed in the literature included both the protection of buried structures from the corrosive effects of stray currents and the control of the generation of stray currents. Engineering practices are also discussed in terms of their applicability to existing and future facilities, including both transit systems and buried structures. Corrosion protection is addressed more often as applying to existing facilities. Control of stray current generation is addressed more often as applying to planned facilities.

Drainage is predominant among the engineering practices addressed (i.e., electrical connections between buried structures and the transit system's traction circuit to afford low resistance return paths for stray currents). Cathodic protection systems are less frequently discussed. There are very few citations covering protective coatings for buried structures, soil conditioning to alter electrolytic environments, or electrical connections between buried structures to control the flow of stray currents. Numerous methods for controlling stray current generation, such as storage and maintenance yard isolation and rail bonds, are described in considerable detail. Maintenance practices for corrosion control methods are addressed at a low level throughout the search period.

Also addressed in the literature are nontechnical aspects of stray current corrosion and, to some extent, effects of stray currents indirectly related to corrosion. Information on training and education, regulations and standards, and stray current

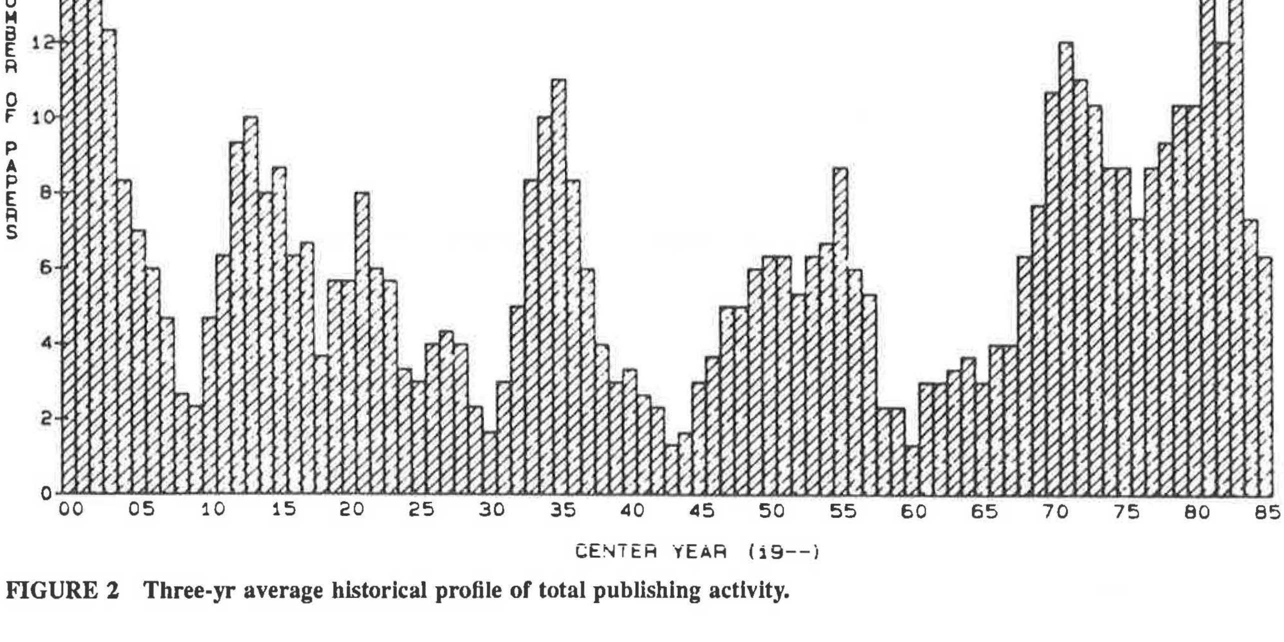

FIGURE 2 Three-yr average historical profile of total publishing activity.

coordinating efforts is included in the literature, but there is little discussion or substantial verification on economic and legal issues. Likewise, electric safety issues related to stray currents and their control are discussed infrequently, although more so in recent years.

The literature search revealed great diversity among the references in the areas and depth of coverage. However, a large number of the references dealt only with one or a few subjects within the broader area of stray current corrosion. As a result, there is no body of literature available that addresses the stray current corrosion problem in all its detail or that addresses sufficiently the options available to engineer and manage stray currents and their effects. The comprehensive bibliography and subject index compiled and included in the literature review report for this project fulfill this need in part (2).

Survey Results

The site and mail surveys contributed significantly to this investigation of stray current and its effects. The direct experience of the transit agencies, public utilities, municipalities, and others in dealing with stray currents were critical in determining the severity of corrosion, clarifying the issues, and developing specific research recommendations.

The mail survey distribution list was developed using the American Public Transit Association's membership index with additional contacts obtained from site surveys, corrosion control memberships, and the National Association of Corrosion Engineers (NACE). Forty-one responses were received from parties affiliated with gas, oil, power, telephone, water, transit, research, public works, and consultant groups.

The site and mail surveys indicated that transit agencies are perceived to be moderate sources of stray current corrosion. There was more concern regarding transit systems in close contact with earth than with transit systems electrically isolated from earth over most of their extent. Isolated transit agencies, however, tend to have higher capital and maintenance expenses. Institutions using pipelines (i.e., gas, oil, and water) perceived themselves as more severely affected by stray current corrosion problems than others. Consistently, gas companies tend to have larger budgets and more people involved with corrosion control (possibly in response to federal influence).

Generally, safety is not perceived as a significant problem and precautions are felt to be adequate. Nevertheless, safety was ranked among the most critical research needs. This reflects a commonly perceived climate of litigiousness. Other top research priorities were information dissemination and engineering practices pertaining to transit agencies.

In almost all instances, concerned parties are involved in corrosion coordinating committees. These committees are more interested in interorganizational relations and the solution of local problems than in generic concerns.

One of the most significant findings of the site and mail surveys was the indication that the main factor inhibiting resolution of stray current corrosion problems is low transit management priority. This was the case even when respondents provided evidence of moderate self-corrosion of transit system facilities. It was attributed to a lack of sufficient economic data, and, to a lesser extent, uncertainty concerning liability. It might be concluded from these results that there are some unresolved technical issues, but the state of the art is sufficiently mature to allow stray current problems to be resolved. The principal missing element is reliable economic data for which to choose cost-effective technical measures.

Workshop Results

The diversity and expertise of the workshop participants provided a unique opportunity for a cross-fertilization of views regarding research needs and priorities of stray current research. Through reviewing, evaluating, and building on the previous findings of the literature review and surveys, the workshop participants were the final source for the engineering practice descriptions and recommendations, priorities for research needs, research budget estimates, and specific research projects. In almost all cases, the comments and recommendations of the participants were found to be independent of their affiliations (i.e., gas, telephone, transit, and so on). This was felt to be a good indication that the results described below are universally applicable.

Brochure

As a result of the literature review, site and mail surveys, and the workshop, it was found that managers of both transit systems and affected agencies are hampered by a lack of sufficient information, primarily in the areas of the true costs of stray current corrosion and its control. Therefore, a brochure (7) was published to address these needs.

The objectives of the information contained in the brochure were to introduce transit and utility management to the problem of DC transit stray current corrosion, to convince management of the need for design, test, and maintenance measures to counteract stray current corrosion, and to educate engineers about the value of corrosion control measures. The brochure is intended for utilities and transit agencies, management, transit system designers, transit and utility corrosion specialists, and corrosion coordinating committees.

ENGINEERING PRACTICES

Cataloging and making recommendations on engineering practices used in controlling stray currents and associated corrosion is formidable: stray current corrosion control has been likened to a "black art," with no single method the answer for every system nor all its effects predictable. Each system must be analyzed individually to determine which method or methods will best achieve cost-effective stray current control. It was therefore decided to identify the effectiveness of engineering practices independent of specific system engineering in the hope that these efforts would become a foundation for more detailed future work. Immediately, it is hoped that this review will clarify which methods can be beneficially employed on proposed and existing systems.

Maintenance is the most essential element of a stray current corrosion control program. It must be well thought out, detailed, consistent, and routine. No matter what type of engineering practice is chosen, it can only be as effective as its maintenance routine.

Drainage refers to electrical connections between buried structures and the transit system traction circuit to control where stray currents flow off buried structures. Drainage is recommended only as a last resort. It tends to increase the geographic area in which stray currents are significant, especially for electrically isolated transit systems. Direct drainage, where simple cables connect buried structures and transit systems, is not recommended. Current flows in either direction, potentially contributing to corrosion. Diode drainage, placing rectifying semiconductor devices in series with drainage cables, is limited to currents typically less than 200 A. In addition, forward bias voltages remain during conduction. Reverse current switches (mechanical rectifying devices in series with drainage cables) are recommended when diodes do not provide the necessary characteristics. However, mechanical switches have a tendency to malfunction, especially at high current loads.

Utility interconnections, electrical connections between buried structures of collocated utilities, present problems like those associated with drainage. Each connection alters the electrical network and can thereby increase or redistribute stray currents.

Impressed current rectifiers, which actively bias underground structures to force protective current flow, are not normally effective for stray current control. Noncompensating rectifiers must be adjusted to account for worst-case stray current conditions. Adjusting to the worst-case conditions can cause nontransit stray current problems at other buried structures, and can overprotect the original structure because of excessive negative potentials and resulting hydrogen evolution. Constant potential rectifiers can be used to avoid overprotection, but they must have wide operating ranges to effectively counter stray currents.

Isolating devices for interrupting the continuity of the current path, especially in buried pipe, have high maintenance requirements that may not be cost-effective. Additionally, current can bypass isolating devices through the earth, contributing to localized corrosion. They should be used only in conjunction with other stray current control methods.

Protective coatings, not considering modern jacketing of electrical cables, can be effective in limiting stray current pickup. As with isolating devices, protective coatings should be used in conjunction with other schemes to account for the possibility of accelerated corrosion at localized flaws. The use of noncorrodible materials is extremely effective when installing new underground structures.

Frequent substation placing is effective in reducing stray currents, but is not necessarily a cost-effective approach for existing facilities. It should be a goal for proposed transit systems and routes.

Rail bonds, electrically connecting cables across rail joints, are effective in reducing traction circuit return path resistance and associated voltage gradients. However, they break easily and often and therefore require constant maintenance. Welded rails offer the same protection with considerably less maintenance.

Cross bonds, electrical connections between running rails, offer the same advantages as rail bonds and ensure equal potentials on each rail. Direct connections cannot be used if one rail is part of a signaling circuit. With proper care, low-pass impedance bonds can be used in these instances.

Voltage equalization at traction substations controls voltage differences between track sections and, therefore, stray currents. Substation performance is normally determined by operation considerations, and may not be available as a stray current control technique.

Special ballast can reduce stray currents, but must be kept as dry as possible and free of contaminants to remain effective.

Diode grounding, rectifying devices placed between substation ground and earth ground, is effective only if all other parts of the transit system are isolated from ground. Completely isolated systems are recommended.

Insulated negative feeders, insulated electric cable returning currents from distant sections of isolated track to common points, can reduce potential differences between portions of a transit system. Capital and maintenance costs are high, and large reductions in stray currents are difficult to achieve.

Electrical isolation of maintenance and storage yards from main lines can significantly reduce stray currents by increasing the total resistance of the traction circuits to earth. It should be practiced wherever feasible, especially with otherwise electrically isolated systems. Appropriate yard procedures are required. For example, train cars should not be parked where isolation devices might be bypassed inadvertently.

PRIORITIZING RESEARCH NEEDS

Beyond the development of the individual research projects described later, research needs at a more fundamental level were investigated. The 35 workshop participants were asked to distribute an unspecified budget among research categories and subcategories. This approach is believed to be a good indication of relative priority. Research category descriptions and budget distributions are shown in Table 1.

Regardless of professional affiliation, the workshop participants indicated by a large margin that engineering research should be given priority over management research. Within the engineering category, more emphasis was placed on stray current reduction than on corrosion protection (27 percent and 19 percent of the available research budget, respectively). In fact, research to improve methods for monitoring stray currents and corrosion was given nearly equal importance with corrosion protection research. Within the management category, education slightly outweighs other research areas. Examination of budget distributions showed that there was little dependence on professional affiliation for any category or subcategory.

ESTIMATE OF 5-YR RESEARCH BUDGET

Workshop participants also considered the present research budget established by the Transportation Research Board for stray current corrosion control problems. Only two participants expressed satisfaction with the current budget. Twenty-nine respondents proposed budgets substantially higher than current funding. Two participants offered formulas by which to calculate yearly budgets. One suggested the present budget be increased by 12 percent, plus inflation, for each of the next 5 yr. The other suggested a yearly budget of 0.5 percent of the value of existing transit systems plus 2 percent of the cost of newly planned routes and systems. A summary of estimates is shown in Table 2.

TABLE 1 RESEARCH CATEGORY BUDGET DISTRIBUTIONS

Research Category Description	Mean Percentage
Corrosion Control Engineering: Technology and techniques for measuring and controlling stray current corrosion, including activities on behalf of both transit systems and affected systems.	74
Measurement/Monitoring: Survey inspection and data acquisition techniques to determine current, potential, corrosion parameters, and system conditions.	17
Corrosion Protection: Methods and technology, usually employed by owners of buried structures, intended to counteract the corrosive effects of stray current.	19
Stray Current Reduction: Methods and technology, usually employed by the transit agency, intended to reduce the magnitude of stray currents.	27
Safety: Effects stray current generation or corrosion protection methods may have on public and worker safety, including electric shock hazards and buried structure integrity.	11
System Management: Nontechnical activities of corrosion control, including activities on behalf of both the transit agency and affected systems.	26
Interagency Management: Organization and mechanism of cooperation among the affected parties and transit systems (i.e., corrosion coordinating committees). Also legal and economic agreements between parties on responsibility for corrosion control.	8
Internal Management: Upper management's point of view and corrosion engineer's influence on it. Includes new systems and extension planning, retrofitting existing systems, maintenance, cost factors and trade-offs, safety, and liabilities.	8
Education: Availability of documentation on practices and techniques. Role of national organizations (i.e., NACE and others) and regional organizations (i.e., corrosion coordinating committees) in establishing and maintaining consistency and quality of corrosion control activities, including standards, regulations, and guidelines. Role of training programs in maintenance and testing.	10

TABLE 2 ESTIMATED 5-YR RESEARCH BUDGETS

Workshop Groupings	No. of Partic-ipants	Mean 5-Yr Budget in 1986 Dollars (million)	Range of Estimates in 1986 Dollars (million)
All participants	29	4.3	0.4–10.0
Consultants	8	3.5	2.0–5.0
Transit agencies	8	4.3	0.4–10.0
Electric utilities	7	5.3	1.0–10.0
Pipeline operators	4	5.6	3.5–5.0

Unlike most other areas of workshop input, budget estimates varied widely and depended on professional affiliation. The 5-yr budget estimates ranged from $400,000 to $10 million in 1986 dollars. However, group mean by affiliation ranged only from $3.5 million to $5.6 million. Interestingly, the low and high extremes of the mean were estimated by consultants and pipeline operators, respectively. In both cases, the range of estimates within each of these groups was less than for other groups. These results probably indicate relative familiarity with costs: prices charged by entrepreneurs in the case of consultants; and costs incurred by institutions in the case of pipeline operators.

PROPOSED STRAY CURRENT CORROSION CONTROL RESEARCH PROGRAM

As stated previously, the workshop participants were the primary sources for developing the proposed research plan described below. Each participant worked within one of six groups to evaluate and clarify 19 research projects previously developed by IIT Research Institute staff on the basis of literature review and survey results. Each group was composed of a cross section of the professional interests in order to fairly evaluate each project. The working groups suggested an additional 12 projects.

The results of the working groups were consolidated and resubmitted to the participants. A scale of 1 (no apparent benefit) to 5 (critical need) was used to rate each project. Individual ranks were then assigned based on the computed mean rating and the accuracy of the mean as inferred from the 95 percent confidence interval. (The 95 percent confidence interval establishes the range around the computed mean within which the true mean falls with 95 percent probability.) The results are listed in Table 3.

An examination of final ranks revealed differences dependent on professional affiliation were greatest for the 10 most highly rated projects. Dependence diminished considerably for the last 10 projects.

