1152

TRANSPORTATION RESEARCH RECORD

Rapid Rail Transit and Planning Tools

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C. 1987

Transportation Research Record 1152
Price: $9.00
Editor: Edythe Traylor Crump
Typesetting and Layout: Lucinda Reeder

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Printed in the United States of America

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

Rail rapid transit and planning tools.
p. cm. — (Transportation research record, ISSN 0361-1981 ; 1152)
ISBN 0-309-04661-0
1. Street-railroads. 2. Subways. I. National Research Council (U.S.). Transportation Research Board. II. Series.
TE7.H5 no. 1152a
[HE4211]
380.5 s—dc19
[388.4'2'068] 88-20035
CIP

Sponsorship of Transportation Research Record 1152

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Transportation Research Record 1152

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Contents

Foreword

Transit station design is the subject of the first three papers. Benz uses a time-space approach that considers pedestrian facilities as time-space zones in which moving and standing pedestrians require different amounts of space and occupy that space for different periods of time. He demonstrates how the method can be used to reflect various platform conditions and configurations. Hall uses an analytical queueing model for predicting passenger delay in a busy rapid transit station. The model accounts for the "lumpy" arrival pattern of passengers exiting trains. The size of the headway reflects the lumpiness of the arrival pattern. When headway is small, passenger delay is small and when it is large the delay per passenger is large. In the third paper, Ishimaru and Calkins describe a prototype system for the preliminary design of transportation interface facilities and show how computer-aided design techniques can enhance the station design process.

Chapleau et al. present an impact analysis of a subway extension in Montreal. The analyses are based on large-scale origin-destination surveys. The nature of the data allowed some disaggregate studies to identify the main impacts relating to the extension. The impacts varied; the extension did not reverse the tendency of decreasing population. It did, however, have a positive influence on transit ridership.

The subject of train operations is treated in two papers. Miller and Bunt describe a model that simulates light rail vehicle operations on the Queen Street Route in Toronto. The model is designed to analyze the impact of a range of operating strategies and policies on streetcar performance. These include alternative short-turn strategies, vehicle monitoring systems, traffic signal priorities, reserved rights-of-way, and larger vehicles. Hoess summarizes the results of a study concerned with identifying and evaluating the issues and problems that are inherent in the conversion of older U.S. rapid-transit multiple-unit trains to one-person operation.

The engineering design features of rapid transit systems are also discussed in this Record. Shaffer presents an overview of the historic aspects of stray currents created by DC-powered transit system operations and their control. He presents theoretical aspects of the reasons for stray currents and the methods available for their control with practical applications for new systems and revitalization programs for old systems. Gildenston reviews the past use and future potential of direct fasteners. He discusses past procurement practices and proceedings with suggestions for possible improvements to the balance between trackwork and vibration requirements in specifications for direct fixation fasteners.

Transit Platform Analysis Using the Time-Space Concept

GREGORY P. BENZ

The time-space concept is a new approach to the planning and design of pedestrian facilities. Conceptually, it considers pedestrian facilities as time-space zones in which moving and standing pedestrians require different amounts of space and occupy that space for different periods of time. The subject of this paper is the application of the time-space approach to a transit station platform. The time-space approach can address many issues that cannot be considered by using traditional analytical procedures. These issues include the (a) duration of peak loadings, (b) amount of time spent waiting, (c) amount of walking on the platform, (d) location of access points, (e) spatial distribution of passengers on the platforms, and (f) the way in which passengers actually use the platform. This paper shows how the time-space concept can be used to analyze platforms at a relatively simple, aggregate level, and then goes on to develop more detailed, disaggregated analyses, exploring how the level of detail at which the problem is analyzed affects the results. The location of the platform access stairs is changed in a final example to demonstrate the ability of the time-space method to reflect various platform conditions and configurations. Examined in this application study is a platform of a downtown bus tunnel station in which buses will operate in platoons of four vehicles at close headways. However, the time-space concept presented here has wide application to many types of facilities that must handle large volumes of pedestrians involved in many types of activities.

From the standpoint of passenger level of service, platforms have been difficult spaces to analyze. Platform shape and configuration are usually dictated by various systemwide factors or site constraints. Train or vehicle length establishes platform length. Structural considerations, vertical circulation requirements to meet emergency evacuation standards, and operational parameters affect platform width; type (high or low, side or center); space available for passengers; and entry/exit locations.

The traditional analytical procedure does not take into account several significant variables. The maximum accumulation of people waiting on the platform during the peak period, typically estimated during the ridership forecasting step, is multiplied by a waiting, or queue, area per person to determine the platform area required to accommodate the passenger load. The space requirement is compared with the space available on the platform. Elements not considered during the usual study of platform space include the (a) duration of peak loadings, (b) amount of time spent waiting, (c) amount of walking on the platform, (d) location of platform access points, (e) spatial distribution of passengers on the platforms, and (f) the way in which passengers actually use the platform.

Parsons Brinckerhoff Quade & Douglas, One Penn Plaza, New York, N.Y. 10119.

The pedestrian time-space concept can analyze platforms and address the issues previously listed, however, because it considers the time passengers spend walking and waiting on the platform and the space they require while involved in these activities. The manner in which the time-space concept can be used to analyze platform activity and performance is demonstrated in this paper. Initially the platform is modeled at a relatively simple, aggregate level and then more detailed, disaggregated analyses are developed, with an exploration of how the level of detail at which the problem is analyzed affects the results.

TIME-SPACE CONCEPT

Conceptually, the time-space method considers pedestrian facilities as time-space zones with moving and standing pedestrians requiring different amounts of space and occupying the zones for different periods of time (*1*). Time-space is the product of an area (or space) and a time period (*2*). For example, a pedestrian walking through a waiting room may require up to 24 ft^2 of space for movement, but will occupy that space for a relatively short period of time (e.g., 10 sec). This would be 240 ft^2-sec or 4 ft^2-min. A pedestrian waiting on a platform requires 5 to 10 ft^2 for a longer period of time, such as up to 5 min. This would be equivalent to 25 to 50 ft^2-min. The time-space concept considers the type of activities occurring in a space within a given time period and the number of people involved in each activity. The amounts of time-space required for each activity are summed and compared with the time-space available or proposed within the facility.

Mathematically, the time-space concept can be described as

$$T\text{-}S_{req.} = \sum P_i M_i T_i \qquad (1)$$

where

$T\text{-}S_{req.}$ = time-space required,
P_i = number of people involved in activity i,
M_i = space (area) module required per person for activity i, and
T_i = time required for activity i.

$T\text{-}S_{req.}$ is then compared with the time-space available ($T\text{-}S_{avail.}$) to determine the adequacy of the space for the expected activities. $T\text{-}S_{avail.}$ is the product of the area available ($A_{avail.}$) and the time it is available ($T_{avail.}$), or

$$T\text{-}S_{avail.} = A_{avail.} \times T_{avail.} \qquad (2)$$

The first application of the time-space concept was to sidewalks, corners, and crosswalks, as presented in the 1985 *Highway Capacity Manual* (*2*). Application of the time-space concept to a commuter terminal corridor and waiting area was demonstrated by Benz (*3*). Furthermore, Grigoriadou and Braaksma described the application of the time-space concept to a station platform (*4*). Their approach treats the portion of the platform analyzed as one zone and examines the level-of-service conditions during passenger alighting periods and the gap between the arrival and departure of trains. The approach described in this paper demonstrates the merits of subdividing the platform into a set of subareas or zones and comparing the time-space required in each zone to what is available.

One of the most important elements in understanding and using the time-space concept is the pedestrian level-of-service standards, as developed by Fruin in *Pedestrian Planning and Design* (*5*). These criteria and other essential principles are described in Fruin's book, and also in the 1985 *Highway Capacity Manual* (*2*) and *Urban Spaces for Pedestrians* (*6*). These sources should be consulted for further information on the fundamentals of pedestrian level of service.

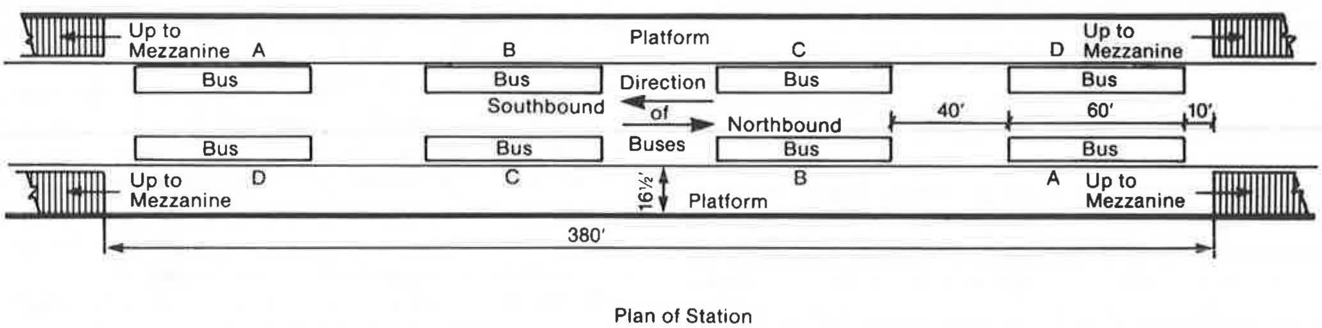
APPLICATION STUDY DESCRIPTION

An underground transit station platform served by buses is described. The station is part of a downtown bus tunnel project. The buses—60-ft, 3-door, articulated vehicles—operate through the tunnel in platoons of four. The stations are side platform arrangements with stair connections from the ends of the platforms to the fare control mezzanine above. Each platform is 380 ft long by $16^1/_2$ ft wide (see Figure 1).

The bus routes operating through the tunnel are clustered into four groups. Routes having similar service areas are grouped together so that riders who have the choice of several routes for their trips will find their route options within one group. Each of the four groups, labeled A through D, has a designated loading location on the platform. Each four-bus platoon will typically have one bus from each group ordered in the A-B-C-D sequence. Riders will go to the A location to board a bus from the A group and so on. The platforms are paid areas so fares are not collected onboard the vehicle. Therefore, all three sets of bus doors can be used by entering passengers.

The afternoon peak 15 min-period has the heaviest passenger loads on the platforms because downtown commuters heading home are waiting for their buses. During the peak 15 min, 910 people will arrive on this platform (one of two side platforms) by the stairs at each end to board the buses. Of the 910 passengers, 474 will use the south stairs and 436 will use the north stairs. Another 40 people will arrive by bus on the platform, and when exiting they will be evenly split between the two sets of stairs. Passengers from each stair are evenly distributed among the four bus loading locations. (Conceivably, passengers would tend to use the stair closest to their respective loading location. Thus, the passengers from each stair would not necessarily be evenly distributed among the loading locations.)

Many types of platforms are subject to short-duration, peak-load conditions created by train arrivals or departures—relatively discrete events. This analysis examines a repetitive series of events that constitute a type of steady-state condition within a design period. Platoons of buses arrive at the platform with relatively short intervals between arrivals and departures throughout the analysis or design period.



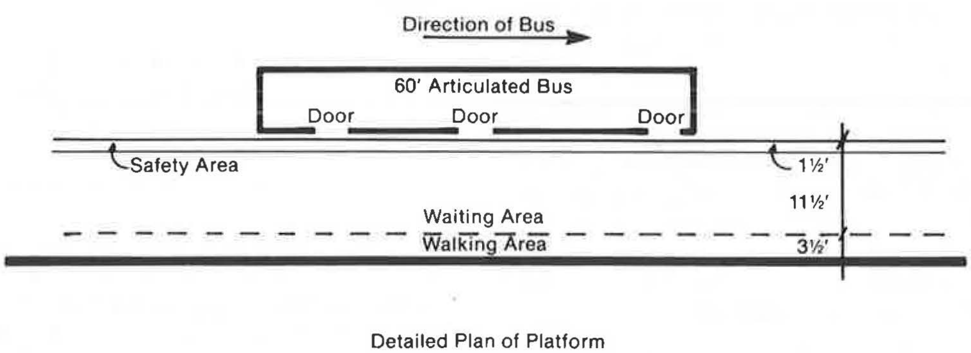


FIGURE 1 Downtown bus terminal station platform.