The final proposed research plan illustrated in Figure 3 is a result of the priorities given by workshop participants. Note that there is some duplication of research shown in Table 3. This duplication was omitted from the final proposed plan. A complete discussion of the plan and detailed descriptions of each research project are included in the research plan report (*6*).

The emphasis of the proposed program is engineering. Nearly all projects contribute directly to the development of an engineering handbook for transit system stray current corrosion control. As such, most projects emphasize collecting and coordinating existing information. Most other projects present possibilities for cost sharing with industry. Management projects stress cost in both dollar and liability terms. The relative effort in each research category is not quite the same as that obtained from workshop ratings. However, the areas most important to workshop participants are consistent.

The proposed plan can be accomplished over a period of 6½ fiscal years for an estimated cost of $5 million (1986 dollars). The scheduling allows a logical flow of findings from one project to others requiring that information. It recognizes the realities of national priorities and federal budget limitations. The program can be implemented entirely, starting with a modest investment of $500,000 in the first fiscal year, followed by a 50 percent commitment of the total budget during the subsequent three fiscal years. Funding between the fourth and fifth years would drop by 10 percent, and only about 10 percent

TABLE 3 PRIORITIZATION OF RESEARCH PROJECTS

Project Title	Average Score
1. Engineering Handbook for Transit System Stray Current Corrosion Control	3.91
2. Insulation Fastener for Wood Ties	3.51
3. Corrosion Control Measurement Methods	3.47
4. Effectiveness and Applicability of Stray Current Drainage Technologies	3.41
5. Application of Automatic Stray Current and Corrosion Monitoring Systems	3.29
6. Development of Track/Rail Insulating Fasteners	3.27
7. Track Bed and Tunnel Maintenance Requirements and Practices	3.26
8. Analyses of Costs Associated with Corrosion Prevention and Corrosion Damage	3.23
9. Development of Techniques and Equipment for Measurements in Stray Current Areas	3.18
10. Isolation Between Transit Facilities and Traction Circuits	3.17
11. Stray Current Reduction, Corrosion Protection, and Safety	3.11
12. Effectiveness and Applicability of Cathodic Protection in Stray Current Environment	3.11
13. Corrosion Effects of Stray Current Transients	3.09
14. Safe Voltage Levels in DC Transit Systems	3.08
15. Causes of Stray Currents and Their Effects on Reinforced Concrete Facilities and Structures	2.96
16 Wet Weather Performance of Insulating Track Fasteners	2.96
17. Causes of Stray Currents and Their Effects on Transit System Facilities	2.93
18. Influences of Electric Substation Separation on Stray Currents	2.93
19. Development of Faster and More Effective Reverse Current Switches Considering Both Mechanical and Semiconductor Technology	2.90
20. Survey Guidelines in Candidate Locations for DC Powered Transit Systems	2.88
21. Computer Software for Modeling Interactions Between Transit Systems and Collocated Buried Structures	2.66
22. Predictive Stray Current Corrosion Experiments	2.63
23. The Causes of Stray Currents from DC-Powered Transit Systems	2.60
24. Compendium of Legal Precedents Regarding Responsibility for Corrosion Control	2.53
25. Predictive Stray Current Corrosion Experimental Facilities	2.48
26. Trade-Offs Between Designing and Retrofitting Mitigation Engineering in Transit System Planning	2.41
27. The Causes of Stray Currents and Their Effects on Buried Metallic Structures	2.33
28. Installation of Ground Fault Interrupt (GFI) Circuitry at a Transit System DC Substation	2.28
29. The Causes and Effects of Stray Current on Affected Facilities Other Than the Transit Agency	2.19
20. Benefits and Disadvantages Associated with Transforming Solidly Grounded Transit Systems into Diode-Grounded or Isolated Systems	2.05
31. Alternative Propulsion Methods	2.03

of the total budget would be required during the last two fiscal years. In order to facilitate the program, a program management task has been included at approximately 15 percent of the research budget.

CONCLUSIONS

The work reported here illuminates the present state of stray current corrosion problems associated with DC powered transit systems. From published literature, personal interviews, mail questionnaires, and group evaluations, the issues have been identified, engineering practices evaluated, and a research plan proposed to develop the information needed to control stray current corrosion practically and effectively.

What has been found, with few exceptions, is that the necessary engineering knowledge is sufficiently developed to control and resolve stray current corrosion control problems. However, this knowledge cannot now be used easily or efficiently. There is therefore a strong need to develop a detailed compendium of engineering knowledge and make it available to both transit agency personnel and the owners and operators of affected structures. The groundwork for such a source has been laid in this work.

It has also been found that managers are most hampered by lack of sufficient information. There is a marked lack of information quantifying the true costs of stray current corrosion and its control. Likewise, very little is available to offer guidance in judging legal obligations and liabilities. These factors, perhaps more than any other, contribute to inadequate stray current corrosion control. To address this need, a brochure has been published as a result of this study describing the stray current corrosion problem in nontechnical terms for distribution to key management personnel. Work on the proposed research plan that will improve understanding of the nontechnical aspects of stray current corrosion has also been included.

The stray current corrosion problem needs to be controlled if DC powered transit systems are to continue to be safe, reliable, and efficient. There is ample room for improvement at present. The areas where improvement will be most beneficial have been identified and a plan by which to do so has been developed. The proposed plan can be accomplished over a period of $6^1/_2$ fiscal years for an estimated cost of $5 million (1986 dollars). If implemented, the results of the plan will enhance stray current corrosion control through knowledge and cooperation. Only then can DC transit systems be a benefit without the drawback of stray current corrosion.

ACKNOWLEDGMENTS

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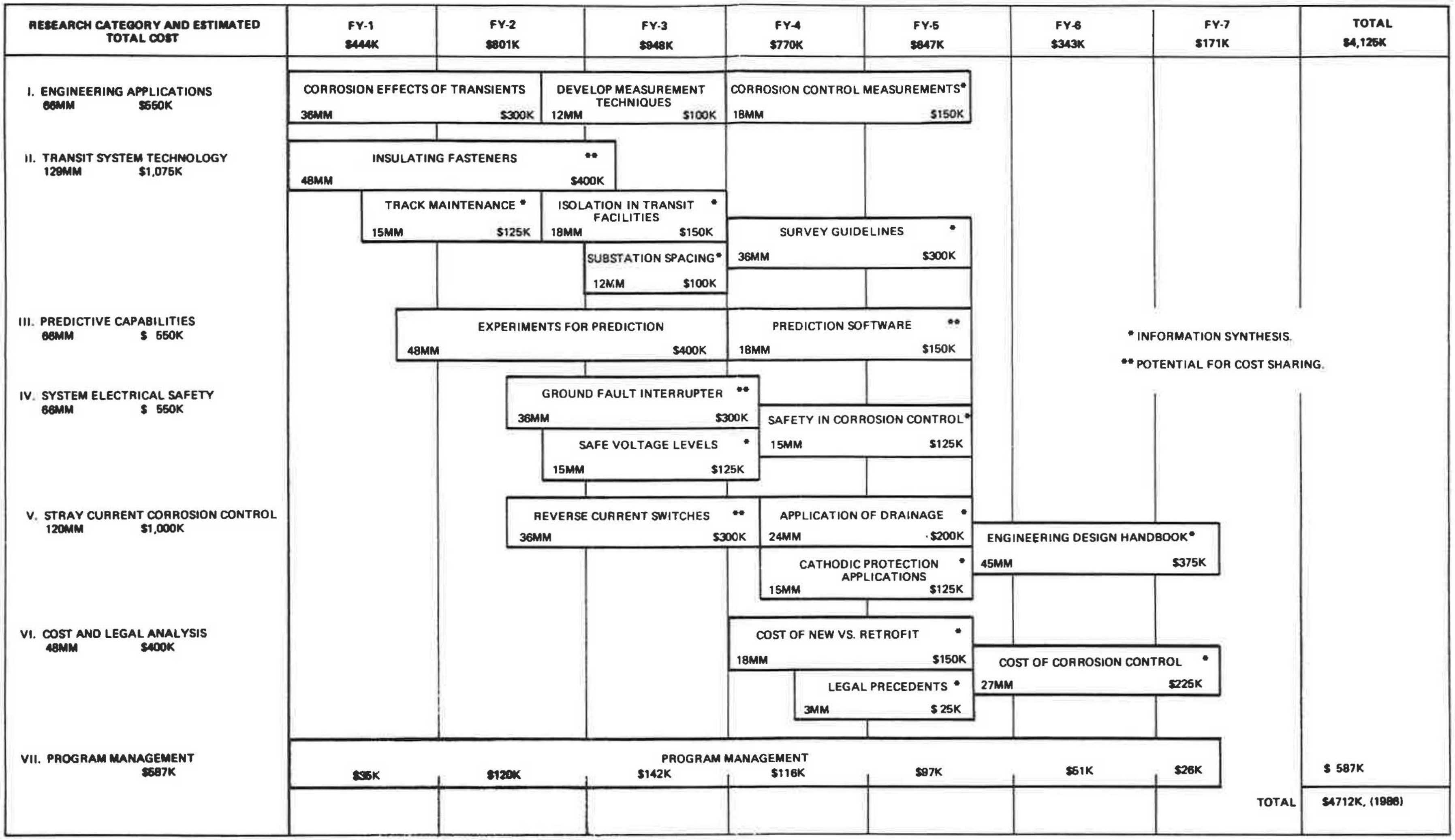

FIGURE 3 Proposed research program (and estimated cost in 1986 dollars based on $100,000/man year) for stray current corrosion from DC powered transit systems.

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Hoboken Terminal: Pedestrian Planning for the Twenty-First Century

JOHN S. CHOW, FOSTER NICHOLS, JR., AND GREGORY P. BENZ

New Jersey TRANSIT's Hoboken Terminal is currently a major hub for rail rapid transit, commuter rail, and bus riders in northern New Jersey and the New York metropolitan area. Major physical and operational changes are being planned for Hoboken Terminal and its immediate vicinity in the next 15 yr. These changes will bring significantly more people, primarily commuters and office workers, into the terminal. Examined in this paper is the ability of the terminal to handle the increased number of pedestrians in the year 2000 from a level-of-service point of view. A microcomputer model of pedestrian flow was developed to examine the impact of various changes on the pedestrian facilities. Of particular concern is the possibility that a set of sales windows for commuter rail tickets would be moved from a separate waiting room out onto a heavily traveled rail concourse. Various alternatives, including automated ticket vending machines, ordered queues, and new window configurations, are proposed to relieve the expected congestion.

New Jersey TRANSIT's (NJ TRANSIT) Hoboken Terminal is currently a major hub for rail rapid transit [Port Authority Trans-Hudson (PATH)], commuter rail, and bus riders in northern New Jersey and the New York metropolitan area. Major physical and operational changes are being planned for Hoboken Terminal and its immediate vicinity in the next 15 yr. These changes will enhance the terminal's role as an intermodal transfer facility, bringing significantly more people, primarily commuters and office workers, into the terminal.

Future transportation services that will affect Hoboken Terminal are a reinstitution of ferry service to New York City, the new light rail system for the rapidly growing Hudson River waterfront, and the reverse Kearny rail connection. The proposed light rail station at the terminal is expected to be a major transfer point for waterfront commuters changing to PATH or ferry service to Manhattan. The reverse Kearny rail connection will allow certain trains that currently travel only to the New York Penn Station to also go directly to Hoboken Terminal, where commuters destined for lower Manhattan can transfer to PATH. Expanded bus activity will be handled in a new enclosed bus-loading area.

In addition to the new transportation facilities, a major joint development project, sponsored by the Port Authority of New York and New Jersey, is being proposed adjacent to the terminal. Two new office buildings and two new parking garages with indoor pedestrian connections to Hoboken Terminal are planned, as is a new hotel above the eastern side of the rail concourse. One proposal is to locate the new hotel's lobby within the historic rail terminal waiting room where rail passengers currently wait for trains and purchase tickets at NJ TRANSIT windows. As part of the joint development project, it has been proposed that the rail ticket sales windows be moved from the waiting room out onto the concourse at the head of the commuter rail platforms.

The Hoboken Terminal pedestrian activity analysis was undertaken to examine the ability of Hoboken Terminal to handle the increased number of pedestrians from a level-of-service (LOS) point of view. Described in this paper are the existing and proposed transportation services at Hoboken Terminal and the results of the analysis for the year 2000 from the standpoint of pedestrian planning. In particular, the level of congestion caused by moving the rail ticket windows from the waiting room onto the rail concourse is examined.

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TRANSPORTATION SERVICE AT TERMINAL

The Hoboken Terminal is one of the busiest transportation centers in the New York-New Jersey metropolitan region. Daily, more than 60,000 commuter rail and bus passengers transfer to and from PATH, which connects Hoboken to midtown and lower Manhattan (see location map, Figure 1). Until 1967, ferries also carried passengers across the Hudson to Manhattan.

Hoboken Terminal, as it is generally called today, is the former Delaware Lackawanna and Western Railroad-Ferry Terminal. This structure was built in the early 1900s in conjunction with the electrification of suburban services and is now a national landmark. The original architectural renderings are shown in Figure 2. Ferry service was offered at both Barclay and Christopher Streets in lower Manhattan until 1954, when the Christopher Street ferry was abandoned. Between 1956 and 1959, the Erie Railroad commuter operations were added to the Hoboken Terminal as a result of the Erie-Lackawanna merger. In 1967, the Barclay Street ferry was closed, leaving PATH, formerly the Hudson-and-Manhattan Railroad (Hudson tubes), as the primary means of transfer to Manhattan via tunnels under the Hudson River.

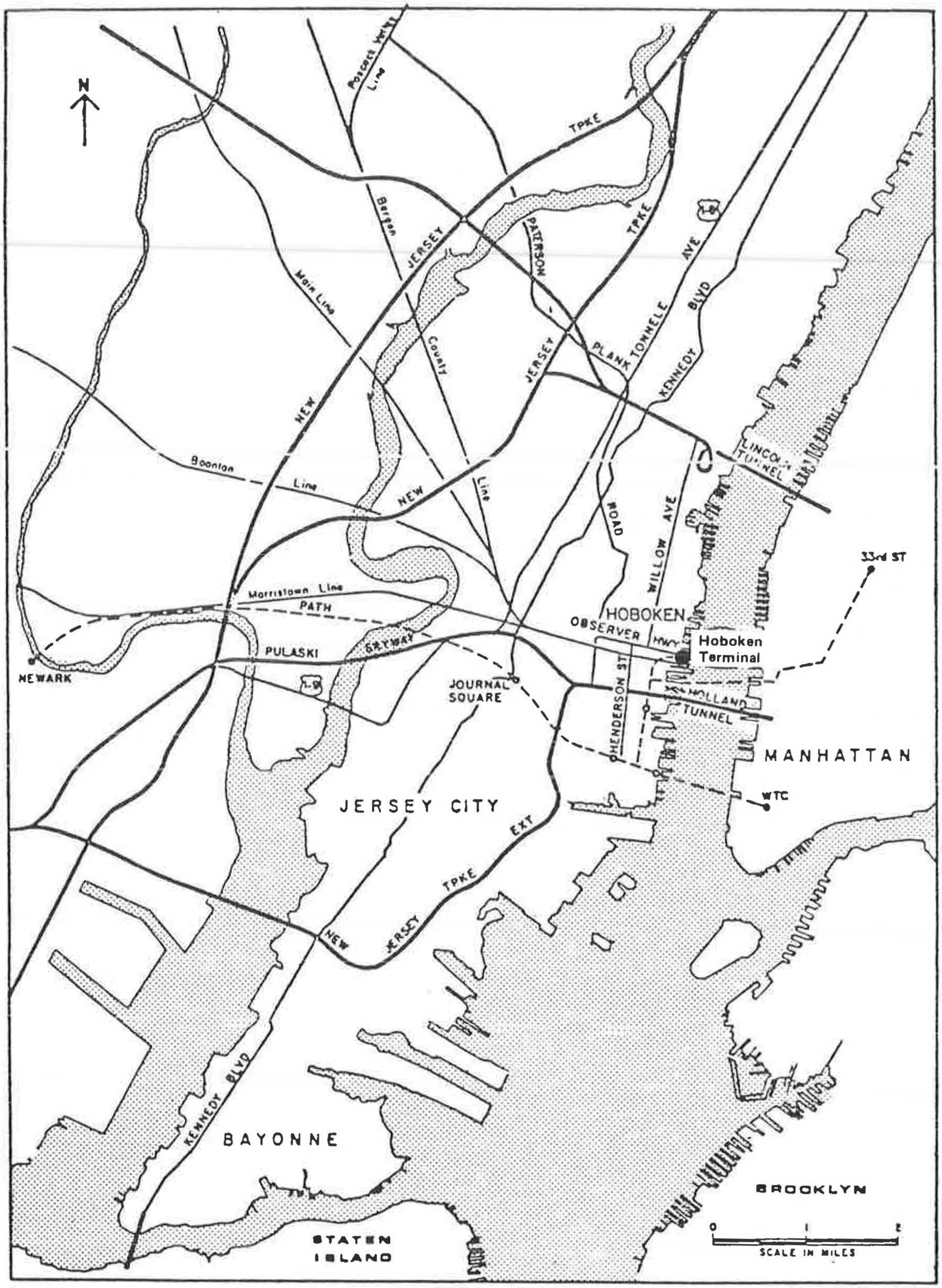

FIGURE 1 Transportation access to Hoboken.

Hoboken is the eastern terminal point for NJ TRANSIT's Hoboken Division commuter rail services. These services involve 116 daily trains to Hoboken, serving 115 separate stations on eight rail lines. Both diesel-powered push-pull and electric multiple-unit trains serve the terminal. Hoboken Terminal is primarily used as a transfer point between NJ TRANSIT trains and PATH, with an increasing number of NJ TRANSIT riders also working within walking distance of the terminal. Another segment of the NJ TRANSIT ridership transfers to the various bus routes serving the terminal.

Hoboken is the terminal point for two separate PATH rapid transit services. The first originates at 33rd Street and Sixth

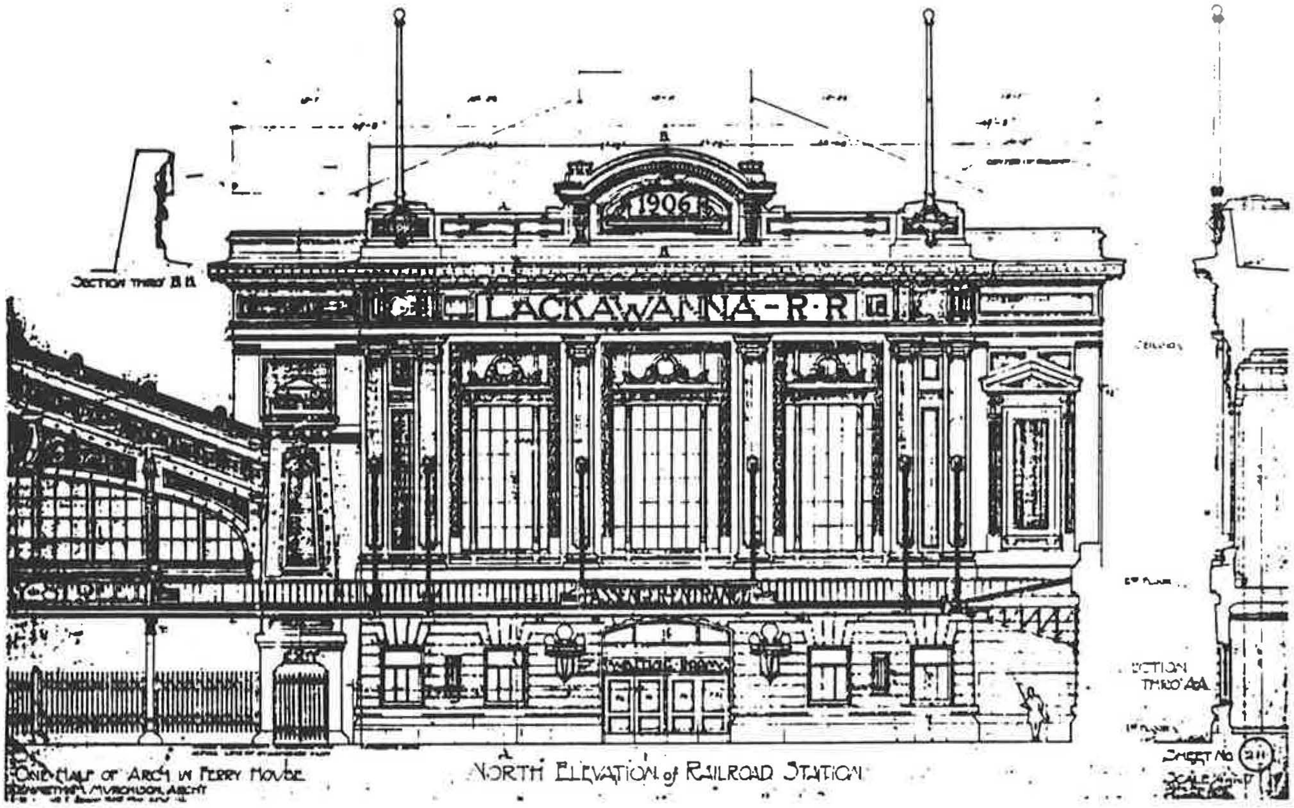

FIGURE 2 Original architectural rendering of Hoboken Terminal.

Avenue (Herald/Greeley Squares), one block from Penn Station, Manhattan. This service runs south along Sixth Avenue with stops at 23rd Street, 14th Street, 9th Street, and Christopher Street in Greenwich Village. Running time from 33rd Street to Hoboken is 14 min. The second service originates at the World Trade Center in downtown Manhattan and stops at Exchange Place and Pavonia in New Jersey. Running time from the World Trade Center to Hoboken is 10 min. Service also runs to Journal Square (Jersey City) and Newark.

Hudson Place, located immediately north of the terminal building, is the site of a former trolley terminal. Today it is the terminal point for eight local bus routes serving Hudson and Bergen Counties, plus a trans-Hudson bus route to the Port Authority Bus Terminal in midtown Manhattan.

Hoboken Terminal is already a heavily used intermodal transfer facility for three modes of transit service—PATH, rail, and bus. The terminal has a distinctive pedestrian flow pattern because it is a commuter hub and transfer point for these transit modes. During the morning rush hour, the majority of the pedestrians passing through the terminal arrive by NJ TRANSIT commuter trains from suburban communities, and transfer to PATH service bound for Manhattan. In the afternoon, the same Manhattan commuters ride PATH to Hoboken Terminal to wait for their departing train trip home. In addition, many local bus routes serve passengers who transfer to PATH, as well as people with local destinations.

With the introduction—or reintroduction—of ferry service to Manhattan, the light rail transit (trolley) stations, and the proposed construction of adjacent office, hotel, and parking garage developments, Hoboken Terminal's role as an intermodal transfer facility will be enhanced. Pedestrian flow pattern will be significantly changed. Flows to the ferry portion of the terminal will reach the original volumes attained before the ferries were abandoned. The light rail station that will be on the opposite (south) side of the terminal from the original trolley depot and the joint development projects will result in new patterns—significant reverse flows, crossflows, and multidirectional flow. In addition, a second-floor pedestrian concourse will connect the joint development sites and portions of the bus terminal with the rest of the terminal.

The plan to locate the new hotel's lobby in the terminal waiting room will displace the commuter rail ticketing facilities, putting them out onto the concourse area at the head of the terminal's 11 stub-end platforms. This concourse normally handles very heavy pedestrian flows following the discharge of passengers from arriving trains. During the afternoon peak period, large numbers of passengers waiting for departing trains gather in the concourse area to take advantage of the concessions, telephones, and other amenities located there. The concourse space functions reasonably well today. The volume and new flow pattern created by the new transportation and joint development projects at the terminal create the need to examine future pedestrian flow conditions. Of particular concern is the allocation of space in the concourse area, especially in the area where the commuter rail ticketing facilities are proposed for relocation.

Described in the remaining sections of this paper are the approach and analytic tools used to examine pedestrian flow activities and conditions, especially the analysis of alternatives for ticketing facilities.

METHODOLOGY

A computer model of pedestrian flow was developed to examine the effects of various changes on the pedestrian facilities. First, a flow network was developed to represent all pedestrian movements within the terminal. A flow network consists of "sources" and "sinks" of pedestrians, and walking links. A source represents a place where people enter the pedestrian network, such as at a platform where they get off the train. A sink is where they leave the network. Shown in Figures 3 and 4 is the flow network, divided into first- and second-floor plans. Each proposed and existing transportation service, office building, or other trip generator was treated as a source or sink for pedestrians. These 19 sources and sinks are shown as circles in Figures 3 and 4. Each distinct walking area was modeled as a link (shown as a thick black line) with an associated capacity for pedestrian flow. All the links are interconnected to allow the tracing of a path through the links from any source to any sink. The model includes 20 vertical circulation links to connect the first floor (street level) to the second floor (mezzanine). There are 108 one-way links on the first floor (two directions for 54 corridor spaces), with the greatest detail shown on the concourse at the head of the rail platforms, allowing closer study of the area for the proposed location of the ticket windows. The second floor is represented by another 40 one-way links.

The number of people walking from each source to each sink was summarized in a pedestrian trip table. The trip table, representing a weekday afternoon peak hour (5 p.m. to 6 p.m.) in the year 2000, was developed jointly by the Port Authority of New York and New Jersey and NJ TRANSIT and is shown in Figure 5. It is interesting to note that more than half of the nearly 38,000 pedestrians arrive by PATH, and three-quarters of these PATH patrons continue their trips by commuter rail.

The trip assignment followed the same methodology that was used by Benz, Chow, and Lutin in a pedestrian analysis of proposed new exits at New York City's Grand Central Terminal (*1*). The trip assignment was undertaken in two steps: (a) the determination of a probable path for each source-to-exit pair, and (b) the assignment of a number of pedestrians to the probable paths. Previous studies show that, particularly for commuter facilities, people take the most direct or easiest route from a source to a sink. For each source-to-exit pair, a shortest path through the network passageways was assigned. The path assignments were completed manually by inspecting the network and distance and ease of passage were taken into account. The path was coded into the simulation program as a probability that trips between a source and exit would make use of a particular link.

The pedestrian assignment model was completed on an IBM AT microcomputer using the Lotus 1-2-3 spreadsheet and taking advantage of the increased memory capabilities of Lotus Version 2. The entire network was represented on the spreadsheet in tabular form, with 168 rows representing links and 19 columns representing sinks. One such table, or base

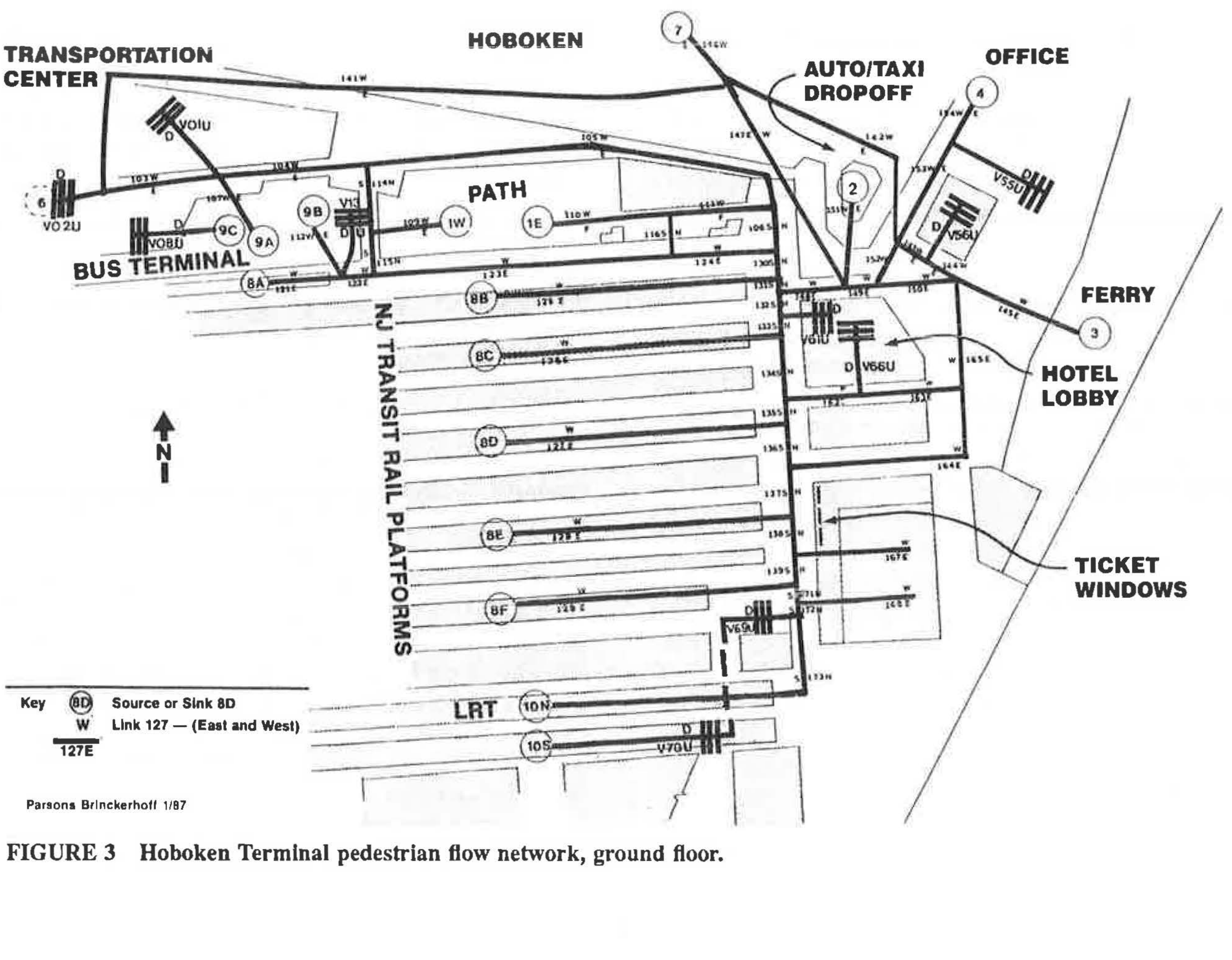

FIGURE 3 Hoboken Terminal pedestrian flow network, ground floor.