TIME-SPACE APPROACH TO PROBLEM

The platform is analyzed here using the time-space technique at three levels of detail. The first level treats the platform as one space and uses average values for the walk and queue times for all the passengers. The second level of detail treats walk and queue times separately for each of the four loading locations while still treating the platform as one space. The third level of detail divides the platform into time-space zones representing various areas used for walking or queueing and areas that generally are not used by passengers.

Level of Detail 1

The platform and the passenger activities on it are treated in an aggregated manner. The platform is treated as one large time-space zone, and average walk distances and wait times are used to model passenger activities.

Time-Space Available

The platform is 380 ft long and has an effective width of 15 ft. (A 1½ ft-buffer-strip is deducted along the platform edge.) Using a 15 min analysis period, the time-space available on the platform is 85,500 ft^2-min.

Walk Time-Space Required

Referring to Figure 2, the average distance a passenger will have to walk between the south stair and the midpoint of the bus loading area is 180 ft; the average distance between the north stair and the loading midpoint is 200 ft. (The midpoint of the loading bus location is not the middle of the platform length because of the bus vehicle door location and the operational requirements of the bus platoon.)

The average walking speed is 250 ft/min or 4.1 ft/sec. At this walk speed, the area per person is 22 ft^2. The average walk time between the stairs and the loading/unloading midpoint is 44 sec for the south stairs and 49 sec for the north stairs. From the south stairs, 474 people will walk to the bus loading area, whereas 20 people will walk in the reverse direction. Each of the 494 people will take 44 sec and 22 ft^2; the walk time-space requirement is 7,970 ft^2-min (494 people × 44 sec × 22 ft^2/sec ÷ 60 sec/min). On the north stair, the walk time-space required is 8,193 ft^2-min (456 people × 49 sec × 22 ft^2/sec ÷ 60 sec/min). The total walk time-space required is 16,163 ft^2-min.

Queue Time-Space Required

The average wait time per passenger on the platform will be 5.4 min (as determined from operational studies). Although buses will be much more frequent than indicated by the average wait time, every bus platoon will not necessarily include the bus route for every passenger. Several bus platoons may pass before one containing a particular passenger bus route arrives. The 910 passengers (474 + 436) will require 7 ft^2 per person. The queue time space required is 34,398 ft^2-min (910 people × 5.4 min × 7 ft^2).

Total Time-Space Required

The total walk time-space required is 16,163 ft^2-min, and the total queue time-space required is 34,398 ft^2-min. The total time-space required for passenger activities on the platform is 50,561 ft^2-min. The platform has 85,500 ft^2-min available so that the overall platform area is adequate to meet expected passenger loads.

Level of Detail 2

In the second example, calculation of passengers' time-space requirements considers the different paths and waiting times for each of four loading areas. The total time-space available is the same as in the previous example—85,500 ft^2-min. Figure 3 shows a diagram of the platform, with the pedestrian flow volumes between the stairs and loading locations indicated.

Walk Time-Space Required

The data in Table 1 show the calculation of time-space required by walking on the platform. The four loading locations are designated by the letters A through D. The two sets of stairs between the platform and the mezzanine are designated I for the south set and II for the north set. For each path, the distance is listed along with the walk time, calculated by using a walk speed of 250 ft/min, or 4.1 ft/sec. At this speed, the area per person required is 22 ft^2. The number of people walking between each stair-loading location pair is shown—those going to and from the buses. The walk time-space required for each path is the product of the walk time, the area per person, and the volume of people. The total walk time-space required (the sum of the individual path requirements) is 16,129 ft^2-min.

Queue Time-Space Required

The average wait time at each of the four loading locations is different because of differences in the number of bus routes that require stopping at each location and the headways. The average wait time by location is given in Table 1. The queue time-space by boarding location is the product of the average

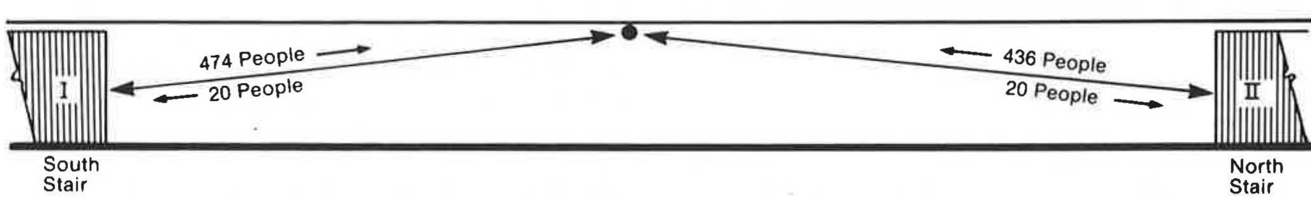
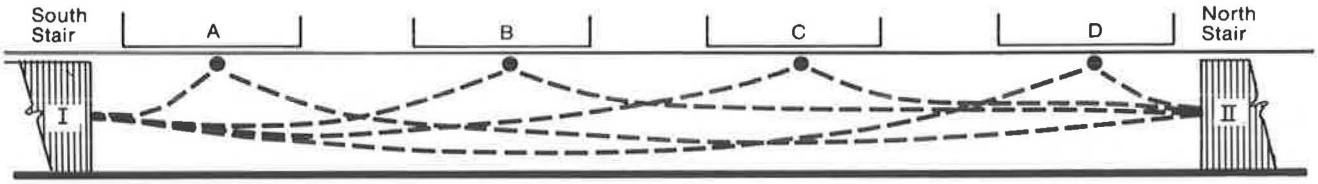


FIGURE 2 Platform study level of Detail 1: simple network.



Peak 15-Minute Passengers Between Stair I and Loading Location:

	A	B	C	D	Total
Into Station	118	119	119	118	474
Out of Station	5	5	5	5	20
Total	123	124	124	123	494

Peak 15-Minute Passengers Between Stair II and Loading Location:

	A	B	C	D	Total
Into Station	109	109	109	109	436
Out of Station	5	5	5	5	20
Total	114	114	114	114	456

FIGURE 3 Platform study level of Detail 2: complex network.

TABLE 1 TIME-SPACE CALCULATIONS PLATFORM STUDY LEVEL OF DETAIL 2

WALK TIME-SPACE

STAIR	LOADING LOCATION	DISTANCE (ft)	WALK TIME @ 4.1ft/sec (seconds)	VOLUME	TOTAL WALK TIME (min.)	WALK TIME-SPACE @ 22sqft/per. (sqft-min)
I	A	31	8	123	16	341
I	B	130	32	124	66	1442
I	C	230	56	124	116	2551
I	D	330	80	123	165	3630
II	A	350	85	114	162	3568
II	B	250	61	114	116	2549
II	C	150	37	114	70	1529
II	D	51	12	114	24	520
			TOTAL WALK TIME-SPACE REQUIRED			16129

QUEUE TIME-SPACE

LOADING LOCATION	NUMBER OF PEOPLE WHO WAIT	AVERAGE WAIT TIME (min.)	AVERAGE SQFT/ PERSON	TOTAL WAIT TIME-SPACE (sqft-min)
A	227	5.8	7	9216
B	228	6.8	7	10853
C	228	3.7	7	5905
D	227	5.4	7	8581
TOTAL QUEUE TIME-SPACE REQUIRED=				34555

TOTAL TIME-SPACE REQUIRED = 50684 SQ.FT-MIN

TOTAL TIME-SPACE AVAILABLE = 85500 SQ.FT-MIN
(380 FT.*15 FT.*15 MIN.)

wait time, the number of waiting passengers, and the waiting, or queue, area per person (7 ft^2 per person). The total queue time-space required is 34,555 ft^2-min.

Total Time-Space Required

The walk time-space required is 16,129 ft^2-min, and the total queue time-space required is 34,555 ft^2-min. The total time-space required by passenger activities is 50,684 ft^2-min. This time-space requirement is less than the time-space available, 85,500 ft^2-min, which indicates that overall the platform is adequate.

Increasing the analysis level of detail results in nearly identical time-space requirements—50,561 ft^2-min for the previous, more aggregated analysis versus 50,684 ft^2-min determined here. No apparent benefit was gained from this added level of detail. The platform itself was still treated as one space. In the next example, the platform is subdivided into zones, and the time-space analysis is performed for each zone.

Level of Detail 3

In the third example, the platform is subdivided in time-space zones that encompass the various types and intensities of passenger activities, and the time-space required in each zone is compared with the time-space available. This technique models the ways in which platforms are actually used.

Platform Time-Space Zones

Two primary passenger activities occur on platforms: walking and waiting. These activities do not occur evenly over the platform area but take place in varying degrees on specific portions of the platform. Some portions are used primarily for walking, in this case those near the stair connections to the mezzanine and along the back edge of the platform. Other areas are used primarily for waiting, in this case the four loading and unloading locations. These four zones also are areas where walking takes place as people enter and leave the zone. Some areas of the platform, such as the "dead" areas between the bus loading locations, have little if any walking or waiting activity; because of their locations they are not used by passengers.

In this example, the platform is divided into time-space zones representing areas where walking and waiting activities occur in varying degrees. The total time-space required for walking and waiting activities in each zone is estimated and compared with the time-space available in each zone. In this way, the performance of the platform can be analyzed in a detailed disaggregated manner to determine how the various parts perform rather than in an aggregated manner, such as in the two previous examples, which may cover up problems. Treating the platform as a single area, or even as several large areas, does not recognize the way platforms are used and may give credit to areas that are not used, hiding overloaded areas.

The platform in the application study is divided into 14 zones (Figure 4). Zones E and N are the vestibules of the stairs and areas primarily used for walking. (The peak period when the primary passenger movement is into the station to board the buses is examined in this study. If the opposite peak period was analyzed; that is, when the primary passenger movement was out of the station, Zones E and N might also have queueing activity at the base of the stair because of the bulk discharge of passengers from the bus platoons.) Zones F, H, J, L, and M are along the back portion of the platform away from the platform edge, which is used as a corridor for walking between the loading/unloading locations and the stairs. (Presumably, some means will be provided to encourage this use.) Zones A, B, C, and D are the loading/unloading areas where passengers queue to wait for the buses. The passengers also walk in these areas to wait for the bus or to leave after stepping off the bus. Zones G, I, and K are the areas along the platform edge between the loading/unloading zones that are not generally used by passengers. The unused areas fall between the designated loading areas and are used only if the adjacent areas become overloaded.

The 16.5-ft platform width is divided into three zones: 3.5 ft along the back edge is for walking and thus is the width of Zones F, H, J, L, and M; 11.5 ft is for waiting, loading, and unloading and is the width of Zones A, G, B, I, C, K, and D; and the remaining 1.5 ft is a safety strip along the edge where vehicle movements take place; it is not part of the space available for passenger activities.

The length of the platform is divided as follows: each of the four loading/unloading zones is 60 ft long, reflecting the length of the articulated bus (all three sets of doors are used for loading and unloading). The spaces between the vehicles, not used by the waiting passengers, are 40 ft wide. The two vestibules at the ends of platforms are 10 ft long along the vehicle edge but widen to 20 ft along the back edge. The walk portion of the platform is divided according to changes in walk volumes between the various loading/unloading areas and the stairs (see Figure 4). The area of each zone is given in Table 2.

Time-Space Available

The time-space available in each of these zones is determined by multiplying each area (in square feet) by the 15-min analysis period. The results are given in Table 2.