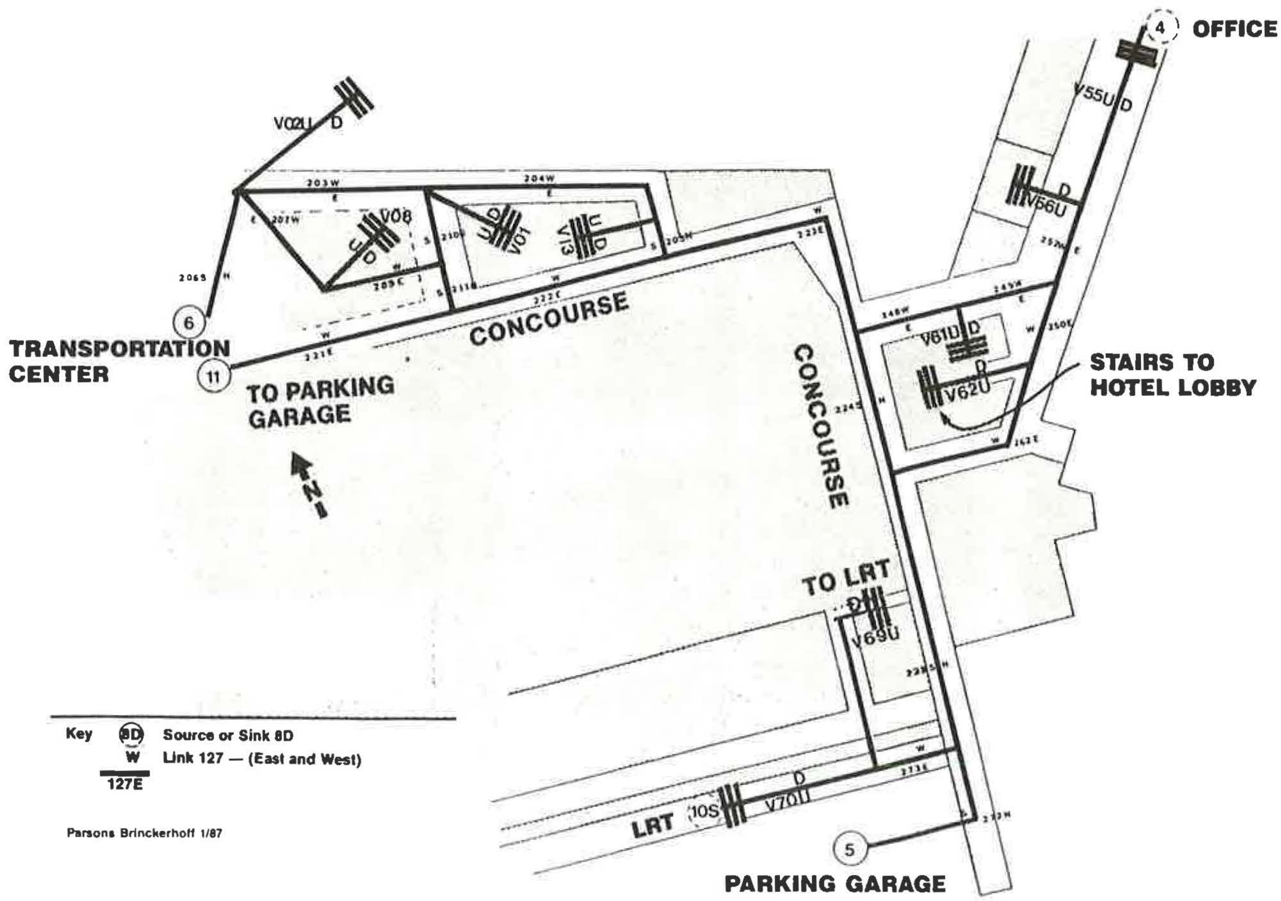

FIGURE 4 Hoboken Terminal pedestrian flow network, second floor.

assignment matrix, was set up for each of the 19 sources. The table was filled in with ones and zeros; a 1.0 in a spreadsheet cell represents a link traveled on the probable path for the source-exit pair, and a 0 represents an untraveled link. In cases where there were two equally likely paths, a factor of 0.5 was used for each of the two links involved.

The second step of the trip assignment is to assign a number of pedestrians to the probable paths. Pedestrians are assigned to the links by multiplying each column of a base assignment matrix by the number of pedestrians coming from that source to each sink. This matrix multiplication process results in one table of link volumes for each of the 19 sources. These 19 source tables were summed together cell by cell, according to the rules of matrix addition, resulting in one table of link volumes for all sources. For example, assume that the trip table shows 100 people going from Source *A* to Sink *B*. Assume there are two equally probable paths, with one traveling through link *X* (probability factor in the base assignment matrix = 0.5), and the other through link *Y* (probability factor = 0.5). Then the matrix multiplication for this *A*-to-*B* pair will contribute 50 trips to link *X* and 50 trips to link *Y*. Other source-to-sink pairs will contribute additional trips to links *X* and *Y*, with the number of trips depending on the trip table volumes and on the path assignments. The resulting link volumes for the various simulation scenarios were plotted on diagrams of the rail concourse area.

PEDESTRIAN LEVELS OF SERVICE AND LINK CAPACITIES

The capacity of a link is the number of pedestrians able to walk through the corridor in the specified time period at a given LOS. To evaluate the performance of pedestrian facilities, criteria are needed that relate pedestrian volumes to levels of congestion and pedestrian comfort for various types of facilities. One measure is the LOS developed in the field of traffic engineering and adapted by John Fruin to pedestrian planning (*2*).

The level of service for corridors and stairways reflects the freedom of pedestrians to select their normal walking speed and bypass slow-moving and reverse-flow pedestrians at various pedestrian traffic concentrations. For escalators, platforms, and concourse waiting areas, the LOS reflects the amount of queueing that occurs at the facility under various pedestrian loadings. In all cases, level of service is a measure of pedestrian congestion. LOS *C* over the peak 5- to 15-min period is generally accepted as the design standard for commuter facilities. The standard used in this analysis, LOS *C*/*D*, is 10 pedestrians/min/ft for stairways, and 15 pedestrians/min/ft for corridors.

Another measure of congestion is the volume-to-capacity ratio (V/C), which is related to the LOS. A pedestrian facility (i.e., a corridor, stair, or escalator) that operates at an LOS on the boundary between LOS *C* and LOS *D* is defined as having a V/C of 1.0. A ratio greater than 1.0 means that the LOS

HOBOKEN TERMINAL TRIP TABLE. Year 2000, pm peak hour
Created 09-Dec-86 R. W. Feingold
Includes reverse Kearny

Going to destination SINK: Page 1

	Source	1	2	3	4	5	6	7	8A	8B	8C	8D	8E	8F	9A	9B	9C	10N	10S	11	Total
1	PATH, E & W entrances	0	513	0	243	0	81	2759	437	1167	4377	2480	4377	1751	270	330	270	185	41	0	19281
2	Auto dropoff	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	Ferry	0	68	0	95	0	32	338	104	279	1048	594	1048	419	63	77	63	30	6	0	4264
4	North Office	1535	0	156	0	360	22	480	24	66	248	140	247	99	200	244	200	283	62	266	4632
5	South garage	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	Transportation Ctr	512	0	51	22	74	0	159	8	22	83	47	82	33	66	81	66	94	21	135	1557
7	Hoboken	1022	0	117	61	442	20	0	23	62	232	131	232	93	257	315	257	284	62	394	4003
8A	NJT Rail track 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8B	NJT Rail track 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8C	NJT Rail tracks 3-6	35	9	4	8	0	3	19	0	0	0	0	0	0	9	12	9	51	12	0	172
8D	NJT Rail tracks 7-10	30	8	4	7	0	2	15	0	0	0	0	0	0	8	9	8	44	10	0	145
8E	NJT Rail tracks 11-14	21	5	2	5	0	2	11	0	0	0	0	0	0	6	8	6	30	6	0	102
8F	NJT Rail tracks 15-21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9A	Bus, south side	20	15	3	30	0	10	28	3	8	30	16	30	12	0	31	20	0	0	0	256
9B	Bus, north side	24	19	4	35	0	12	34	4	10	36	20	36	14	31	0	31	0	0	0	309
9C	Bus, center island	20	15	3	30	0	10	28	3	8	30	16	30	12	20	31	0	0	0	0	256
10N	LRT northbound	140	0	18	18	0	5	21	5	12	42	24	42	17	49	60	49	0	0	0	502
10S	LRT southbound	635	0	81	77	0	25	96	19	51	192	109	192	77	221	273	221	0	0	0	2270
11	West garage	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Totals	3994	652	443	631	876	224	3988	630	1685	6318	3577	6316	2527	1199	1472	1199	1001	220	795	37747

Source: Port Authority year 2000 am peak hour trip table. E. Lessieu, 7/24/86
Modified and redistributed by R. Feingold for 2000 pm peak hour. 12/2/86

FIGURE 5 Hoboken Terminal year 2000 p.m. peak hour pedestrian trip table.

degrades below the design standard, which may result in acceptable queueing if it lasts for only a short duration. A V/C of less than 1.0 means that the facility is functioning at LOS *C* or better and meets the design goal.

The pedestrian flow model simulates pedestrian flow volumes on each link. The volumes indicate the number of people walking on each link during the evening peak 15-min interval. Shown in Figure 6 are the printout results from the flow simulation for Scenario 1 (year 2000 weekday afternoon peak 15 min, with heavy month-end rail ticket sales). Each row represents one link in the network. Given in the first five columns are measurements that determine the link capacity to carry pedestrians. Shown in the next three columns are the link capacity per min, per 15 min, and per hr. Pedestrian LOS guidelines are used to determine the carrying capacity of each link at LOS *C*.

The effective width of a corridor, concourse, platform, or stair is always less than its actual width from edge to edge. The effective width of the Hoboken Terminal rail concourse takes into account the presence of structural columns, phone booths, and other obstructions in the center of the concourse and the propensity of pedestrians to stay away from side walls and edges when walking.

To calculate the future effective width of the Hoboken Terminal concourse, the following deductions are made from the actual 41-ft edge-to-edge width: 2.5 ft for the west and east edges of the concourse, and 7.5 ft for the central column line and public phone clusters. At Tracks 5 and 6, two additional feet are deducted for the NJ TRANSIT information booth, resulting in an effective width of 29 ft.

The resulting effective width is 31 ft (except opposite the information booth, where the effective width is 29 ft). The V/C ratios are calculated by the model for the peak 15-min interval. The resulting V/C levels determine the ability of particular Hoboken Terminal corridors to handle the expected peak pedestrian volumes.

TICKET AREA QUEUEING ANALYSIS

The pedestrian flow model was used to examine Hoboken Terminal's ability to handle pedestrian flows in an afternoon peak hour on a month-end weekday in the year 2000. With the exception of the rail concourse area, which is discussed below, Hoboken Terminal is shown to function well under future conditions.

Rail Concourse Without Ticket Queues

In the middle of the month, when rail ticket sales are low, pedestrian flows are relatively smooth. Queues generally form at the ticket windows. The resulting free-flow V/C ratios are shown in Figure 7.

Conditions are not entirely free flowing, however, during a typical evening peak period. Passengers who wait for their departing trains for train departure information or to meet friends, as well as passengers who stand in line to purchase items from the concession windows, take up space and constrain movement through the concourse by other pedestrians.

Concession queues extending outward from the east wall also pose a greater constraint to pedestrian flows. These queues can extend outward 5 to 10 ft and then bend in a north–south direction, limiting the north–south flow of pedestrians to a double file to the east of the telephones and central columns. The analysis accounted for these waiting passengers by reducing the effective width of the concourse by 5 ft, from 31 to 26 ft. This reduction approximates the amount of additional space taken up by nonmoving passengers occupying the concourse during the peak evening period. These passengers are mostly concentrated in the northern part of the concourse but are relatively spread out in the north–south direction, especially those who are awaiting train information. The resulting V/C levels are presented in Figure 8, which also shows schematically that part of the concourse width is taken up by waiting passengers. The figure shows V/C levels increasing from south to north, reaching congested levels at the northern end of the concourse.

Rail Concourse with Ticket Queues

Greater congestion would be imposed on the rail concourse by moving the rail ticket sales windows out of the waiting room and into the concession area of the relatively narrow rail concourse. People standing in line to buy tickets would reduce the amount of space available for moving pedestrians.

HOBOKEN TERMINAL PEDESTRIAN CAPACITY CALCULATIONS — 11-Feb-87 — S1ESUM Page 1 10-Dec

Link	Description	Corridor width (ft): Actual	Obstruction	Effective	doors or stairs	Unit cap /min	CAPACITY: persons /min	persons /15-min	persons /hour	Link	Link total	Peak 15-minutes: volume 28%	2-way vol	Volume /capacity
	ZONE 1. TRANSPORT CTR													
103 E	TranspCtr, front lobby	6.7	1.5	5		15	78	1170	4680	103 E	2779	778	1613	138%
104 E	Bus term, NE side				4	50	200	3000	12000	104 E	2654	743	1833	61%
105 E	Sidewk N of PATH	NA		NA		15	NA	NA	NA	105 E	0	0	0	NA
106 N	E of PATH	NA		NA		15	NA	NA	NA	106 N	1198	335	2458	NA
107 E	Bus term, N platfm	19.9	7.5	12		15	186	2790	11160	107 E	1200	336	408	15%
109 E	PATH W turnstiles	NA		NA		NA	NA	NA	NA	109 E	1598	447	1600	NA
110 E	PATH E turnstiles	NA		NA		NA	NA	NA	NA	110 E	15165	4246	4917	NA
111 E	PATH E entr				8	50	400	6000	24000	111 E	7582	2123	2458	41%
112 E	Bus term, S platfm	17.4	7.5	10		15	148	2227	8910	112 E	310	87	499	22%
114 N	Bus term, NE side	16.4	7.5	9		15	133	2002	8010	114 N	3893	1090	1833	92%
115 N	Bus term, SE side	17.3	1.5	16		15	237	3555	14220	115 N	1339	375	1108	31%
116 N	PATH E entr	25.6	4.2	21		15	321	4815	19260	116 N	1198	335	2458	51%

FIGURE 6 Hoboken Terminal year 2000 p.m. peak 15-min pedestrian flow volumes, capacities, and V/Cs.

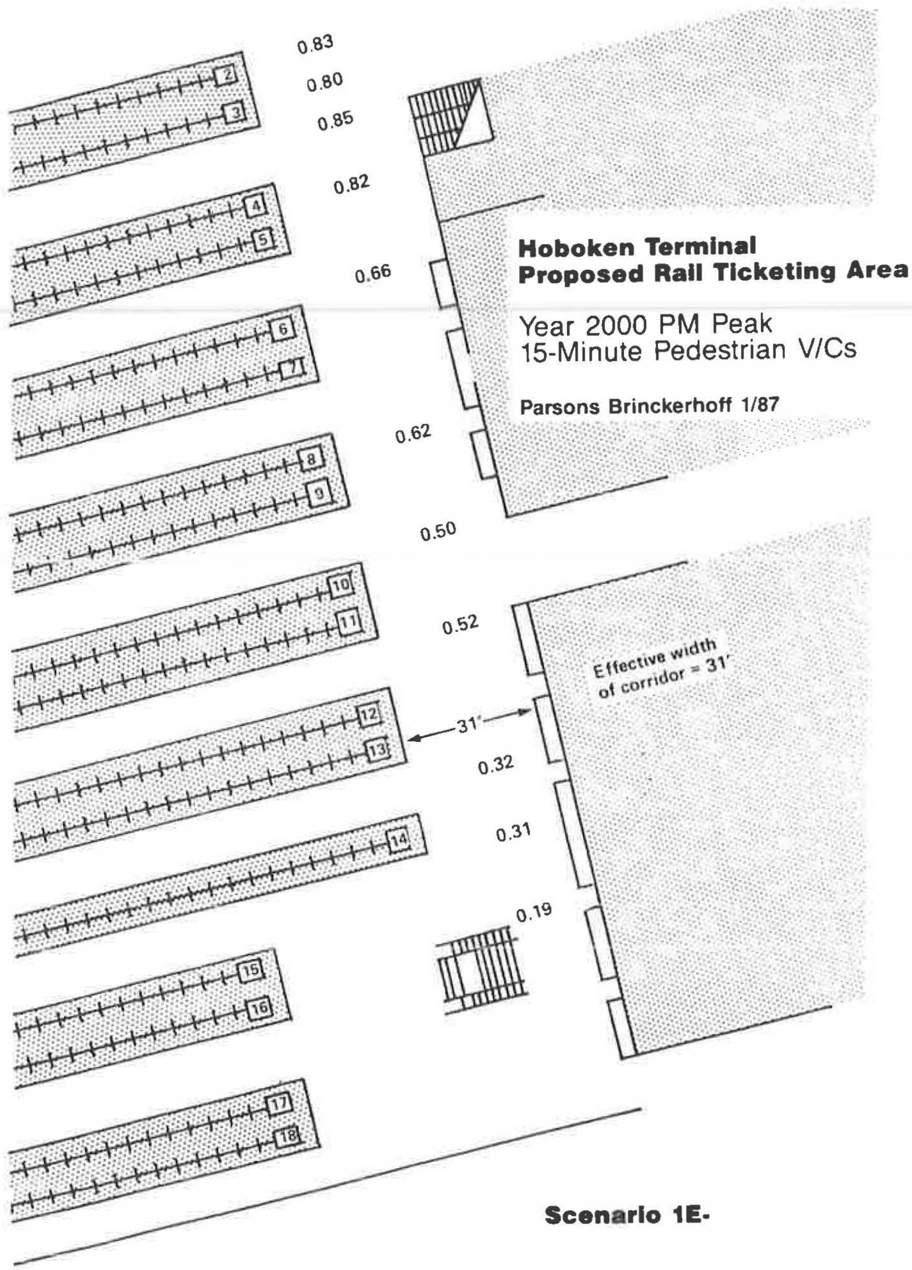

FIGURE 7 Free-flow pedestrian LOS without queues.

The impact on pedestrian flows of moving the railroad ticket office to the southern end of the rail concourse was investigated. Ticketing activities reach a relatively high peak at the beginning and end of every month when passengers buy their monthly commutation tickets. The highest peaks occur when the first or last day of the month occurs on a Monday, which also happens to be the busiest day of the week for the sale of weekly tickets.

Existing ticketing conditions were observed from a 1-day survey on May 1, 1986 (a Thursday). Detailed ticket sales records were obtained from the railroad for the same day, and daily ticket sales data were obtained for the years 1985 and 1986. On May 1, 1986, during the 5 p.m. to 6 p.m. period, a total of 660 passengers purchased tickets. During the hour, there were from five to six ticket windows open in the main waiting room, all staffed with agents. Substantial queueing occurred, reaching a maximum of 16 people in each line (a 10-min wait) and 68 people overall. (At present, a separate line forms at each window.) Average queues over the hour were 9 people/window and 52 people overall.

The processing time for each ticket purchase is an important determinant of queueing at the ticket windows and can be used to determine the number of ticket windows required to keep peak period queueing at an acceptable level. The average processing rate from 5 p.m. to 6 p.m. on May 1, 1986, was calculated to be 38 sec/person (or 1.6 persons/min). Many monthly ticket purchases are made by check and take longer than the average 38 sec, sometimes in excess of 2 min. This is offset by purchases of single-ride tickets, usually with cash, which generally require much less time per transaction.

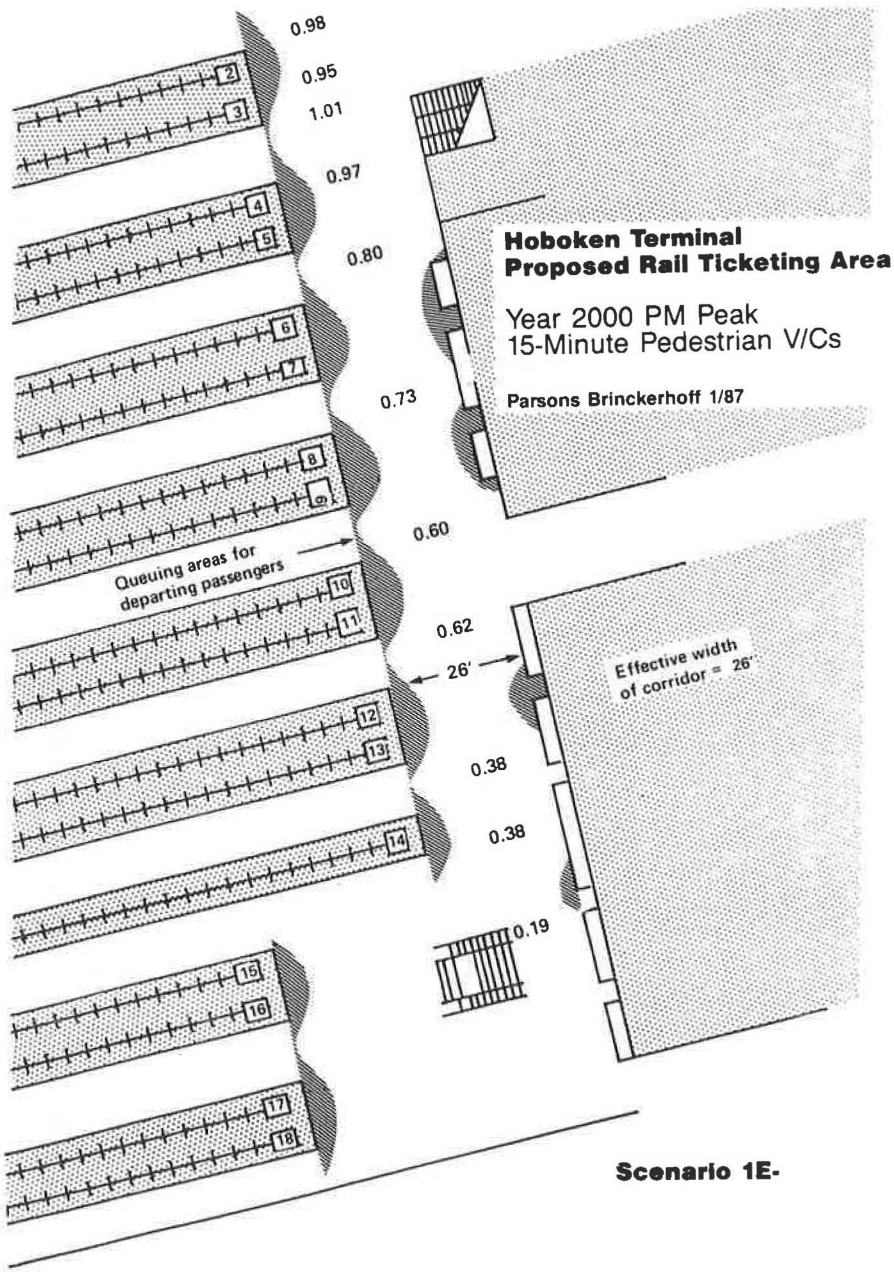

FIGURE 8 Pedestrian LOS with departing passengers waiting and without ticket queues.

Peak ticketing activity was projected to the year 2000, using the year 2000 forecast of NJ TRANSIT rail ridership at Hoboken Terminal. In order to estimate a typical worst case condition for ticketing, the design day was assumed to be a Monday occurring at the end or beginning of the month. The analysis assumes that the percentage of rush hour rail passengers who stop to buy tickets will remain at its present 7 percent rate. First, the observed May 1, 1986 (Thursday), ticketing activity was increased by 17 percent (from 660 to 770) to account for the fact that the Monday design day is a busier one than the Thursday. Then this number was projected to the year 2000, resulting in a forecast of 1,500 passengers desiring to purchase tickets between 5 p.m. and 6 p.m. on the year 2000 design day.

The processing rate for ticket sales is assumed to be 1.6 persons/min/window—the same as it is today. The extent of peak-period queueing at the ticket office is a function of this processing rate and is also a function of the number of ticket windows in operation. A queueing analysis was undertaken to determine the required number of ticket windows in the year 2000. To handle the projected volume without allowing a prolonged queue to build up at the ticket office, 15 window positions would be needed. Because a moderate amount of queueing is tolerable at peak times, the ticket window requirement may be reduced by one or two positions. Fourteen open windows would cause a buildup of a queue to the point where a person would wait 7 min in line, queues would extend to 11 people per window, and a total of 150 people would be in the queue. Providing only 13 windows would increase the maximum wait to 12 min and maximum queues to 19 people/window—250 people overall.

Part of this increased ticket-selling capacity may be provided through the installation of automatic ticket vending machines (TVMs) at Hoboken Terminal, capable of vending monthly and weekly commutation tickets as well as single-ride tickets. These machines have proven practical at other commuter rail terminals but are not currently provided at the terminal. TVMs could be located both within and without the rail concourse, although one potential problem is that these machines themselves can impede pedestrian flow when queues form. If it is assumed that one-third of the peak ticketing demand in the year 2000 is accommodated at TVMs, then the ticket window requirement may be reduced to 10 (moderate queue buildup) or 11 (no queue buildup) positions.

Another possible way to reduce the volume of ticket sales in the terminal is to sell tickets off site or by mail. Tickets could be sold off site at local banks or by business employers. NJ TRANSIT already has a program to sell tickets by mail, but more people could be encouraged to use Mail Tiks.

Each ticket window position in the terminal is assumed to require approximately 5 linear ft of ticket counter, to provide adequate space for booking office machines, ticket stock, and cash drawers. This translates into a requirement of 50 linear ft for 10 windows and 75 linear ft for 15 windows. The required depth of the ticket office may vary, depending on the location of and requirements for supporting space. A 20 to 25 ft depth is assumed here for planning purposes.

The space originally proposed for relocation of the ticket office occupies the east wall of the rail concourse at the south end. Approximately 75 linear ft are available for ticket office frontage. If the proposed retail space facing the rail concourse in this area is eliminated, then there is approximately 25 ft of ticket office depth available. Thus, a relocated ticket office with up to 15 windows could be accommodated in the proposed space.

Queueing for passengers buying tickets, however, would occur entirely within the rail concourse. Based on the results of the queueing analysis, a maximum of 200 passengers would accumulate in the ticket queue in the year 2000 design day, corresponding to a requirement of between 9 and 14 open window positions (depending on the number of TVMs provided).

Two basic types of queue are possible:

- Separate queues at each window (the existing situation at Hoboken);
- A single ordered queue. These queues, often used at banks, operate on a first-in, first-out basis—a procedure where the first person in line goes to the next available window. Movable barriers are used to channel the flow.

Separate queues are less efficient than a single ordered queue in terms of use of space. However, separate queues allow for separate lines for different types of ticket purchases: monthly tickets, cash purchases, credit cards, checks, and so on. A single ordered queue provides more equitable service for passengers waiting in the queue.

Both types of queue were analyzed to determine their impact on north–south movement in the rail concourse. Because the rail concourse is only about 40 ft wide, any elongated queue in the east–west direction would substantially reduce the north–south pedestrian flow capacity of the concourse in this area.

Examined in Figure 9 is the impact of the first type of queue, the separate queue, on north–south movement when the ticket windows are moved to the rail concourse in a configuration similar to that which exists in the waiting room today. In the existing waiting room at the end of the month, when ticket sales are the highest, there have been as many as 16 people standing in each line at one time. Each person adds about 2 ft to the queue, resulting in a 32-ft queue. If the ticket office is moved, even if enough additional windows are added so that future queueing is no worse than at present (16 persons maximum per line), the resulting peak queues would block 80 percent of the width of the concourse. Such queues would severely constrain the normal flow of pedestrian traffic, considerably diminishing the effective capacity of the concourse link. The 2,200 people who are trying to walk north and south on the concourse east of Track 13 would have only a 5-ft-wide corridor through which to pass, resulting in an unacceptable V/C of 1.39. This analysis shows that even under the current demand for tickets, there is not enough space on the concourse to operate the existing number of ticket windows with a single line in front of each window.

The second type of queue, the single ordered queue, is illustrated in Figure 10, which shows an ordered queue with a capacity of 200 people occupying the eastern half of the rail concourse. This arrangement would leave only a 20-ft-wide space for north–south circulation. V/C ratios, shown in Figure 11, reflect a crowded but acceptable condition. These ratios assume completely free-flowing movement without, however, any waiting passengers or other obstructions in the concourse. If the same degree of passenger waiting is assumed as in the rest of the rail concourse (i.e., a reduction in the effective width of 5 ft), then the V/C ratios, shown in Figure 12, would change to 1.22 at the north end of the ticket office, which is an unacceptable condition.

Alternative Rail Ticketing Arrangements

The foregoing analysis indicates that ticket window arrangements that cause queues of ticket buyers to extend into the rail concourse will result in peak period congestion that exceeds accepted standards. Ticket queueing, therefore, should be accommodated away from the main circulation area.

One alternative would be to retain the ticketing function at its existing location in the waiting room. However, expansion of the seven to eight existing window positions would be physically difficult, and the future use of the room as a hotel lobby would be precluded. Another alternative would be to use a greater part of the ground floor of the proposed new building directly east of the rail concourse opposite Tracks 10 through 14. The ticket windows could then be recessed (and possibly angled at 45 or 90 degrees to the rail concourse) to provide adequate queueing for 200 or more passengers outside (but adjacent to) the concourse. Such a scheme would reduce the ground floor space available for retail or building services by 2,500 ft^2 to 4,000 ft^2 (plus an additional 1,000 ft^2, if a backup office is provided adjacent to the ticket office). On the other hand, these alternatives would allow greater flexibility to accommodate longer queues when they occur, allow future expansion of the ticket office, provide space for ticket vending machines and a seated waiting room, and maintain adequate pedestrian flow conditions in the concourse.

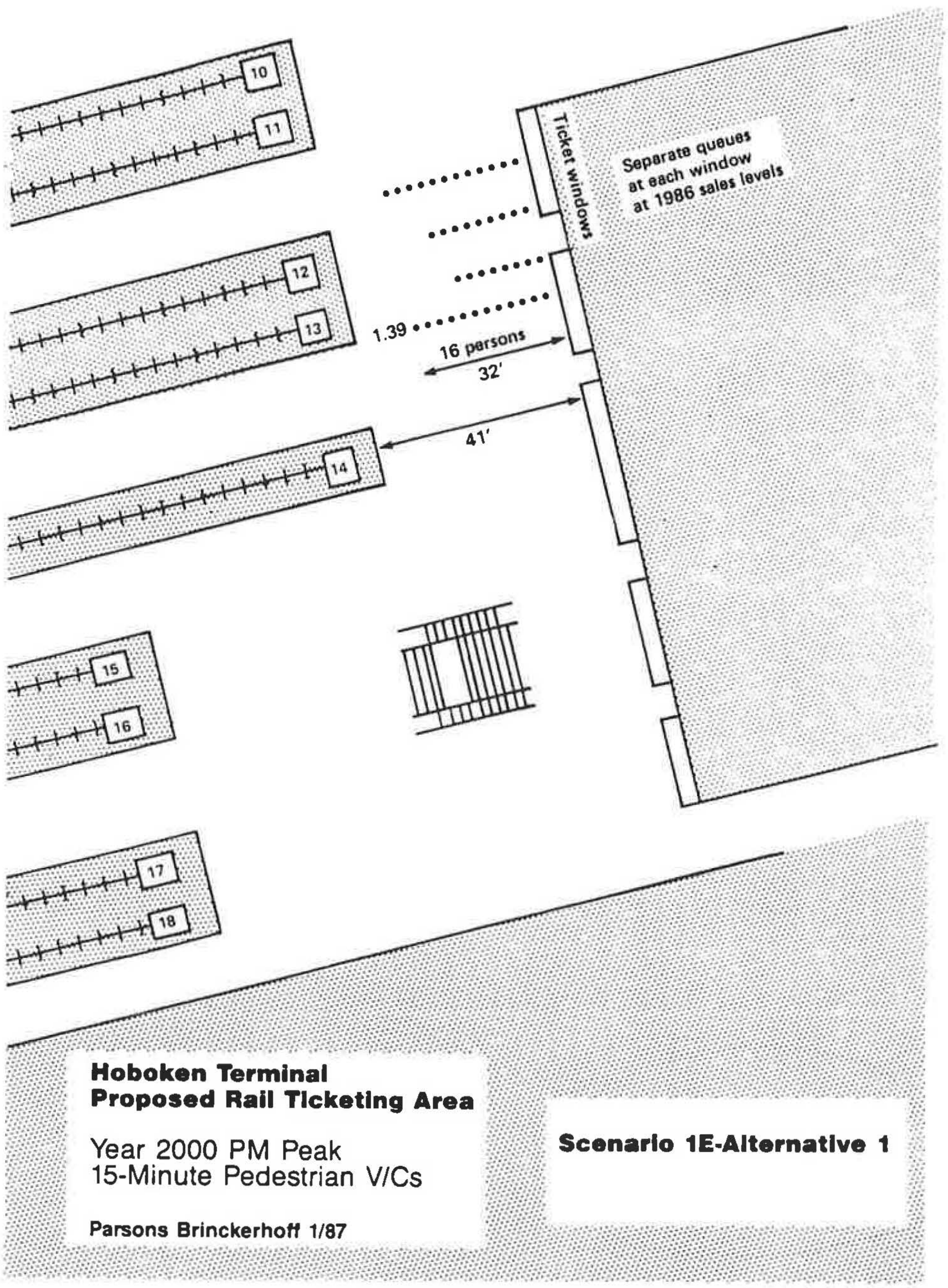

FIGURE 9 Pedestrian LOS with 1986 ticket queues.