Time-Space Required

The total time-space required for each zone consists of the walk time-space and waiting (or queue) time-space requirements in the zone.

The walk time-space requirement for each zone is a function of the volume of people who walk through the zone, the time spent walking through the zone (which is a function of the walk distance and the walk speed), and the space (area) per person required for walking (at the walk speed used earlier). The walk time-space requirement for a zone is computed as follows:

$$T\text{-}S\ walk_i = P_i \cdot T_i \cdot M_v \tag{3}$$

where

$T\text{-}S\ walk_i$ = time-space requirement for walking for zone i;
P_i = volume of people walking in zone i;
T_i = walk time in zone i, which is a function of walk distance (d_i) and walk speed (v) or d_i/v; and
M_v = area per person required at walk speed v.

Figure 4 also shows a diagram indicating the volumes of people walking through each zone during the 15-min analysis period. An estimate of the walk speed can be determined by calculating the level of service in walk zones along the back edge of the platform. The 15-min, two-way walk volumes range from 554 to 583 people, which for the 3½-ft wide space, result in flow rates of 10.6 to 11.1 people per min per ft width. The flow rate, equivalent to Level of Service C/D, requires a space module of 22 ft^2 per person and has an average walk speed of 245 ft/min, or 4.1 ft/sec. Average walk distance (in feet) in each zone is listed in Table 2, along with the walk time (in seconds) using a walk speed of 4.1 ft/sec and the volume of people walking through the zone. Multiplying the volume of people for each zone by the walk time in a zone results in the total walk time in a zone. Multiplying total walk time required by the 22-ft^2 per person space module, the walk time-space for a zone is determined. The calculations of the walk time-space requirement are given on the left-hand side of Table 2. Note

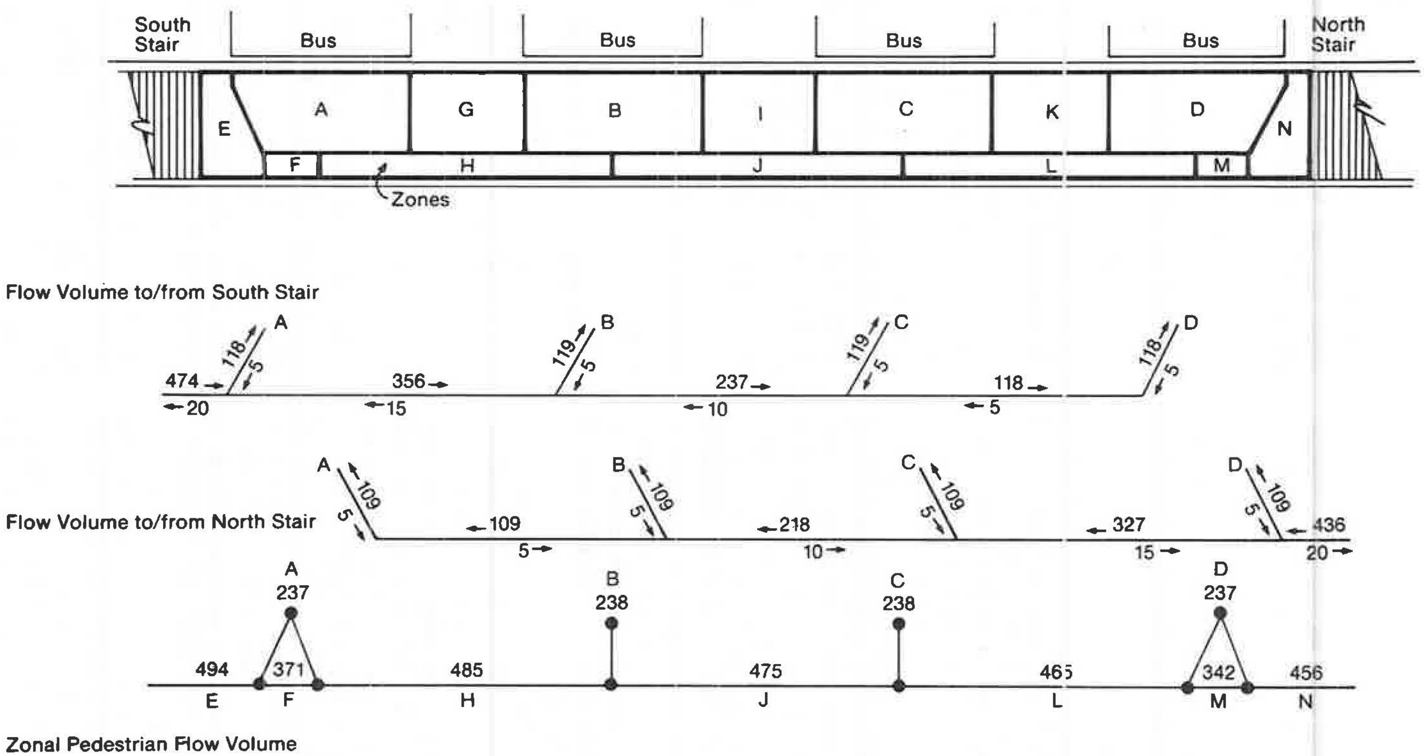


FIGURE 4 Platform study level of Detail 3: time-space zone.

TABLE 2 TIME-SPACE CALCULATIONS PLATFORM STUDY LEVEL OF DETAIL 3

ZONE	WALK TIME-SPACE REQUIRED					QUEUE TIME-SPACE REQUIRED					AVAILABLE TIME-SPACE	
	DISTANCE (ft)	WALK TIME @ 4.1ft/sec (seconds)	VOLUME	TOTAL WALK TIME (min.)	WALK T-S @ 22sqft/per. (sqft-min)	NUMBER OF PEOPLE WHO WAIT	AVERAGE WAIT TIME (min.)	AVERAGE SQFT/ PERSON	TOTAL WAIT T-S (sqft-min)	TOTAL T-S REQUIRED (sqft-min)	AREA (sqft)	T-S AVAILABLE (sqft-min)
E	15	3.7	494	30.1	663					663	235	3525
F	20	4.9	371	30.2	664					664	70	1050
A	5	1.2	237	4.8	106	227	5.8	7	9216	9322	640	9600
G	5	1.2	-	-	-					-	460	6900
H	100	24.4	485	197.2	4337					4337	350	5250
B	5	1.2	238	4.8	106	228	6.8	7	10853	10959	690	10350
I	5	1.2	-	-	-					-	460	6900
J	100	24.4	475	193.1	4248					4248	350	5250
C	5	1.2	238	4.8	106	228	3.7	7	5905	6012	690	10350
K	5	1.2	-	-	-					-	460	6900
L	100	24.4	465	189.0	4159					4159	350	5250
D	5	1.2	237	4.8	106	227	5.4	7	8581	8687	640	9600
M	20	4.9	342	27.8	612					612	70	1050
N	15	3.7	456	27.8	612					612	235	3525
TOTAL					15718					50273	5700	85500

* STAIRS AT PLATFORM ENDS

that the zones along the platform edge between the loading area have no walk time space-needs.

The queue time-space requirement for each zone is calculated by multiplying the number of people in queue by the average wait time and by the queue area per person. The number of people in queue and the average wait time are the same as in the two earlier examples. Only those zones representing the four bus loading/unloading areas have queue time-space needs.

The total time space requirement for a zone is the sum of the walk time-space and queue time-space requirements for each zone.

Evaluation

The time-space required for each zone is compared with the time-space available to determine overloaded or underused portions of the platform. In Table 2, Zone B, one of the bus loading areas shows a slight overload—time-space required exceeds the time-space available. Two other loading areas, A and D, have time-space requirements approaching the time-space available as do two walk corridor zones H and L. The zones adjacent to loading areas have excess available time-space where people can spill over. Also, the manner in which zone boundaries are defined can affect the outcome of the results and must be kept in mind when evaluating the findings.

Analysis of Alternative Platform Configuration: Center Stairs

The platform in the preceding application has a set of stairs located at each end. Another possible stair location is at the center of the platform (see Figure 5). To further demonstrate the capabilities of the time-space concept, the station platform is analyzed with the stairs at the center location.

With the stairs located at the center of the platform instead of at the ends, there is a noticeable effect on the amount of walking required on the platform. With stairs at the ends of the platform, passengers coming down the stairs at one end who are destined for the loading location at the opposite end must walk nearly the entire length of the platform. With a center stair location, the maximum walking distance is less than one-half the length of the platform. A center stair, however, may increase the overall walk distance for a passenger between the loading/unloading location and passenger origin/destination, and the passenger may double back or back track.

In situations in which a constraint exists on the size of the platform, particularly the width, it might be appropriate to shift, as much as possible, the time-space requirements to another space, such as a mezzanine, even if the result is a net increase in the overall passenger walking distance. The increase in walking time may be more than offset by the reduced crowding, congestion, and delay time on the platform. The center stair platform configuration is analyzed in the following paragraphs by using the time-space concept; the procedural steps are the same.

Platform Time-Space Zone

The platform is divided into time-space zones in a manner that is similar to the end-stair configuration (Figure 5). The size and shape of the zones are different, reflecting the location of the stairs at the center of the platform.

Time-Space Available

The areas of each zone and the amount of time-space available in each area during a 15-min analysis period are given in Table 3 (last two columns). Although the total time-space available on the platform is the same as the end-stair configuration, the time-space in the various zones does vary.

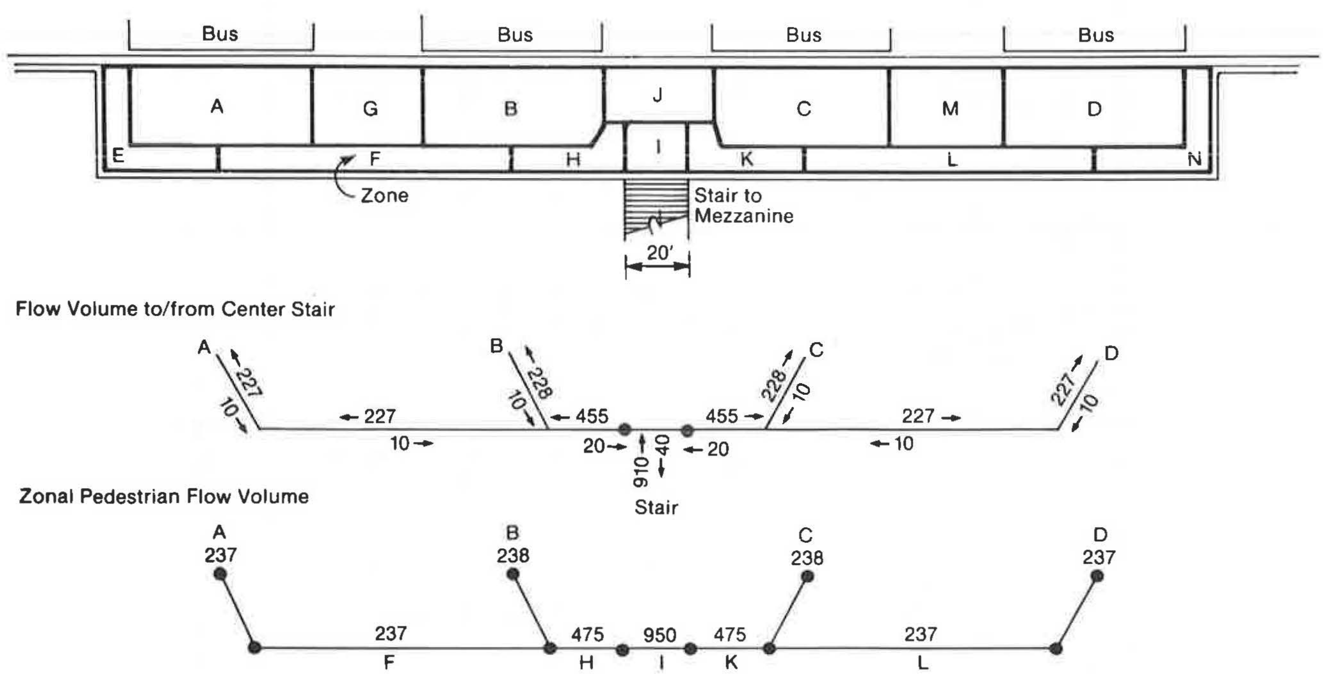


FIGURE 5 Center stair platform time-space zone.