CONCLUSIONS

Based on the foregoing analysis, a number of conclusions may be reached regarding ticketing facilities for NJ TRANSIT trains at Hoboken Terminal:

- The increased railroad ridership forecast for the year 2000 (21,000 p.m. peak-hour trips) will result in a corresponding increase in demand for ticket sales and unacceptable queues at peak end-of-the-month times if ticket selling facilities are not expanded.
- A generous supply of automated ticket vending machines (TVMs) scattered throughout the terminal would help considerably to reduce ticket window (and agent) requirements and reduce the concentration of queueing at ticket windows. However, the rail concourse area is already congested and further analysis is required to determine whether sufficient space exists to accommodate the TVMs.
- In order to accommodate year 2000 peak ticket demands, 9 to 10 windows with 200 ft^2 of backup space are required, supplemented by a number of TVMs. If no TVMs are provided, then 13 to 14 windows with 300 ft^2 of backup space are required. Because NJ TRANSIT currently staffs a maximum of 6 windows, the opening of more than 9 windows would require additional staff and therefore additional operating expense to NJ TRANSIT.
- If the above ticket window requirements are met, an estimated 1,500 ft^2 of concourse area (equivalent to 200 persons), separate from the areas of pedestrian flow, will be required for

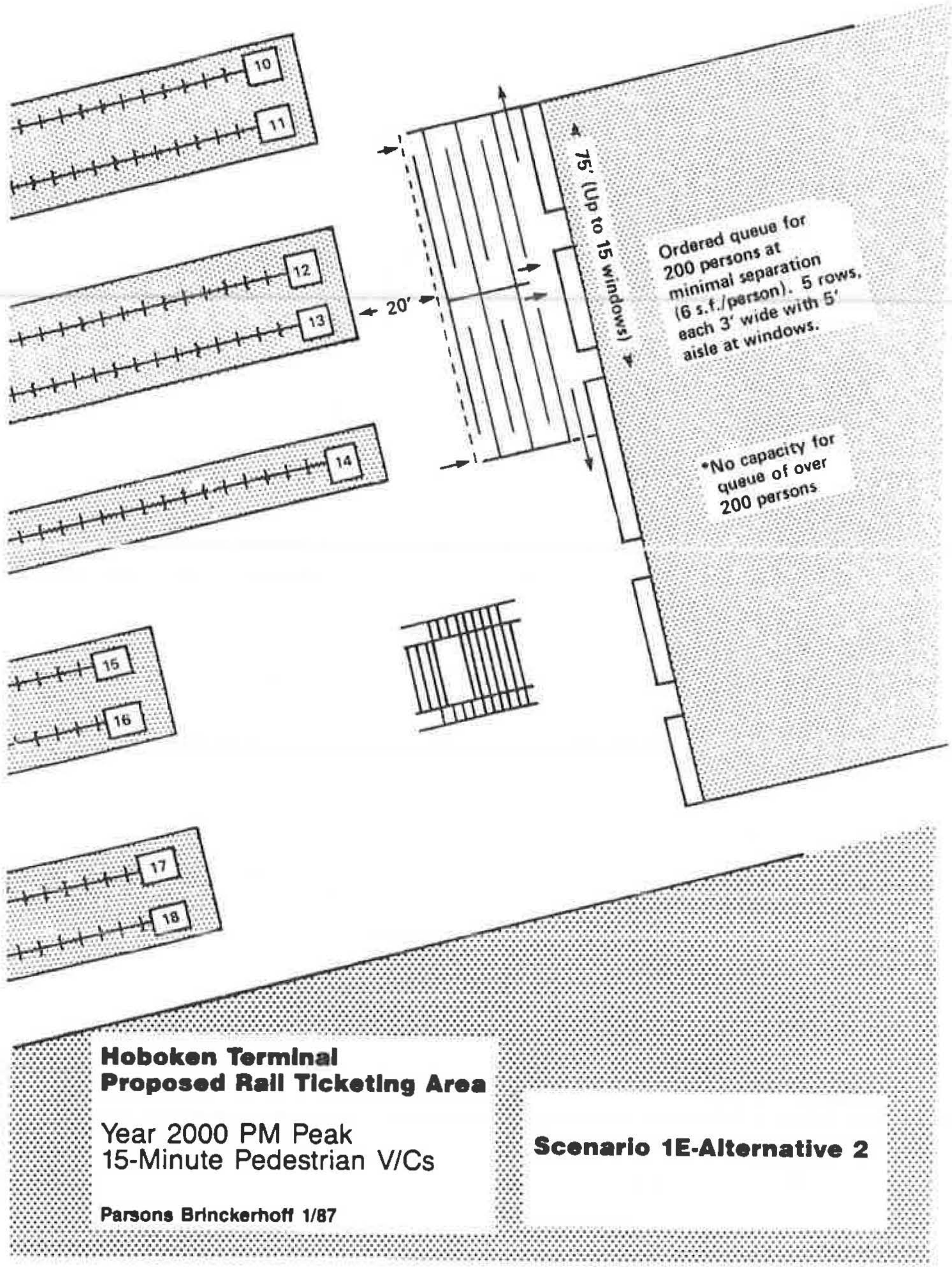

FIGURE 10 Ticket sales with ordered queues.

peak queueing at the ticket office. The queue will fluctuate in size during peak periods and may at times exceed this level.

- An ordered-queue arrangement (similar to a typical bank queue, with a single queue and movable barriers to channel the flow) provides a greater density of queueing, a smaller total required queueing area, and more equitable service to passengers than individual queues at each window.
- The site proposed for relocation of the ticket office—on the east wall of the rail concourse—is inadequate to serve the projected volumes of queueing passengers buying tickets as well as other passengers and pedestrians traveling in a north–south direction along the concourse. Ticket queues would block through movement and unacceptable levels of service and V/C ratios would result in this part of the rail concourse, even if TVMs are provided and an ordered-queue arrangement is used.
- Acceptable LOS can be achieved if the new ticket office is angled and recessed, thereby eliminating most of the retail space provided in this area.

Regardless of the site ultimately chosen for the ticket office, the use of TVMs, both at Hoboken Terminal and at outlying stations to supplement manual ticket selling, is strongly recommended. The placement of TVMs at Hoboken Terminal is the subject of continuing study, and a set of logical locations for TVM clusters is being developed. At any location, space for queueing at the TVMs will be provided away from the main pedestrian flows.

The pedestrian flow model is a flexible design tool for testing a variety of physical plans. As plans for the future of Hoboken Terminal change with fluctuating economic conditions, the flow model can be modified and adapted to simulate those

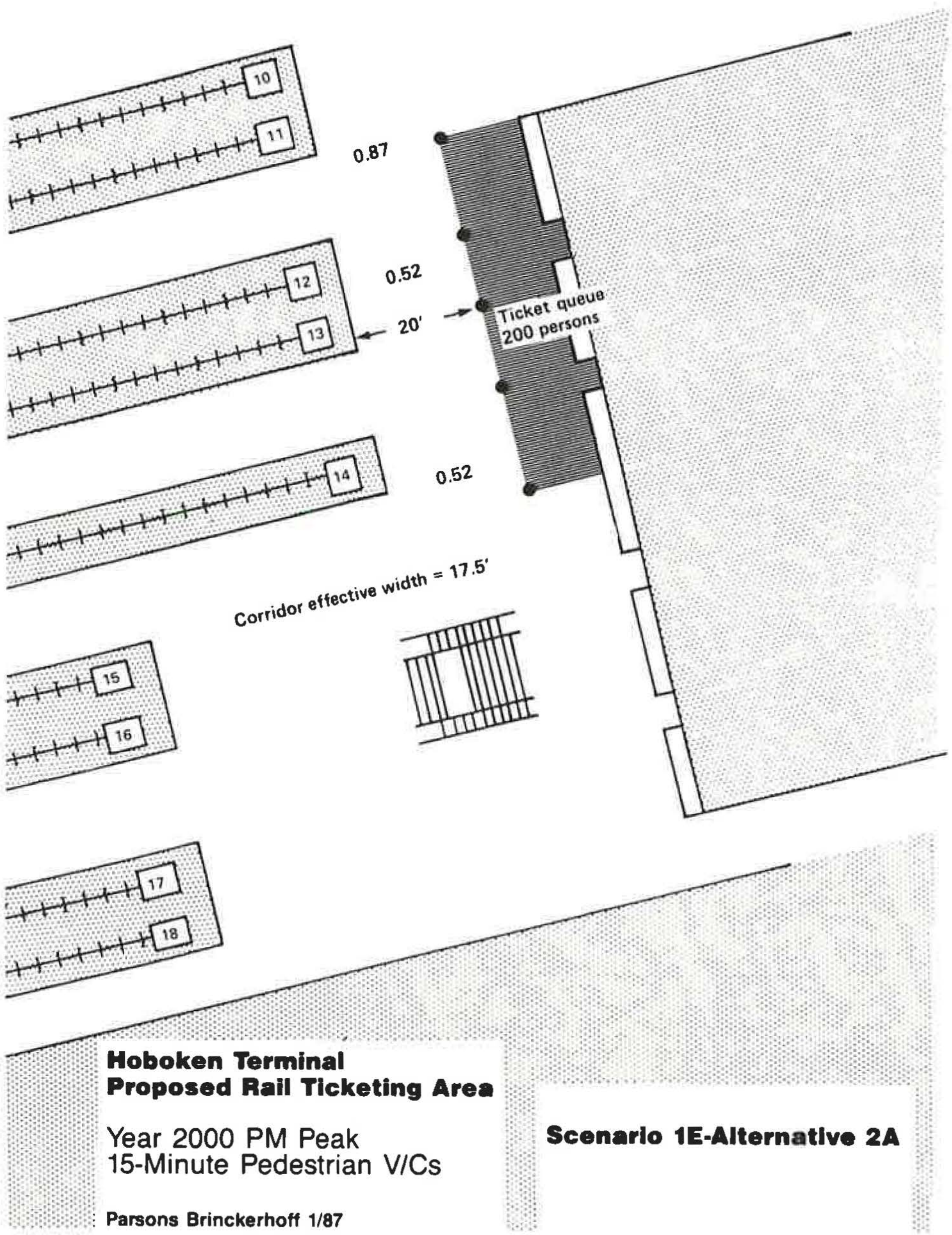

FIGURE 11 Pedestrian LOS ordered ticket queues.

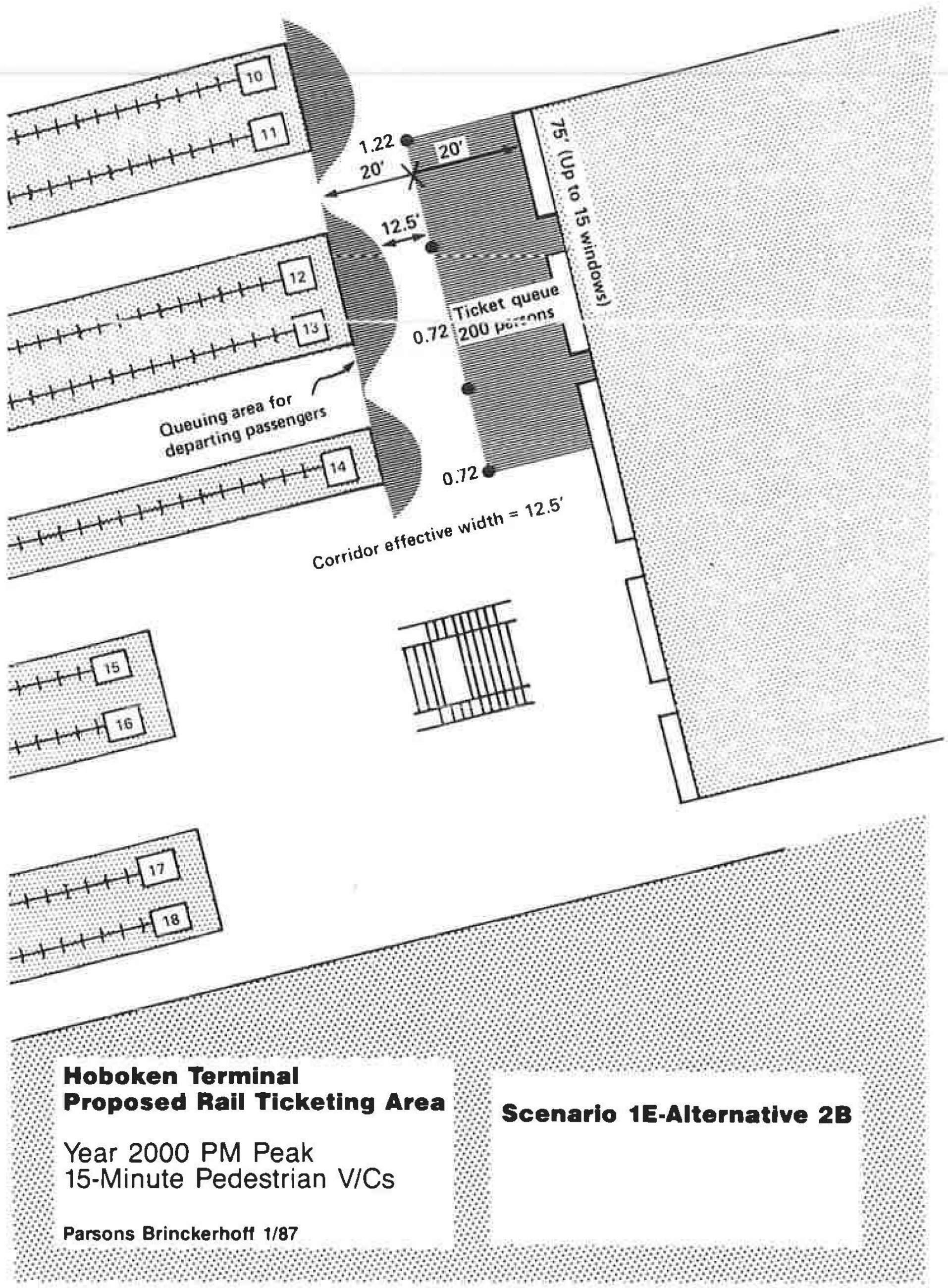

FIGURE 12 Pedestrian LOS with ordered ticket queues and departing passengers waiting.

changes. This type of flow model is well suited to intermodal transfer facilities, and it is expected that this methodology will be applied to other pedestrian facilities.

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Staging Area Simulation Model for Seattle METRO Bus Subway

JEROME M. LUTIN, MARK A. HORNUNG, AND JOE BECK

Documented in this paper is the development of a staging area simulation model for the Municipality of Metropolitan Seattle Transit Department (Metro) bus subway. The bus subway, currently under construction, will use dual-powered buses that can operate on diesel engines above ground and from DC electric traction power from an overhead trolley wire in the tunnel. Before construction of the bus subway took place, Seattle's Metro planners wished to analyze the operation of staging areas at each end of the subway. These staging areas provide locations for changeover of traction power for the dual-powered buses and for dispatching buses into the subway in "platoons." It was believed that these areas could present capacity constraints and might introduce delay into the proposed subway operations. An interactive simulation model was developed for use on an IBM-PC. This simulation model operated in real time, featuring graphic displays of the proposed staging area. The model allowed planners to measure schedule delays and throughput at the proposed staging areas. The model also allowed planners to evaluate the performance of bus dispatchers and automatic dispatching at these locations.

Discussed in this paper are the development and structure of an interactive computer graphic model of a typical bus staging area for the Municipality of Metropolitan Seattle Transit Department (Metro) (Seattle METRO) bus subway. The objective of the model development was to create a tool that would analyze the staging area operations and could possibly be used later in training dispatchers.

Described in this paper are the system configuration to be modeled, the capabilities built into the model, the displays, and the overall model operation and structure.

SYSTEM MODELED

The Seattle METRO tunnel, shown in Figure 1, is under construction as a 1.3-mi transit subway serving five stations and running under Pine Street and Third Avenue in downtown Seattle. Three stations will be built in the subway and one station at each end will be constructed at grade outside the tunnel portals. These end stations were the focus of the simulation model. Each end or portal station will include a transition area for changeover of the dual-powered buses between diesel and electric operation, as well as for passenger boarding and alighting. Additional functions are described herein.