TABLE 3 TIME-SPACE CALCULATIONS CENTER STAIR PLATFORM

ZONE	WALK TIME-SPACE REQUIRED: DISTANCE (ft)	WALK TIME (seconds) @ 4.1ft/sec	VOLUME	TOTAL WALK TIME (min.)	WALK T-S @ 22sqft/Per.	QUEUE TIME-SPACE REQUIRED: NUMBER OF PEOPLE WHO WAIT	AVERAGE WAIT TIME (min.)	AVERAGE SQFT/ PERSON	TOTAL WAIT T-S (sqft-min)	TOTAL T-S REQUIRED (sqft-min)	AVAILABLE TIME-SPACE: AREA (sqft)	T-S AVAILABLE (sqft-min)
E	5	1.2	-	-	-					-	255	3825
F	100	24.4	237	96.3	2120					2120	350	5250
A	5	1.2	237	4.8	106	227	5.8	7	9216	9322	690	10350
G	5	1.2	-	-	-					-	460	6900
H	40	9.8	475	77.2	1699					1699	181	2715
B	5	1.2	238	4.8	106	228	6.8	7	10853	10959	684	10260
I	10	2.4	950	38.6	850					850	140	2100
J	5	1.2	-	-	-					-	320	4800
C	5	1.2	238	4.8	106	228	3.7	7	5905	6012	684	10260
K	40	9.8	475	77.2	1699					1699	181	2715
L	100	24.4	237	96.3	2120					2120	350	5250
D	5	1.2	237	4.8	106	227	5.4	7	8581	8687	690	10350
M	5	1.2	-	-	-					-	460	6900
N	5	1.2	-	-	-					-	255	3825
TOTAL					8912					43467	5700	85500

Time-Space Required

Figure 5 shows a diagram of the volume of people walking through each zone during the 15-min analysis period. The walk speed is estimated to be 245 ft-min, or 4.1 ft/sec. The walk time-space required is calculated in Table 3. The total walk time-space for this platform configuration is 8,912 ft^2-min, compared with the 15,718 ft^2-min required for the end-stair configuration. The queue time-space required is the same as in the previous configuration because the average waiting time and the number of waiting passengers at each location have not changed. The data in Table 3 show the queue time-space requirement for each zone. The total time-space requirement for each zone—the sum of the walk and the queue time-space requirement—is given in Table 3.

Evaluation

The time-space required for each zone is compared with the time-space available to determine overloaded or underused portions of the platform. As can be observed from Table 3, Zone B, one of the bus loading areas, shows a slight overload, as was the case in the other platform configuration, primarily because of the long average wait time for the passengers in that zone. The zones on either side of Zone B have time-space available to accommodate the overflow.

The walk time-space required for the center stair platform is 8,912 ft^2-min, as compared with 15,718 ft^2-min required for the end-stair platform, reflecting the reduced amount of walking that is necessary on the center-stair platform, particularly in the walk zones at the ends of the platform (E, N).

CONCLUSION

The time-space technique is a new way of looking at transit platforms. Dividing the platform into time-space zones enables the analyst to observe what happens in different areas of the platform. The time-space concept models the activities on the platform—walking and waiting—where they occur, the number of people involved, and the amount of time required. The time-space technique is able to model differences in platform configuration. In this example, access stairs at the ends of the platform versus one set of stairs in the center were modeled. The different amounts of walking that result from these different stair arrangements are reflected in station and zone walk time-space requirements.

The time-space technique offers a new tool for analyzing and designing platforms. Traditional techniques are not able to consider the specific intensities and locations of the activities that occur on platforms. The time-space technique is able to model the way platforms are used and can analyze different configurations and types of user behavior. For instance, if passengers tend to cluster in certain parts of the platform, as they frequently do on rail transit platforms, the time-space technique can model their behavior in the same way that the passengers were assigned to specific locations of the bus platform for this analysis.

The time-space concept is applicable to a wide variety of spaces and situations involving pedestrian activities, such as station fare control areas; elevator lobbies; vestibules for stairs and escalators; vestibules for auditoriums or stadiums; curbside areas at airports, hotels, or terminals; and museum and exhibition areas. The concept can address issues in spaces with many different activities and with multidirectional flows. In addition, the characteristics (walk speeds, space requirements, time to perform an activity) of different user groups (commuters, intercity travelers, shoppers, children, elderly, and handicapped) can be modeled.

ACKNOWLEDGMENT

This research was conducted with the support of the William Barclay Parsons Fellowship, an annual award provided by the Board of Directors of Parsons Brinckerhoff, Inc.

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Publication of this paper sponsored by Committee on Intermodal Transfer Facilities.

Quick Estimation of Queueing Delay for Passengers Exiting a Rapid Transit Station

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A method for estimating queueing delay for passengers exiting a rapid transit station is described. The method requires estimates of the average number of people exiting each train, average headway, and average service rate as inputs. The average delay is easily calculated with a hand calculator.

The purpose of this paper is to describe a method for estimating queueing delay for passengers exiting a busy rapid transit station. The model presented here is described in greater detail in "Passenger Delay in a Rapid Transit Station" (*1*).

APPLICATION

A typical rapid transit station serves two tracks, which carry trains in opposite directions. The station may have a central platform, which serves both tracks, or two side platforms, each of which serves a separate track. Passengers exiting trains may be delayed when queues form at any one of several places: (a) entrance to stairs or escalators; (b) fare gates or turnstiles; or (c) train doors. These will be refered to as "servers."

In most rapid transit systems, queues are larger exiting the station (after exiting a train) than entering the station (before boarding a train). This is not because less capacity is provided for exiting passengers. Instead, it results from the passenger arrival pattern. The arrival pattern for boarding passengers tends to be fairly steady: passengers arrive independently of each other at a rate that does not change abruptly. The arrival pattern for exiting passengers is "lumpy." If 100 passengers exit a train, then 100 passengers arrive simultaneously. A lumpy arrival pattern is more difficult to accommodate than a steady pattern. For this reason, this paper concentrates on the delays encountered by exiting passengers.

The bottleneck is the server with the smallest capacity and is usually easy to identify because it is the last place where passengers encounter a queue. Passengers encounter little or no delay after passing through the bottleneck. A well-known characteristic of queues is that when servers operate at full capacity, total delay can only be reduced by increasing the capacity of the bottleneck (*2*). Increasing the capacity elsewhere can only move the delay from one place to another. For example, increasing the capacity at the train door only moves a portion of the delay from the train door to the next server (perhaps an escalator). This is why servers in series are typically designed to have similar capacities.

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The "time-in-station" is described in the sections that follow. The first section contains a description of how to estimate time-in-station when each track is served by its own platform; the second section contains a description of how to estimate time-in-station when both tracks are served by the same platform. Time-in-station is the time from when the train door opens until the passenger exits the station. It includes both the walking time from the train door to the exit and the time spent in queue.

PASSENGER DELAY: SEPARATE PLATFORMS

When a station has separate platforms and separate exits for each track, total passenger delay can be calculated as follows.

The bottleneck capacity, c, is the minimum capacity of all of the servers encountered by the passenger (stairs, fare gates, etc.). From "Passenger Delay in a Rapid Transit Station" (*1*):

$$D \approx \frac{A^2 + V(A)}{2ch} + T\frac{A}{h} \tag{1}$$

where

D = average time-in-station (hr per hr of operation),
A = average number of people exiting each train,
$V(A)$ = variance of the number of people exiting each train,
h = average train headway (hr),
c = capacity of the bottleneck server (passengers per hr), and
T = average walking time from the train door to the exit if no queue is encountered (hr).

For a given volume (passengers per hour), time-in-station tends to increase as load size increases. In essence, it is better to have 12 trains per hour, each with 50 passengers, than to have 6 trains per hour, each with 100 passengers. Time-in-station declines as the capacity of the bottleneck increases.

Sample calculations for time-in-station are given in Table 1, and the results are summarized in Table 2. Equation 1 is used to assess the relationship between time-in-station and the capacity of the fare gates. With six or fewer fare gates, the capacity is less than any other server. However, with eight or more fare gates, the capacity is greater than the stairs and the stairs are the bottleneck. Therefore, time-in-station does not decrease when more than eight fare gates are provided.

TABLE 1 STATION DATA

Load Size Data (28 trains)

111	397	223	343
308	339	313	198
271	382	391	349
163	193	451	295
366	390	205	199
278	409	319	260
179	403	405	257

Server Capacities

Train Door: 50,000 passengers/hour
Stairs: 20,000 passengers/hour
Fare Gate: 3,000 passengers/hour per gate

Walking Time to Exit: 45 seconds = .0125 hours
Headway: 4 minutes = .0667 hours

Calculations

$$n = \text{number of data points} = 28$$

$$A = \sum_{i=1}^{n} A_i/n = 8397/28 = 300$$

$$V(A) = \sum_{i=1}^{n} A_i^2/n - A^2 = 2738689/28 - 300^2 = 7810$$

$$\text{Passenger Arrival Rate} = A/h = 4500 \text{ passengers per hour}$$

$$D = \frac{A^2+V(A)}{2ch} + T\frac{A}{h} = \frac{300^2+7810}{2h}\frac{1}{c} + .0125\cdot 4500$$

$$= 733575\frac{1}{c} + 56.25$$

TABLE 2 TIME-IN-STATION PER PLATFORM: SEPARATE PLATFORMS

Gates	2	4	6	8	10
c (1,000 passengers per hour)	6	12	18	20	20
D (hours per hour)	178	117	97	93	93
Delay/passenger (minutes per passenger)[a]	2.35	1.55	1.29	1.24	1.24

[a]Delay/passenger = $D/(A/h)$.

SHARED PLATFORM

The calculation for passenger delay with a single platform serving both tracks is based on the following:

A_1 = average number of passengers exiting each train on Track 1,
A_2 = average number of passengers exiting each train on Track 2,
$V(A_1)$ = variance of number of passengers exiting each train on Track 1,
$V(A_2)$ = variance of number of passengers exiting each train on Track 2,
h_1 = headway on Track 1 (hr), and
h_2 = headway on Track 2 (hr).

The calculation for passenger delay is more complicated for a single platform than for separate platforms:

$$D = \left[\frac{A_1^2 + V(A_1)}{2ch_1} + T_1\frac{A_1}{h_1}\right] + \left[\frac{A_2^2 + V(A_2)}{2ch_2} + T_2\frac{A_2}{h_2}\right] + \left[\frac{V(A_1)A_2 + A_1V(A_2) + A_1A_2(A_1 + A_2)}{2c^2h_1h_2}\right] \quad (2)$$

The third term accounts for the "interference delay" when two trains on opposite tracks arrive at nearly the same time.

The data in Table 3 show time-in-station for a shared platform (based on load sizes given in Table 1, assuming that the arrival pattern is the same on both tracks). Notice that the delay per passenger is only slightly larger for the shared platform than for separate platforms, even though one-half as many fare gates are required.

DISCUSSION OF RESULTS

The equations are most useful in answering "what-if" questions, such as, what will be the change in passenger delay if an

TABLE 3 TIME-IN-STATION: SHARED PLATFORM

Gates	2	4	6	8	10
c (1,000 passengers per hour)	6	12	18	20	20
D (hours per hour)	539	280	214	202	202
Delay/passenger (minutes per passenger)[a]	3.59	1.87	1.43	1.35	1.35

NOTE: $A_1 = A_2 = 300$; $V(A_1) = V(A_2) = 7{,}810$; $h_1 = h_2 = 0.0667$ hr; $T_1 = T_2 = 0.0125$ hr. Equal loads on platforms.

[a]Delay/passenger = $D/(A_1/h_1 + A_2/h_2)$.

additional fare gate or escalator is built, or what will be the change in passenger delay if equipment malfunctions? The equations are most accurate if they are applied to limited time periods during which conditions are fairly constant. This is accomplished by dividing the day into time blocks during which train loads and headways are fairly constant.

Caution should be exercised if passengers exit the station at more than one location. If this is the case, Equations 1 and 2 should be applied to each bottleneck separately. The load sizes (A_1, A_2) should be scaled accordingly to account for the number of passengers using each exit. Caution should also be exercised if servers are used simultaneously by passengers entering and exiting the station (e.g., if passengers travel up and down a staircase at the same time). Such interaction can lead to delays larger than those predicted by the model.

The equations are most accurate for moderately busy stations. If passenger queues are so large that they do not dissipate between the arrival of one train and the arrival of the next train on the same track, then Equations 1 and 2 will underestimate time-in-station. If load sizes are so small that queues rarely materialize, then Equations 1 and 2 will overestimate time-in-station. For this reason, the equations should generally not be used to estimate delay during off-peak hours.

ACKNOWLEDGMENT

The author appreciates the assistance of the San Francisco Bay Area Rapid Transit District.

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Publication of this paper sponsored by Committee on Intermodal Transfer Facilities.

Computer-Aided Design of Transportation Interface Facilities

JOHN M. ISHIMARU AND DALE E. CALKINS

A prototype system for the preliminary design of transportation interface facilities is described. The design system exploits computer-aided design techniques including a microscopic computer simulation model and interactive capabilities to create an environment that enhances the transportation pedestrian facility design process. A summary of developments in transportation interface facility design, computer-aided design techniques, and user interface concepts is presented, followed by a discussion of a prototype facilities design system. Potential applications of the system are discussed, and promising areas of future development are outlined.

Transportation interface facilities are a critical element of the modern transportation system. Studies have documented the elasticity of transit pedestrian behavior with respect to station services, particularly with regard to the onerous nature of wait times (*1*). During the past two decades, significant progress has been made in the development of systematic procedures for the efficacious design of such facilities as well as specific objective techniques for the analysis of potential interface design layouts. Nevertheless, there remains a need for further development of design analysis techniques that specifically address the iterative, incremental nature of the design process.

In the following discussion, a computer-aided design environment for the analysis of preliminary transportation facility layouts is described. This design system takes advantage of techniques and computer tools that have been developed in other areas of engineering analysis; specifically, the system utilizes the capabilities of modern computer systems to perform complex microscopic simulations of pedestrian movement and provide an interactive design interface between the simulation model and the transportation professional.

PROBLEM STATEMENT

This paper is a status report of an ongoing research effort to develop a design system that exploits state-of-the-art computer-aided design techniques to perform preliminary geometry analyses of potential transportation interface facility layouts. The design system specifically addresses issues involving preliminary space allocation of a potential pedestrian facility design. This system exploits a high-performance computing environment in combination with a highly interactive user interface to enhance the preliminary facility design process.

The prototype design system features five integrated components (see Figure 1) linked to one another via a master driver program that implements user choices. The interrelatedness of the design system components provides an environment that seeks to improve the productivity of the facility design process by operating more harmoniously. To assist such a design process, the prototype design system features a highly responsive interface between the designer and the design system, which uses a variety of interactive hardware devices. In addition, the system offers the planner a variety of information display formats and design modification and analysis options in an attempt to incorporate user judgment and insight into the pedestrian facility design process.

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FACILITIES DESIGN PRACTICES

The design of a transportation interface facility is often considered first in architectural terms. Traditional architectural engineering design techniques may be used that treat a transportation station or terminal simply as a typical building design planning task. Specific issues that affect transportation pedestrian facilities are considered to be one part of a more broadly defined problem that includes land, buildings, building interiors, furniture, equipment, and machinery. This more generalized approach, referred to as facilities planning, offers the insights of an approach that does not specifically focus on the transportation aspect; in addition, the broader scope of this planning approach offers a glimpse into the advantages of a systematic integrated procedure for the design of a facility used by transportation patrons and other pedestrians.

The facilities planning approach defines building activity in terms of activities and departments, and attempts to accommodate interactivity flow patterns while anticipating present and future design constraints and expansion opportunities (*2, 3*). A variety of qualitative, and some quantitative, techniques may be used in each stage of this planning process. Of the analytical techniques available for the scientific and objective analysis of design alternatives, layout algorithms are most directly related to the transportation interface facility design problem (*3*). Developed over the past 25 years, these layout algorithms hypothesize the relative locations of key activities by using initial space requirement estimates in combination with matrices that indicate the degree to which activities are related. An example of such an algorithm uses a sequential operation to locate activities and departments based on the optimization of a computed distance coefficient, subject to prior constraints on the locations of key activities. Such facilities planning algorithms do not specifically focus on the pedestrian mobility issue, and hence do not generate layout geometries that necessarily accommodate realistic pedestrian flow. Because activity

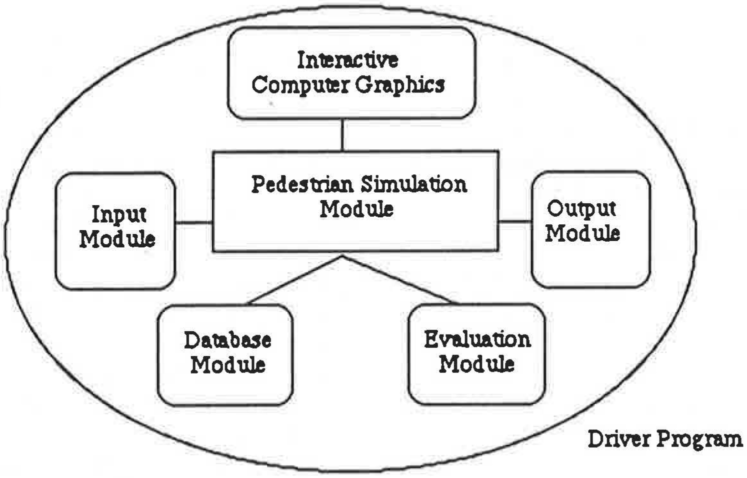

FIGURE 1 Prototype pedestrian facilities design system.

locations, rather than interactivity pathways, are of primary concern in such facility planning algorithms, this methodology, while illustrative of a comprehensive approach to building design, does not fully accommodate many of the important considerations that must be addressed by the transportation planner.

TRANSPORTATION INTERFACE FACILITY DESIGN PRACTICES

The challenge of effectively designing a transportation interface facility arises in part from the multiple functions that the facility must perform, as well as the often conflicting objectives that it must attempt to meet. Such a facility must accommodate not only the line-haul transportation system itself, but also the pedestrian ingress/egress process, pedestrian services, and facility operation as well. During the preliminary transportation facility design process, special interest is focused on the areas of passenger processing, transfer, and movement patterns (*1*, *4*).

The multiple functions of a transportation interface facility affect the nature of the design process. A number of complementary and competing design principles have been developed that reflect the multidisciplinary engineering and transportation planning inputs that are required in such a design effort. Typical considerations for such a facility include (a) physical geometry of the facility, (b) information services for patrons, (c) service/processing facilities, (d) environmental considerations, (e) accommodations for movement-impaired patrons, (f) accommodations for present and future maintenance and growth, and (g) specific local programmatic considerations (*1*). The analytical techniques for these considerations vary greatly in sophistication and data requirements. For example, two of the most important considerations, physical geometries and service facilities, are often addressed through the use of general guidelines for maximum allowable dimensions of passageways and queuing areas. The utility of such guidelines is hampered by their nonspecific nature, a problem compounded by occasional overt contradictions between competing quantitative standards. Potentially useful information is also often unavailable or difficult to obtain because of corporate proprietary nondisclosure considerations.

The development of objective analytical techniques for the design of transportation interface facilities has generally not kept pace with analogous developments in other transportation planning areas. Studies in the mid-1970s concluded that only fundamental rules and guidelines were commonly used in the preliminary design and layout of transportation facilities (*1*); with notable exceptions, the body of work since then that addresses this issue has only occasionally focused on specific design techniques (*5*, *9*). Techniques typically in use today generally fall into the category of deterministic analysis, including empirical studies and extrapolation to determine relationships between key design variables (*1*, *6*). These techniques are marked by the use of aggregate measures of system performance to evaluate a process that is inherently time-dependent. Their shortcomings stem primarily from the difficulty in determining disaggregated design performance data, such as breakdowns by pedestrian mix and time of day, or uncertainties in pedestrian behavior. This shortcoming is understandable in light of the relative paucity of time-domain analysis tools. Other techniques have been developed that accommodate these characteristics; these probabilistic methods attempt to model the stochastic nature of pedestrian facility usage with variable success (*7*).

The most difficult, but potentially most useful approach involves the development of an integrated environment that attempts to model and evaluate the complex interactions of a design in a systematic fashion. One effort to systematize the categorization and design of interface facilities was conducted by Fruin in his classic description of pedestrian planning and design (*8*). Fruin described the inherent nature of a transportation interface facility as being a combination of building and structural considerations (including the physical plant); service considerations related to the mode of transportation being served; and human considerations involving actual and perceived congestion, waiting, and other psychological aspects of human movement. Another significant effort to systematize the station characterization and design process involved the delineation of several major categories and functions of transportation interface facilities. Hoel described these categories as (a) rail terminals with characteristic linear construction, with major emphasis on shelter and passenger service/transfer; (b) bus terminals whose construction is less constrained by virtue of the transportation mode they serve; (c) parking facilities that serve to ease congestion by diffusing the concentration of automobiles in central business districts and shifting them to peripheral garage locations; (d) transportation centers that serve multiple modes; and (e) multipurpose facilities that combine transportation with commercial and public amenities (*1*).

During the 1970s, significant progress was made toward systematizing the station design process, if only on a conceptual basis, in hopes that analytical tools, which would facilitate such a systematic approach, would be forthcoming. In one example of such a process, a procedure was outlined by Vuchic and Kikuchi, which, in many ways, mirrors the traditional transportation planning process. This process begins with an initial collection of station location and demand data, followed by data collection of external influences and conditions near the station. Studies are then conducted of projected alterations in land use and demand. On the basis of this information, the design requirements are specified along with guidelines for their implementation. Alternatives are formulated, and the best of the alternatives is evaluated (*9*). A second example was research conducted by Barton-Aschman and Peat, Marwick, Mitchell and Company, which envisioned a design procedure that emphasized station geometry and levels of service. Their procedure begins with a definition of constraints, followed by the collection of origin-destination data. Design objectives are then determined, after which a design is developed that meets objectives and constraints. This design is then compared with the design objectives to determine actual compatibility; an iterative process then commences, after which an optimal design is then reached. The structure of this approach implicitly assumes or requires the availability of a powerful and flexible analytical design evaluation tool (*10*).

Several prerequisites precede the successful implementation of procedures such as those described earlier. First, data requirements are imposing. Successful evaluation of alternative designs is predicated on the availability of accurate and detailed information on pedestrian traffic levels, the geometry and scheduling patterns of transportation modes being served, and, in the case of data collected from earlier design efforts, the prevailing conditions associated with those design projects. Other useful information includes the demographics or passenger mix of expected patrons, as well as the cost of passenger processing by transportation mode and service type. Even in the case of a computer-based analytical technique, where data requirements might appear to be less restrictive, some initial calibration information would be necessary for the generation of reasonable results. Second, human factors are often only peripherally considered in station design. Ideally, human factors considerations should go beyond standard design guidelines for ambient temperature, lighting, and noise absorption to also include psychological perceptions of congestion and overcrowding, which may affect space requirements and safety considerations. Fruin's contributions in this area are significant; nevertheless, more field data would be useful (*8*).