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Underground stations will have platforms approximately 380 ft long. Service will be provided by a fleet of dual-powered articulated buses, which receive DC electric traction power from overhead trolley wires in the tunnel. Some existing trolley bus routes will also be rerouted to use the tunnel. The tunnel is being designed for future conversion to light rail, and joint use of the tunnel by both light rail vehicles (LRVs) and trolley buses during the conversion period is being considered. The tunnel will have one bus lane/LRV trackway operating in each direction.

Because the underground station platforms are long and many bus lines will operate in the tunnel, buses will stop at prearranged locations along the platform to reduce boarding time and passenger crowding on platforms. In addition, the tunnel is currently configured as a single-lane operation in each direction with no passing lanes except at stations. These considerations have led to the concept of operating buses in platoons of two to three buses. Each bus route using the tunnel would be identified as belonging to one of two to three groups, and buses from the same group would always stop at the same platform location at each station.

For model design purposes, it was assumed that three groups of bus lines would be used: *A*, *B*, and *C*, although the model was designed to be capable of representing up to four groups with no program changes required. Group *A* buses would always stop at the head end of the platform, Group *B* buses would always stop at the middle of the platform, and Group *C* buses would always stop at the rear of the platform. Each platoon was to include three buses, one from each group in appropriate sequence (*A*, *B*, and *C*) to stop simultaneously in the required locations. Peak-hour bus service is expected to require a capacity of 180 buses/hr in each direction, or one three-bus platoon/min.

BUS PRIORITIES

Each bus in the simulation has a priority that is used to determine the sequence in which buses are dispatched at the staging area. The priority is automatically applied in the automatic dispatch mode of the simulation.

- Deadhead buses: Those buses that enter the tunnel with no passengers aboard and return to a METRO base (bus garage). They display a METRO BASE destination sign. There are many of these in the a.m. peak, few in the p.m. peak. They have the lowest priority and should be dispatched somewhat before the lead bus of a platoon. The model permits them to be dispatched between platoons or in an empty platoon slot. These

FIGURE 1 Seattle METRO tunnel plan.

buses bypass the loading platforms in the model and enter the tunnel directly from a deadhead queue lane.

- Outbound entering service: These buses have no passengers aboard and are coming from a METRO base. They display a route destination sign. They are, however, beginning their runs and need to maintain schedules. At the staging area they enter queues for each platoon group and enter the loading bays from these queues. They must enter the tunnel in correct platoon sequence. In the a.m. hours there will be few buses in this category; in the p.m. hours there will be many. These buses will have a "medium" priority.
- Inbound terminating: These buses arrive loaded from their runs and will terminate at the opposite portal station. Because they will not pick up passengers in the tunnel (except perhaps to shuttle passengers among the tunnel stations), they do not have to be in platoon sequence. Because they have passengers on board, they are assigned a "medium-high" priority. These buses can enter any of the loading bays without regard to platoon designation, and are routed to the shortest queue in the automatic mode of the simulation, especially in the a.m. hours. In the p.m. hours, however, they would probably be directed into the appropriate platoon group to avoid reducing capacity of other platoon groups.
- Inbound through-routed: These buses arrive from specific routes and will be continuing on through the downtown area to an outbound route. These buses have passengers aboard and must proceed to the correct platoon loading bay and into the tunnel in correct sequence. They would both pick up and discharge passengers in the tunnel stations. These buses would receive the highest priority at the staging areas.

STAGING AREAS

The formation of platoons and the change from diesel to electric power will take place at staging areas located at both the north and south tunnel portal stations. Although the design was subsequently revised, the staging-area concept model is shown in Figure 2. Each area has a set of parallel bus boarding areas into which buses would pull to change power and stop for passengers. Each bus group could use only the lanes specifically designated for that group. A dispatcher would be stationed at the staging area to dispatch platoons into the tunnel using traffic control signal lights.

In addition to buses arriving from each group at the staging area, other buses were expected to be merged into the traffic stream. Deadhead buses being placed in service (especially during the p.m. peak period) would be handled by the dispatcher and sent into the tunnel in proper sequence. Delays caused by traffic, bus breakdowns, operation of wheelchair lifts, and other factors were assumed to cause irregularities in the bus stream. The dispatcher could dispatch partially filled platoons when necessary.

Given these assumptions, the task was to design and develop a working interactive simulation model of the bus staging areas to evaluate the performance of the various elements.

MODEL CAPABILITIES

The following capabilities were provided in the model to

1. Simulate the physical parameters of a bus staging area in terms of the flow of buses in time through queue areas and platforms; and typical event times for mode change, passenger stops, and bus movement. Record event-processing times and delays for each bus.
2. Perform simulation in real time, with keyboard signal inputs from a dispatcher, to allow training of dispatchers and evaluation of dispatch performance using prototype schemes.
3. Determine and evaluate ability of the dispatch function to maintain throughput capacity in peak periods, given the following: alternative staging area configurations, information displays, control signal configurations, bus priorities, and simulated delays.
4. Evaluate staging area configurations and platoon operation for number of platoon groups, assignment of bus lines to platoon groups, number of buses per platoon, number of bus bays, and required bus queue area.
5. Evaluate the effectiveness of various bus priority rules, traffic control signals, and information inputs to the dispatcher.
6. Evaluate loading time for variation in passenger demand.

EVALUATION MEASURES OUTPUT BY MODEL

The model was designed to be interactive and perform in real time, accumulate performance data, and, at the end of a simulation session, generate an output file of tabular data containing the information listed below. The performance data accumulated by the model consisted of a matrix in which each row represented a bus, and each column represented a characteristic of the bus, an event, or the time of starting or ending an event. Because buses can operate ahead of schedule, the model had to accommodate negative numbers in analysis of delay.

OUTPUT FILE INFORMATION

The model was designed to generate the following output file information:

1. Scenario description: Text containing date and time of run, configuration tested, dispatcher identification, run number, and special conditions modeled.
2. Simulation times: Simulated start time, simulated end time, and duration of simulation.
3. Throughput measures: Total number of buses input to staging area, total number of buses output to tunnel, total number of buses with passengers input to staging area, and total number of buses with passengers output to tunnel.
4. Platoon performance frequency distribution of number of platoons dispatched by size of platoon, number of platoon slots unfilled, and mean and standard deviation for time interval between platoons entering tunnel.
5. Bus delay performance: Total bus delay compared with bus schedule; total bus delay contributed by staging area; and mean and standard deviation for bus delay from schedule; mean and standard deviation for delay contributed by staging area; and frequency distributions of bus staging area delay by number of buses by delay time in appropriate intervals of seconds. Bus delay performance is reported for all buses and separately for each of the following four types of buses: deadhead buses, inbound through-routed buses, inbound terminating buses, and outbound entering-service buses.

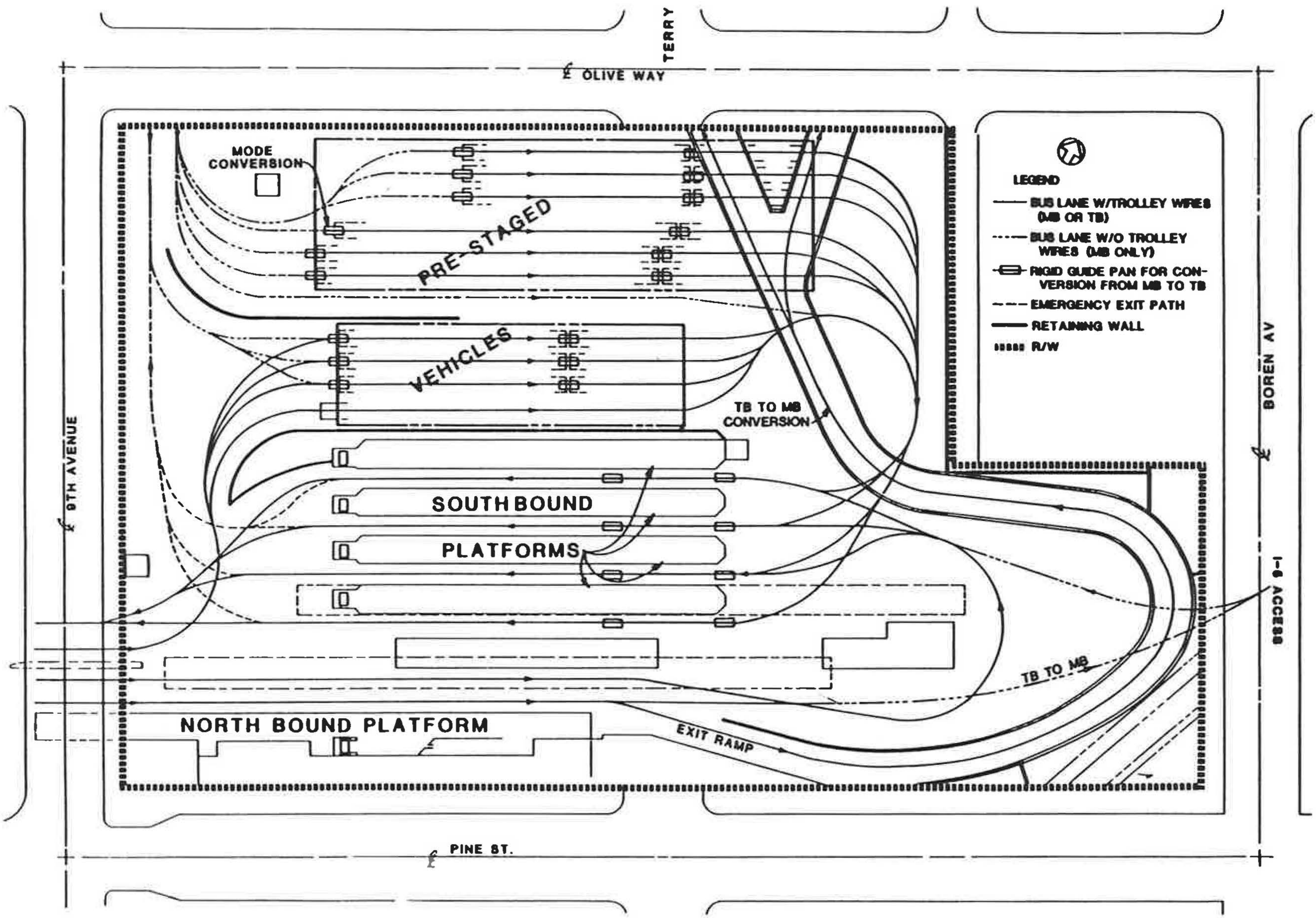

FIGURE 2 North staging area: Convention Center station.

6. Bus bay performance: Number of buses entering each queue and bus bay; number of buses leaving each bus bay; and maximum number of buses in queue at each queue and each bus bay, maximum number of buses in queue for entire staging area.

7. Individual bus performance schedule: The model can print this output file on request. Selected rows or columns can be printed as desired. A report print option is provided in the parameter setup for the model. Items included are

- Record sequence number
- Bus route number (preloaded)
- Bus destination sign text (preloaded)
- Bus run number (preloaded)
- Platoon group alphanumeric symbol (preloaded)
- Whether there are passengers on board at arrival (preloaded)
- Scheduled arrival time (preloaded)
- Schedule variation (preloaded)
- Actual arrival time (calculated)
- Time of entry to platoon bay, scheduled dwell begins (from simulation)
- Time scheduled dwell ends (calculated from above plus scheduled dwell time)
- Time bus leaves platoon bay (from simulation)
- Time bus enters tunnel (from simulation)
- Special notations (handicapped aboard, bus type, and so on) (preloaded)

INFORMATION DISPLAY

The model displays simulation information to the dispatcher on an inexpensive color CRT in real time while the simulation is running. The model operation is sufficiently fast to update the screen at least once every second. An IBM PC with standard color display will be used to operate the simulation. The only graphic capabilities required are the ability to display the normal 24 × 80 character matrix and to define colored rectangles.

Shown in Figure 3 is an example of the information display format to be produced by the model, and in Figure 4 an annotated version of this format. A digital clock, which advances in real time, is located in the upper left-hand corner. In the lower right-hand corner is an indicator of whether the simulation is being run in manual (dispatcher-controlled) or automatic (computer-controlled) mode and the direction of flow. The lower left-hand corner contains an area for the text messages (e.g., "stalled bus in tunnel") which will be loaded in during preprocess to appear at certain times for a certain duration.

Each bus is represented by a rectangle that contains the route designation, platoon letter, and arrival time. The background color of the bus varies by platoon (i.e., Platoon *A* in red, *B* in green, and so on). The foreground color of the writing on each bus change in three states: normal (yellow): loading/unloading (flashing yellow), and trolley pole raised, ready to proceed from platform (white). The loading platforms are at the center

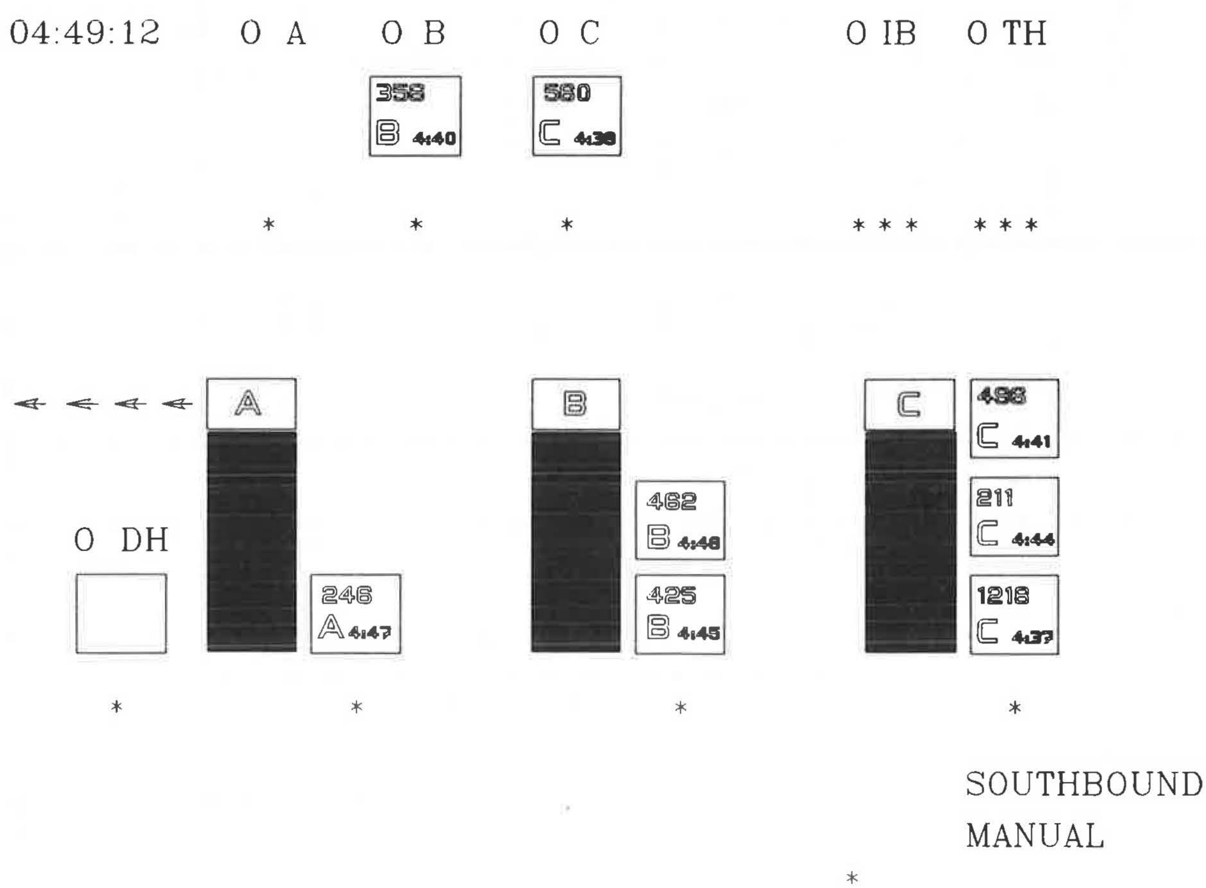

FIGURE 3 CRT display format.