A third important aspect of the design process is the determination of objective criteria by which alternatives may be evaluated and competing choices compared. It is evident that the design of a facility in which complex human and man-machine interactions occur is fraught with complicated, often conflicting design objectives that vary from case to case. The problem of determining specific criteria is compounded by the difficulties involved in rational quantitative measurement of such criteria. In addition, those criteria that are quantifiable must be measured using the proper performance metric/indices. For example, the criterion of wait time may be measured in terms of mean time, maximum time, or some other measure; likewise, queue length may be measured by its maximum, average, or some other measure of length. Fourth, the evaluation process itself may be difficult to develop as well. Typical procedures include (a) cost-benefit analysis, which suffers from the requirement that performance measures must be converted into meaningful monetary values; (b) cost-effectiveness analysis, which becomes difficult to implement when many variables are involved (trade-offs become hard to resolve); and (c) ranking procedures, which typically employ user judgment to weight criteria. Finally research is needed in alternative design generation.

In the face of these imposing requirements, several researchers have addressed the challenges and potential advantages that could arise from the development of an integrated design system for transportation interface facilities. The most sophisticated analytical development of this type involved the construction of a computer-based pedestrian movement simulation model (*11–15*). Developed and tested throughout the 1970s by Barton-Aschman and Peat, Marwick, and Mitchell for the Urban Mass Transportation Administration (UMTA), this model, called USS (UMTA Station Simulation), was designed to be used as an evaluation tool for potential designs of intermodal transit facilities. Such a model would seek to identify capacity bottlenecks and areas of transient congestion to alleviate critical limitations at the early stages of preliminary facility design, thereby increasing the productivity of the design process and reducing design time and cost. The ambitiousness of this effort is rooted in its attempt to model the nondeterministic suboptimal behavior of pedestrians (*12, 16*); that is, develop a plausibly realistic model of actual human decision making. By using stochastic discrete-event digital simulation techniques, USS introduced a degree of randomness and uncertainty into pedestrian motion in order that critical time-varying aspects of pedestrian interaction could best be determined.

A program such as USS had potential implications for nearly every phase of the station design process (*11, 12*); nevertheless, despite, and because of, the complexity of the underlying model, USS is not currently in use. Its utility is constrained by difficulties of operation encountered by testers in actual use, as well as its implementation on limited circa-1975 computing resources. Nevertheless, in many ways USS represents a landmark effort to move beyond the handbook guideline and utilize sophisticated computer-based analytical techniques to model complex human interaction in transportation facilities, and thus offers direction, focus, and challenges for any subsequent efforts seeking to develop analytical tools to facilitate the systematic design of stations and terminals (*15*).

COMPUTER-AIDED TECHNOLOGY

Advances in computer hardware and software have reached a point at which a systematic approach to analytic engineering design is now within the reach of modern computing environments. The mechanical design realm has paid particular

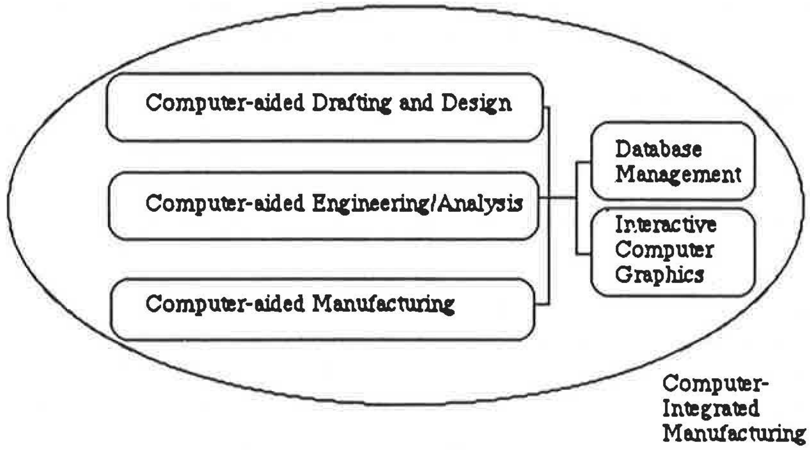

FIGURE 2 Computer-aided technology: mechanical design.

attention to the development of so-called computer-aided technologies such as computer-aided drafting and design, computer-aided engineering, and computer-aided manufacturing. Mechanical design systems are now addressing the issue of computer-integrated manufacturing (CIM), which attempts to unite each island of computer-aided technology into a unified, computerized whole. The computer-aided nature of these technologies arises not simply from the essential use of computers, but from the use of two key components: effective data base management and interactive computer graphics. It is these two components that make a computer-aided environment useful and productive (see Figure 2).

In the case of transportation facilities design, computer-aided technologies have been used in specific instances. For example, some interesting and potentially useful computer-aided engineering programs are available to perform analyses of potential station design layouts (*5*); in addition, computer-aided drafting programs are available for architectural plan generation. In general, however, the computer hardware advances of the past 10 years have not been fully brought to bear on the facilities design issue, even though there remain some potentially useful avenues for exploration. Two such areas of interest are the use of computer-based simulation models and the development of interactive user interface environments.

COMPUTER-BASED SIMULATION

One of the opportunities, and challenges, made available by the advent of the computer age is the development and utilization of computer simulations as an increasingly viable, readily available analytical tool for use by the transportation professional. Computer simulations are most often used when analytical closed-form techniques for the solution of a problem do not exist or are difficult to utilize; that is, when system complexity precludes a tractable formulation and solution. Simulations generally contain two key aspects. First, simulations are usually explicitly dynamic; that is, there is a time-dependent element. Second, simulation models are generally component-oriented. Rather than attempt to describe the system behavior as a whole, the system is modeled in terms of individual components, events, and interactions. Thus, more manageable submodels and local interrelationships can (presumably) be modeled, thereby allowing the resources of the computer to be concentrated on the assessment of the complex interactions and feedback between components of the system as a whole.

Computer simulations offer a number of significant advantages for the engineer-designer, particularly when compared with traditional alternatives such as physical "real-world" experimentation. These advantages include the following (*17*):

- Controlled experimentation. Under the control of the experimenter, the system may be exercised under a variety of deterministic or stochastic conditions. Relatively robust exercises of this type may be limited in a physical experiment because of fiscal or time limits.
- Time compression/expansion. An extended period of time may be simulated in much less than real time, thereby accelerating the analysis and enhancing cost-effectiveness. Likewise, transient phenomena, which may be difficult if not impossible to discern under normal, real-time conditions, may be simulated at slower than normal speeds.
- Sensitivity analysis. The susceptibility of the system to small changes in the values of variables or underlying assumptions may be assessed via manipulation of input parameters.
- Avoiding the real system. Experiments may be carried out without disturbing an existing on-line system or risking the practical and political difficulties that such tampering may entail.
- Training. Computer simulations are excellent training tools for the operation, analysis, and understanding of complex systems.
- Reduction of solution space. Computer simulations can facilitate early elimination of unpromising solution subsets as well as the detection of new, promising approaches that may not have been previously considered.
- Segregation of design validity from operational test considerations. A simulation is able to isolate the validity of the underlying logic of a system from the external and extraneous effects of test hardware that would accompany a physical experiment, thus avoiding the engineering testing analog of the Heisenberg uncertainty paradox.

Despite the attractiveness of these advantages, there are also significant disadvantages and hazards associated with the use of computer simulations:

- Cost. Simulation development and operation can still be an expensive proposition in terms of time, money, and manpower.
- Development uncertainties. Because the development of a proper model of physical reality for use in a simulation is so critical, the development time for an adequate simulation is often uncertain.
- Hidden critical assumptions. The inability to recognize and incorporate subtle interactions into the model may cause simulation results to diverge from reality.
- Initialization of the model. The complexity of the model may lead to substantial data collection requirements and potentially lengthy, even inconclusive model calibration in an effort to properly initialize the model.

Given these advantages and disadvantages, the typical procedure for the development of a simulation involves initial planning and feasibility of available resources, followed by the modeling and coding of salient system features. The coded model is verified for coding and other errors, and is then ready to be validated by testing and comparison with real results. The simulation is then ready to be utilized in an application. Simulation development, while converging on a desired solution, generally does not reach a steady state; the model is and should be subject to subsequent new information and increased resources (*6, 17*).

As an analytical tool, simulation requires the exercise of prudence and judgment in the proper development of the underlying model for a given situation. This requirement will always be of paramount importance. Given the appropriate development of such a model, however, computer simulations provide the means by which complex, otherwise intractable problems may be logically evaluated. Moreover, this tool is rapidly becoming readily accessible, as the growth of computer hardware and software capabilities and the drop in capital costs associated with their acquisition increases the availability of simulation capabilities for even a modest suburban or rural transportation planning operation.

USER INTERFACE DESIGN CONCEPTS

Despite the utility and implications of powerful modern computing systems, a nagging limitation has persisted, one that has afflicted even (or perhaps especially) the most sophisticated and complex programming effort, and that remains a bottleneck that inhibits the optimal interpretation of computer-generated information. This bottleneck involves the often frustrating restrictions placed on the user because of his or her inability to assess the often voluminous numerical output that is typically generated by computer-based tools. Only recently have computer users been provided the hardware and software necessary to obtain more useful information out of unprocessed raw data; nevertheless, computer output is still often in tabular form, making interpretation and assessment arduous.

A welcome development that goes a long way toward the alleviation of this difficulty is the rapid growth of the sophisticated user interface between human and machine. Almost inevitably, this is implemented through the use of advanced computer graphics hardware and software. The increasingly attractive price-performance ratio for computer power and computer graphics capabilities has encouraged the use of such tools to facilitate analysis, interpretation, and processing of computed and measured data (*18–21*). When used properly and exploited fully, a graphical user interface aids evaluation and decision-making processes based on a given data set by assisting the user in the maximum exploitation of the best of both human and computer information-processing capabilities. Moreover, such interfaces generally operate in an interactive environment, which can assist the human processes by providing the ability to pursue creative and intuitive possibilities (or even guesses) without the distractions and loss of concentration that would occur in a slower batch-oriented mode of computer utilization (*22*).

The advent of sophisticated computer graphics hardware and graphics software techniques offers singular advantages:

- Information transfer. The use of a computer graphics-based interface between the user and the computer program allows the utilization of human powers of assessment and assimilation to analyze multiple channels of information, thus facilitating the efficient and useful transfer of analytical information to the user.
- Design processes. By accelerating information transfer, a computer graphics-based interface allows more options of a design process to be evaluated in a fixed amount of time, or conversely, a given number of options to be evaluated in a shorter amount of time; the design time is made more productive.
- Data input correction verification. A visual representation of input data will often provide the user with the means to detect both gross and subtle errors of data input far more readily than with tabular output.

The usefulness of an interactive computing environment and computer graphics to increase the transfer of information to the user has been frequently asserted and almost universally accepted; in addition, research efforts have been conducted that lend scientific validity to that claim (*22*). Two theories have been put forth that attempt to explain, on a psychological, cognitive level the value of an interactive, graphical display of data. Cognitive theory states that an individual's information processing ability is compartmentalized into one of four elements of a two-by-two matrix of cognitive modes (*23*). On one axis, *information gathering* abilities are divided into preceptive and receptive modes (focus on general relationships and patterns versus focus on direct examination of detailed information), whereas on the other axis, *information evaluation* abilities are divided into systematic and intuitive modes (problem-solving via a step-by-step analytical process versus a heuristic, trial and error approach). Rinderle and Kornhauser note that those involved in decision making and alternatives analysis generally fall in the preceptive-intuitive mode, a mode that is difficult to articulate with regard to the precise decision-making process that is being followed, but for which it is theorized that the best assistance would be provided by a computer tool that allows rapid and interactive display of alternative data sets (computed and measured) in an iterative process.

In complexity theory, it is claimed that every individual reacts optimally, that is, maximizes his or her level of information processing, at a certain level of external information stimuli. For example, Miller's classic paper stated that a person is able to respond to and evaluate a maximum of approximately seven unrelated pieces of information at a time, and that the aggregation, or recoding, of raw information into groups of data improves useful information throughput to the user. Others have stated that not only the aggregation, but the format, influences information processing, and that graphical data present themselves in a form that requires little or no "post-processing" on the part of the individual. In short, information transfer is facilitated by the presentation of data in a form that minimizes the need for mental transformation.

The precise quantification of productivity gains as a result of an interactive design environment is elusive. Nevertheless, some studies and anecdotal evidence have strongly indicated significant gains in productivity as a result of a highly interactive user interface, especially when combined with interactive computer graphics. Studies have demonstrated quantitative improvements in productivity as measured by product quality and design cycle duration (*24*). In the case of engineering design, little doubt exists that interactive computer graphics offer greater insight into complex processes and interactions. Peitgen and Richter conclude that "computer graphics is enriching our perception to a degree rarely achieved by any tool in science. In graphical representation, natural processes can be comprehended in their full complexity by intuition" (*25*).

Examples of the use of an interactive graphics-oriented user interface to assess design alternatives include direct comparisons of the numerical attributes of alternative designs through multiple line or bar charts to demonstrate relative strengths of one design over another; such a comparison is performed far more easily and rapidly in graphical form than if the same comparison were made with two tabular data sets (*23*). The use of color-coding to determine critical areas of a network design may more quickly point out the relative advantages of one design over another than the tabular counterpart. Three-dimensional plots of one attribute as a function of two additional attributes help to assimilate multiple criteria relationships. The utility of such comparisons is enhanced when displayed in an interactive environment that facilitates rapid recompilation of revised data to obtain modified analytical results.

The importance of such productivity improvements lies not in their ability to fully supplant the design process, though recent developments in artificial intelligence and especially expert systems offer optimism in this regard. Rather, the significance of the interface between an analytical tool and its user depends on the ability of that interface to facilitate the design process by fully exploiting and merging the unique advantages of the computer in data and image processing with the uniquely human characteristics of data interpretation and image processing that are among the most difficult to model algorithmically in a computer program. The proper use of computer graphics encourages the combination of computer advantages in information processing, such as the retention of massive sets of detailed data and the rapid, consistent, and accurate performance of complex operations, with the human strengths of creativity, flexibility, and the ability to balance conflicting objectives, resolve ambiguity, and make judgments.

The remainder of this paper contains discussions on the capabilities of an interactive, graphics-oriented computing environment, dedicated graphics hardware, and highly interactive graphics to transfer multiple simultaneous channels of simulation-based data of pedestrian behavior to the planner.

PROTOTYPE DESIGN SYSTEM

Pedestrian Simulation

The pedestrian simulation model that forms the central core of the prototype design system follows the concept and inspiration of the simulation model utilized by the UMTA USS project (*14*). The key elements of that earlier effort have been retained, including the implementation of stochastic pedestrian entry to and exit from the system and stochastic queueing, as well as the inclusion of uncertainty into the pedestrian decision-making process, as manifested in the pedestrian path selection process. These stochastic aspects have been modeled in the prototype design system by using techniques developed for discrete-event Monte Carlo simulations. These techniques utilize a combination of pseudo-random number generator algorithms and hypothesized probability density functions to determine an appropriate mix and distribution of pedestrian entry and movement under uncertainty (*14, 26*). In addition to the stochastic modeling of pedestrian ingress/egress and path selection, the queueing process and pedestrian characteristics are stochastically determined as was the case for the USS model.

The selection of a probabilistic simulation approach was predicated on the need for a tool for the evaluation of potentially important time-varying phenomena that occur in pedestrian stations and terminals, thus providing a useful contrast and check for traditional aggregate time-averaged deterministic techniques and guidelines that are commonly used. This prototype simulation model is being designed as an evaluation tool, and addresses design objectives similar to that of USS:

1. Provide enough space in basic queueing areas to assure a safe, convenient, and comfortable pedestrian environment;
2. Provide enough service facilities to assure a convenient and comfortable pedestrian environment; and
3. Connect these areas to assure a secure, continuous, convenient, coherent, and safe pedestrian environment based on acceptable levels of service (*1, 10*).

As with the USS model, this prototype pedestrian design simulation requires input information on station design, including an abstract network that represents expected primary pathways, as well as locations of nodes on that network that represent path-branching opportunities for the pedestrian or queueing areas (gates, turnstiles, and the like). In addition, the user provides information on approximate pedestrian flow levels and general commuting patterns. This prototype model implements an important recommendation made with regard to future USS extensions; namely, that users be allowed to specify parameters such as pedestrian mix, stochastic distributions, specific subregions of interest, data output formats, and design alterations in a relatively painless and easy way. This is accomplished via a graphically oriented user interface that drives the iterative design process of this prototype system (see Figure 3).

Hardware

The prototype pedestrian facility design system utilizes the hardware capabilities of a Digital Equipment Corporation PDP

11/44 minicomputer as a host for the simulation model and other program components. This system offers 1.5 megabytes of main memory for programming applications. The other hardware component of this system is an Evans and Sutherland PS300 interactive computer graphics display system. This component features a high-resolution monochrome vector graphics display and programmable keyboard, along with a graphics tablet and control dials unit. The PS300 is controlled via a local graphics processor dedicated to graphics manipulation tasks and featuring a high-speed pipeline computing architecture. The two components complement each other by combining the general computing and storage capabilities of the host computer with the highly interactive, programmable environment of the PS300; moreover, the availability of a data transfer library allows this interactive environment to encompass both computing components at the same time, rather than operating each component in isolation (27) (see Figure 4).

This complementary environment is enhanced by the conceptual design of the PS300. The availability of local intelligence within the PS300 display system allows the segmentation of computations into graphical and nongraphical tasks, thus allowing the computing environment that is best able to handle each type of task to perform the required operations. In this case, the PS300 performs graphical manipulation calculations efficiently, while the host computer performs general calculations. The PS300's local power manifests itself in real-time, three-dimensional image manipulation and animation capabilities, a feature that is only now beginning to become available in affordable computer display systems (27).

Because programming tasks are distributed among two different hardware components, different programming methodologies are required. In the case of the host PDP computer, the simulation was programmed using a high-level language. Although such a simulation could be developed with any number of specialized languages (*17*), the availability of data transfer routines dictated that a FORTRAN-based simulation model would best serve the interactive goals of this prototype system. The PS300 may be programmed using its own programming and command language. Because tasks for the PS300 are graphically oriented and often involve the use of interactive devices, the PS300 command language is specifically designed to accommodate such operations. Using a data flow programming structure rather than the sequential von-Neumann schema of typical high-level programming languages, programming of interactive devices and linkages between a driver program and a graphics image are performed by using a concatenation of basic command language functions to form a so-called function network. This network analogy may be expanded to form a parallel network of interactive devices operating and interacting simultaneously, rather than in series.

User Interface

Following the initial development of USS, an evaluation was conducted to determine its usefulness and to suggest future improvements. The evaluation team concluded that the analysis tool was a potentially valuable adjunct to the station design process, but suggested that its usefulness could be significantly

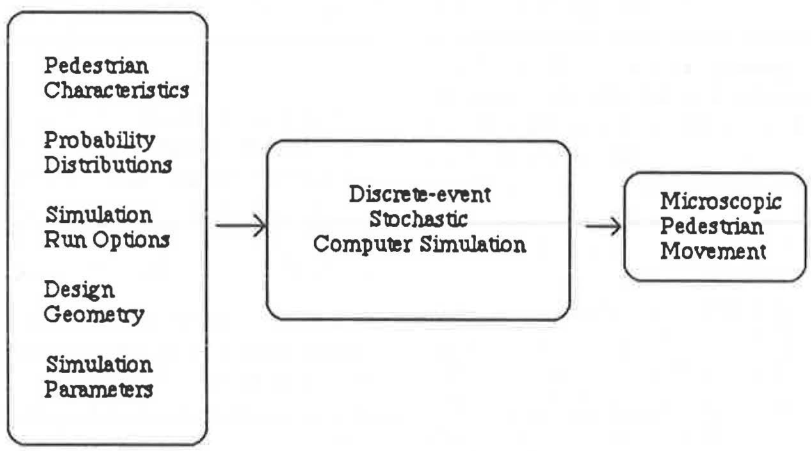

FIGURE 3 Pedestrian simulation flow.

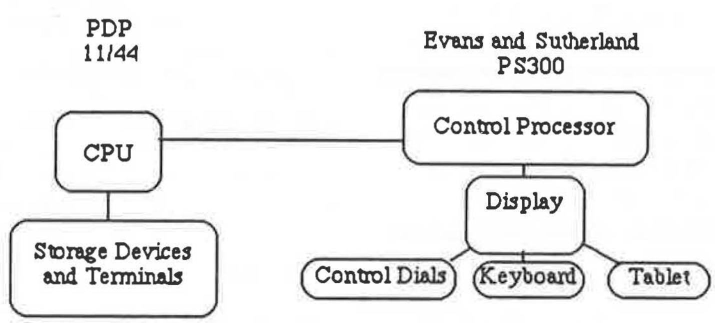

FIGURE 4 Prototype design system hardware.

improved. Among the recommendations was a suggestion that the implementation of an interactive mode of operation, as opposed to the batch mode that was used, would ease the difficulties of operation. In addition, the appropriate use of computer graphics to display input and output data would enhance the clarity of the simulation results. On the basis of these considerations, the prototype pedestrian facilities design system emphasizes a mode of operation that exploits an interactive design environment with a number of user-manipulable hardware input devices, as well as the extensive use of interactive computer graphics-based displays of input and output data.

The current version of the prototype design system implements three of the five components mentioned in the original problem statement (ongoing research is being conducted to implement the remaining modules). These components are the simulation module, the graphical output module, and some aspects of the input module. In addition, an interactive driver program has been developed to act as a shell that straddles the simulation and the output components. This driver program features menu-driven displays on both the PS300 and the PDP and provides the user with the ability to interactively display subsets of the output data, select the format of data display, modify the simulation input data and recompute the results, and compare competing design alternatives.

At present, the prototype system features four methods of interaction. The primary display features a graphically oriented menu on the PS300 that provides all the major design and display choices, including data selection, data display format, simulation input data modification, and simulation recomputation. Menu choices are made using a data tablet and stylus; selection of one of these choices results in the optional display of secondary textual menus that appear on a PDP display. Control of the program may be switched between the host computer and the graphics terminal by using interactive callable data transfer routines. Data displays may be manipulated by the use of other interactive devices. The control dials may be used for input of continuous, smoothly changing values; current implementation allows the dials to control the scrolling of text within a window, scale changes in two-dimensional plots, and three-dimensional manipulation of animated displays. Function keys may be used as toggle switches to interrupt dynamic displays and allow further inspection. These interactive devices are being used in an effort to enhance ease of use and facilitate the design process (see Figure 5). Data may be displayed in two- and three-dimensional forms ranging from line plots to bar charts, animated displays, and textual presentations. The development of these interactive display capabilities is based in part on earlier computer-aided ship design research (*29, 30*).