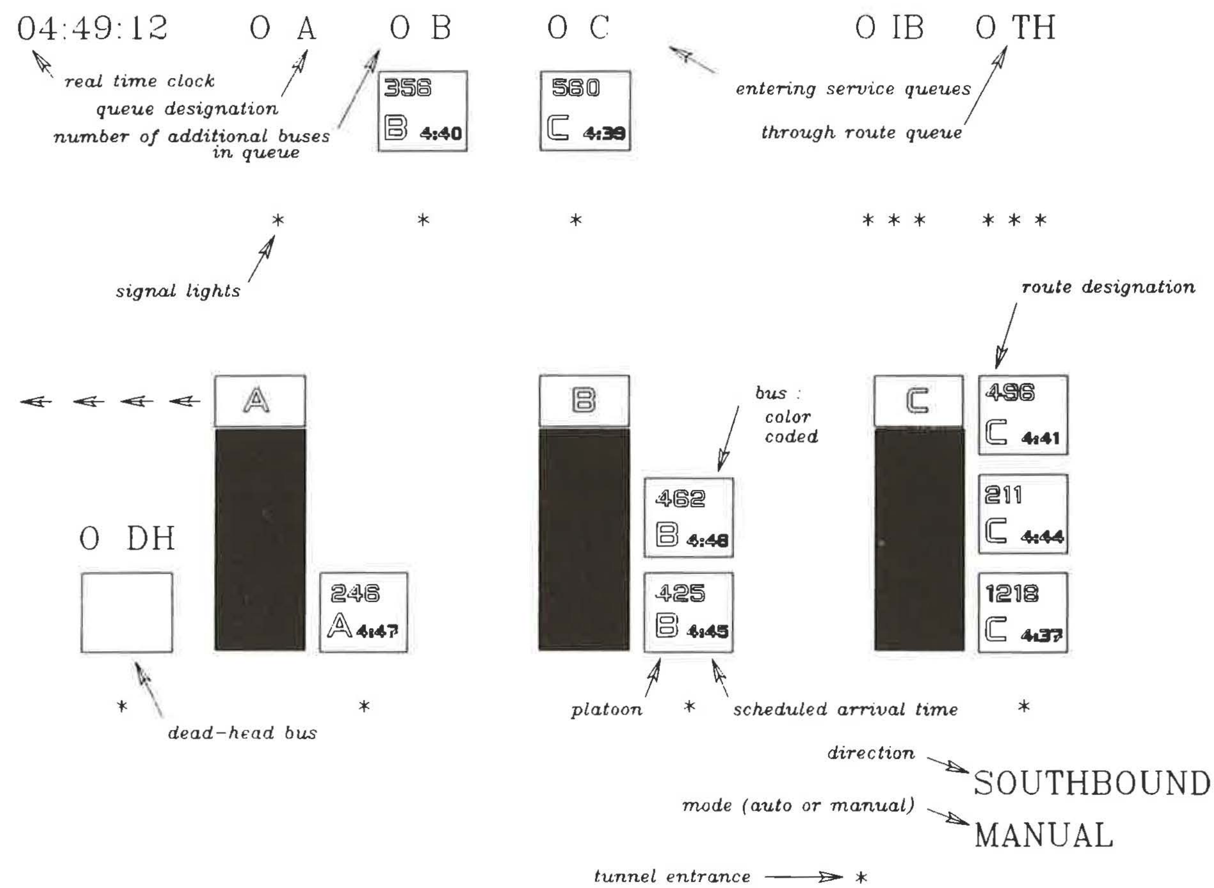

FIGURE 4 Annotated CRT display format.

of the screen and remain statically displayed throughout the simulation.

Bus symbols will first appear at the top of the screen in one of the arrival queues and leave the screen at the bottom at the tunnel portal. The various arrival queues (through bus, inbound unloading, and the entering service queues) are arrayed along the top of the screen, and the deadhead queue is at the left side. In each of these queues, only the first bus is shown. A number above the symbol for the first bus indicates the number of additional buses in the queue. The loading queues are next to the platform, with all buses shown up to the maximum of three per queue. At the bottom of the screen is the tunnel entrance queue. The display advances the bus symbols as the simulation advances in time. Bus symbols will not overlap one another. The exit from each queue is controlled by a signal, shown as an asterisk, located below that queue. The background color of the signals is red for stop and green for go.

INPUT DATA REQUIREMENTS

The input data in Items 1 through 6 in the following list are required to run the model. For data Items 1, 5, and 6, input data formats, test data sets, and interactive methods were provided to allow the user to input data from the keyboard without modifying the programs.

1. Bus schedule (variable),
2. Station configuration shown as a queueing network,
3. Control signal displays,
4. Rules to advance buses in the simulation,
5. Time period for the simulation (variable), and
6. Message text file (variable).

The bus schedule is a matrix in which each bus and its attributes are represented as a row. The items indicated as being preloaded in the discussion of the individual bus performance output file are input here. These are

- Record sequence number;
- Bus route number;
- Bus run number;
- Bus destination sign text (optional);
- Platoon group alphanumeric symbol;
- Passengers on board at arrival (logical code);
- Scheduled arrival time at staging area;
- Bus priority code (inbound through, inbound terminating, outbound entering service, deadhead); and
- Scheduled departure time from staging area.

An editing program is provided for the input schedule file. The file need not be in chronological order during the edit phase. The model is designed to sort it later.

The program provides an option to print out the input bus schedule before the interactive simulation run.

STAGING AREA MODEL

The staging area is represented as a queueing network composed of links and nodes in the program in a format that can be modified without modifying other parts of the simulator. Modifications include the ability to add, delete, and change the characteristics of queues. Preloaded queue characteristics include queue length in number of bus spaces (each bus space equals 75 ft), events that take place in the queue, queue gradient, platoon designation bus service type of designation, and condition logic codes to permit buses to enter or exit the queue. During the simulation, the queue characteristics change as the simulation progresses. These characteristics are number of buses in queue, available queue space (defined as total queue length in bus lengths minus the sum of all buses in the queue), time for a bus to transit the queue, and signal logic for queue entry and exit.

A diagram of the staging area network model is shown in Figure 5.

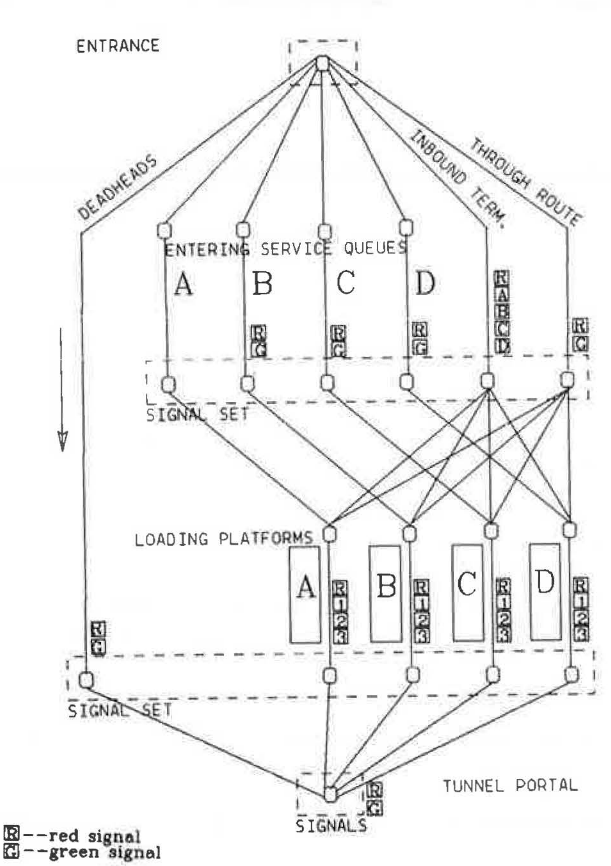

FIGURE 5 Staging area network model.

The program is capable of modifying the staging area at run time to any configuration that falls within the range of the model without changes to the program. One to four platforms may be used with one to four bus bays each. From one to four entering service queues can be specified to feed the bays, with the priority and group of each vehicle indicating the queue to be used. Queues can be set for automatic or flexible routing. Under the former, buses would always proceed to the bay corresponding to their platoon letter. With flexible routings, queues have multiple signal lights for each loading bay. Under manual control and flexible routing, the dispatcher can press a button that causes the signal to direct the bus into the corresponding platoon bay. Under automatic control and flexible routing, the buses are directed by the simulation to the shortest queue. Flexible routing is available at user option for the inbound terminating queue and the through-routed queue. The time to proceed from queue to bay is changeable without modification to the program, as are loading times and power-conversion times.

SIGNAL SYSTEM AND RULES TO ADVANCE BUSES

The signal system is represented by a set of logical condition codes controlled by function keys, which are polled in real time, and for which a change in state results in appropriate simulated bus maneuvers and signal displays. Codes are reset automatically by the program to simulate treadle and timer activation of traffic signals. The signals may also be set automatically by giving instructions on which buses should receive priority in the parameter setup. The signal system displays and positions are shown in Figures 3 and 4. The tunnel portal signal is controlled by the dispatcher. It is set in the parameter setup phase of the model operation.

Rules to advance buses are incorporated into the model and include specifying the appropriate route codes to govern the sequence of events encountered by each bus. A bus will proceed from the entry point to the approach queue and then to the loading bay designated for its platoon. For the bus to advance into the approach queue and loading bay, there must be a slot available. For the bus to advance from the loading bay to the departure queue, the following conditions must exist:

1. All passenger loading and unloading complete,
2. Mode change complete,
3. Proceed signal from the dispatcher, and
4. Slot available in the departure queue.

For the bus to proceed from the departure queue into the tunnel, it must have a proceed signal displayed. The model includes a dwell time variable to simulate conditions 1 and 2.

Preloaded into the model by the user are a start and an end time for the simulation period that may be at any point within the bus schedule chronology provided to the simulation.

The message text file contains the text of user-input preloaded messages to appear on the screen. The time the message is to appear and the duration of the message display are contained in the file.

MODEL OPERATION AND STRUCTURE

The model is used in the following sequence: input schedule editing, parameter setup, schedule variance input, interactive simulation, and output editing.

Input schedule editing: The input bus schedule is modified as needed. The editing function can be used by a trained analyst and does not require reprogramming.

Parameter setup: A list of parameters and variables is displayed at the time the simulation program is to be loaded. The simulation start and end times are input as variables. A text message describing the conditions of the run can be input by the user. This text is printed at the head of the output statistics file. All bus performance characteristics, such as acceleration and deceleration rates, speeds, link travel times and dwell times are represented by variables that can be changed if necessary. The number and size of the bus queues is changeable in the parameter setting.

The parameter setup includes an option to select automatic or manual operation of the model. Under the automatic mode, buses advance in the simulation without keyboard signal inputs from a dispatcher. Under the manual dispatch mode, the model advances buses from the queues only on keyboard input of appropriate signal commands by the dispatcher as the simulation is running. Default values are provided for each parameter. The default values can be overridden by user command.

The parameter setup includes an option to disable the signals shown in Figure 4 as controlling movement of buses from the entering service queues to the loading platforms. This permits operation of the model under the manual mode with dispatcher control only at the signals controlling the advance of buses from the loading bays to the tunnel portal.

Schedule variance input: For each simulation run, the model presents to the user the option to add schedule delay. Schedule delay is chosen from an empirical distribution of Seattle bus delay using a random number generator to select the amount of delay. The delay is added to (or subtracted from) the scheduled arrival time for each bus to determine the actual arrival time. The bus schedule file is then used in chronological order by actual arrival time. A test distribution was obtained from Seattle METRO and used in the model.

Interactive simulation: After the steps already listed have been accomplished, the simulation program is loaded. Loading initializes all arrays and temporary variables. Pressing a start key initiates bus arrivals and generates the screen display. Pressing signal control keys advances buses under the manual mode. An internal clock inputs buses according to the schedule and provides time recording for each event. The bus performance schedule is continually updated. The simulation runs and terminates normally when (a) the scheduled stop time is reached, (b) the end of the bus schedule is reached, or (c) the stop key is pressed. Pressing the stop key stops the simulation clock and keeps all variables and data arrays intact. Pressing the start key restarts the simulation from the point at which it terminated. All other keys are disabled during the simulation.

Output editing: After the simulation is stopped, a command can be input to read the bus performance file, calculate the evaluation measures, and route the formatted output to the terminal for scanning. The program contains an option to route the output file to a printer or other hard copy device.

Shown in Figure 6 is a block diagram of the overall model structure. In this figure, the central portion indicates the interactive part of the simulation. The simulation contains three basic components: the clock, simulation, and display formatter.

The clock controls the operation of the simulation model. It is started and stopped by the user. The clock advances every second and performs the following functions: updates the clock display, determines the execution of the next event, updates the monitor display, checks to maintain the real-time simulation, and updates the bus performance matrix.

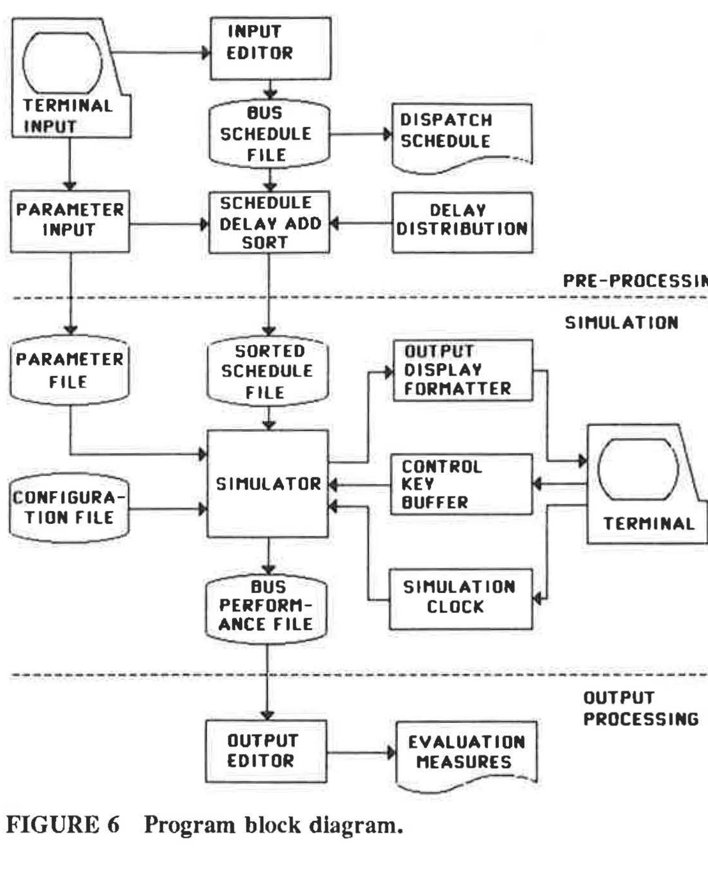

FIGURE 6 Program block diagram.

The simulator starts and stops the clock, enters buses into the approach queue, checks the queue capacity, advances buses into the loading bays, simulates load/unload functions, raises the trolley poles, and advances buses on command.

The display formatter accepts data, refreshes the static graphic display elements from the simulator, and updates the following information on the screen: clock, bus positions, passenger movements, bus symbol destination sign display changes, trolley pole up/down, signal displays, and text messages.

IMPLEMENTATION MODE

The program runs on an IBM PC with programming in the STSC APL language. An IBM PC/XT, with 256K memory, a 10-megabyte hard disk, floppy drive, 8087 math coprocessor, and a 384K extra memory card, was used. A standard IBM or IBM compatible color monitor displaying 24 rows of 80 characters is sufficient for the simulation display.

CONCLUSION

The model was turned over to the Seattle METRO and was used extensively in analyzing the operation of the staging areas. Use of the model led to increased confidence in the unique transit concept to be employed in the tunnel.

One significant result was that the Transit Department decided to use an *A-B* platoon configuration rather than an *A-B-C* configuration to begin operations. This decision was based on the expectation that overall platoon formation time would be shortened. A platoon would be dispatched with a maximum of two *A*s and two *B*s and could pick up a delayed bus at a tunnel station and grow to a five-bus platoon.

The team of programmers working on the project developed a speeded up version of the model that ran well over 10 times faster than the simulation version. Speeding up of the simulation was used for testing and debugging purposes.

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