Current computer graphics hardware provides capabilities that go far beyond static two-dimensional plots and bar graphs. The current implementation of the prototype design system illustrates several of these extended features in anticipation of the availability of such hardware features at a more affordable level in the near future. The first extension adds dynamic display capabilities to two-dimensional plots and bar charts. A second feature that has been developed is a dynamic animation display that illustrates the macroscopic behavior of pedestrians in a design layout. A third feature exploits the ability of the PS300 to generate and manipulate three-dimensional wireframe images by providing the potential for three-dimensional modeling of animated displays. The animated display is currently two-dimensional; three-dimensionality may be implemented to allow the modeling of multiple floors, stairs,

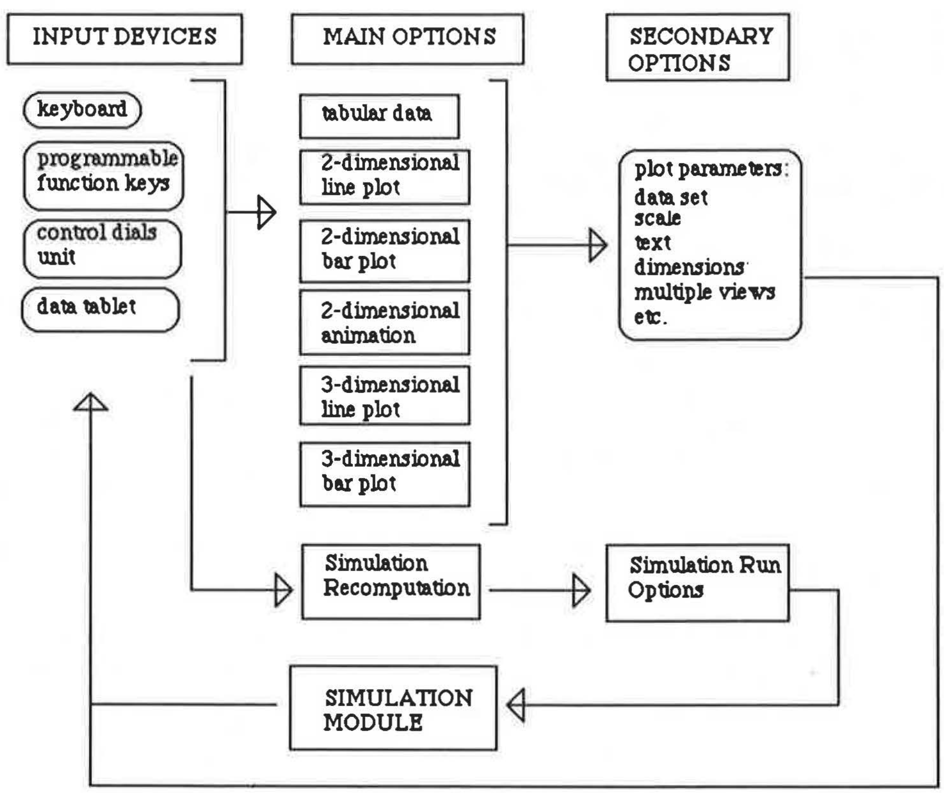

FIGURE 5 Prototype design system options.

elevators, escalators, and ramped areas. Finally, these capabilities are further tied together by the use of multiple tiled windows to allow the simultaneous, synchronized display of different but related data values. An example of this is the generation of an animated display, a two-dimensional congestion index plot, and a two-dimensional bar chart showing current pedestrian counts by link, with all the displays being shown together and dynamically updated and coordinated by the same clocking operation.

Design Process

An emphasis of this research effort is the natural incorporation of the simulation tool into the design process. This is accomplished via the use of a decision-making environment featuring interactive devices, as well as the utilization of dynamic computer graphics to further speed up the information transfer process. The nature of this new interactive design environment in many ways resembles the engineering design process often described in computer-aided mechanical design (*31*). The essential components of this design cycle include two features that may be exploited by computer-aided technologies: conceptual design and engineering analysis/evaluation. These two components are part of an iterative loop that ideally converges on the desired solution. The iterative nature of this process is a common part of this and most other design processes; yet, many analytic tools do not lend themselves to that feature. The mechanical design world has addressed this issue with the development of so-called synthesis models, computer programs that encompass design, analysis, and synthesis in an integrated structure. Its utility has been recognized in marine and aeronautical design applications; the prototype design system described in this paper seeks to implement the concept of a synthesis model by embedding the simulation analysis component within a design environment that facilitates and encourages iterative design and decision making on the part of the planner/designer. Current research efforts are focusing on an even more tightly coupled design, analysis, and synthesis structure in succeeding versions of the pedestrian design system.

The success of a design process that fully incorporates the iterative nature of the design cycle depends in large part on the ease with which the designer can compare competing alternatives. In the transportation planning and design process, decision makers are frequently confronted with the task of evaluating alternative, competing plans of action to address the problem at hand. The efficiency and comprehensiveness with which this task is accomplished has a critical bearing on the ultimate success of the design process, and may influence future station users for many years to come. In general, the process of determining the relative desirability of one alternative design over another should ideally provide the decision maker with information on the impact of proposals, the trade-offs and forgone opportunities involved, and those areas in which further study is warranted. In the field of transportation, design evaluation has evolved from an emphasis in the 1960s on the quantification of relative design advantages to a broader perspective that examines qualitative impacts involving externalities such as air and noise pollution, as well as such questions as the social equity of resource distributions (*32*). In the case of preliminary pedestrian facilities design, special attention should be given to the relationships and trade-offs that involve the level of service of the proposed design as a function of critical physical characteristics of the design, such as physical dimensions, relative locations of station components, the quantity of station features (e.g., ticket booths and turnstiles), and the perturbation of station parameters and simulation model assumptions.

As the complexity of the design problem grows, the degree to which human manual techniques can be used to determine the relative desirability of one alternative design over another decreases. In particular, a large set of evaluation criteria, coupled with variations in the relative importance of one criterion versus another, eventually overwhelms the engineer/designer with a multitude of conflicting data. The introduction of computers into the design problem offers some relief from this dilemma in several key areas of the design process. First, the appropriate use of computers can assist in the generation, aggregation, filtering, and extraction of useful information from large otherwise unusable sets of raw data, thereby easing the task of interpretation on the part of the designer. Second, the computer can be used to assist in the development of new design alternatives by increasing the efficiency of information transfer from computer to user. Third, the computer can in some instances perform automated design improvement based on certain well-defined, though sometimes limited criteria of desirable design features. Fourth, the computer offers the potential for "mechanization" of previously manual design alternative evaluation processes through the use of straightforward computer programs as well as more sophisticated artificial intelligence techniques such as expert systems.

This prototype design system addresses the design process by the use of an interactive environment and interactive computer graphics. Nevertheless, the problem of evaluation is difficult to address via semiautomated computerized techniques. Although a number of algorithms exist for the systematic evaluation of design alternatives, particularly in the field of operations research, caution must be exercised so that an algorithm is not strained in an attempt to extend its utility beyond the scope of applicability for which it was originally intended. The multivariate nature of station design would make the prospect of a single all-encompassing evaluation scheme remote at best. The complexity of the problem requires a flexible approach to evaluation, one that allows the user to select a number of different evaluation techniques in an attempt to extract the salient comparison. The current prototype version provides several means of design alternative evaluation, including simple comparison tables that provide cardinal measures of the values of key parameters for each prospective design, as well as weighted multi-criteria evaluations that use weighting or scoring techniques to evaluate alternatives and provide ordinal measures of design alternative comparisons.

The inclusion of several evaluation techniques reflects the difficulties involved in the computerization of human judgmental processes and expertise. Yet, this approach is consistent with an emphasis on the use of computer tools to assist human judgment rather than generate the "best" real-world solution independently, and also recognizes that the station design process is intimately accompanied by a political component, particularly in the evaluation and alternative selection process, which does not lend itself to automation (*32*). An emphasis in the current phase of research is the development not of a single approach used to the exclusion of all others, but rather the establishment of a systematic framework by which useful trade-off and ranking information may be provided to decision makers. An area of future research that offers an intriguing solution to this challenge involves the use of expert systems, whereby the heuristic knowledge of design processes is encoded into a data base that may be queried by means of an intelligent "inference engine" that performs the tasks of logical reasoning.

PEDESTRIAN FACILITIES DESIGN SYSTEM: EXPECTED UTILITY

The use of computer-aided design and synthesis model concepts in the transportation interface facility design process offers several potential advantages. First, design productivity is enhanced by the immersion of an analytic design tool within an interactive environment that offers rapid response times. Second, the maximization of useful information transfer is facilitated by the use of interactive computer graphics to combine data into useful forms that minimize the need for human post-processing. Third, the synthesis model concept offers an environment that encourages the typically iterative engineering design process. Fourth, computer-aided design concepts systematize the analysis and evaluation process for preliminary station layout designs.

The utility of such a design tool may be extended beyond the preliminary design evaluation of station layouts. The evaluation process could conceivably be extended to include the robustness of the design in the case of unusual or catastrophic events (*33, 34*), as well as sensitivity of the design to alterations in the initial working assumptions of the project. In addition, the increased effectiveness of presentations that utilize data generated in an interactive, graphics-oriented environment has been documented in several studies (*35*). Finally, the modular approach to station analysis offers potential generic utility beyond the transportation interface facility to include other pedestrian areas such as malls and public spaces.

FUTURE DEVELOPMENTS

This research only begins to exploit the potential utility of a highly interactive user interface in the pedestrian facility design process. Further enhancements are essential in the pedestrian simulation; this includes a more sophisticated model of pedestrians behavior as well as extensive testing to validate the model results. The caveats of simulation modeling notwithstanding, simulation-based design systems offer the possibility of analysis into the dynamic characteristics of motion within a design, an aspect that captures the essence of a station design, but for which analytical tools are few and far between. Along those same lines, one of the most important improvements that could be implemented in this prototype system involves porting the system onto a workstation environment that offers a more tightly integrated computing and graphics system, further improving the speed and flexibility of user interaction with the analysis system. The user interface should also be extended to implement a more flexible icon/window/menu-based interface such as that implemented for operating systems on the Apple Macintosh and Xerox Star. In addition, the use of color to enhance information transfer should be addressed. Recent developments in computer hardware have given rise to so-called "superworkstations" offering phenomenal three-dimensional real-time graphics response with greater affordability than ever before. A notable example of such capabilities may be found in workstations such as the Silicon Graphics IRIS 3030 system. Such an environment offers for the first time a "workstation of sufficient power [that] matches the spatial and temporal features of reality" (*25*).

Expert systems offer great potential for the consolidation of human expertise and an expert's line of reasoning into a computerized design evaluation process. Several components of the evaluation process are potential candidates for improvement with the help of expert systems. First, an expert system may be used to accumulate a data base of expert guidelines, judgments, and rules of thumb, as well as relevant city and county municipal codes, which could then be used to dynamically evaluate design alternatives and flag illegal design components, areas of potential improvement, and the expert's assessment of the degree of improvement. An expert system could also be used to process and compare several design alternatives at once; the rule data base could include expert judgments on the degree to which a typical "in-the-field" architect or contractor could correct a given number of illegal components and rule out those designs that exceeded the maximum number of flagged elements beyond which the design is deemed to be beyond help or completely unacceptable by the experts.

Yet another use for expert systems in the design alternatives evaluation process includes the implementation of a data base that contains design standards on lines of sight, lighting, and the like. Used in conjunction with an admittedly highly sophisticated modeling program, the expert system could be used to evaluate competing designs on the basis of expert assessments of architectural, psychological, and aesthetic characteristics. Given the highly subjective nature of such responses, it may even be appropriate for experts to provide a personal segregated data base in order that they could provide computerized, albeit subjective, design critiques on-line. Expert systems offer the ability to evaluate design alternatives based on legal, technical, architectural, and perhaps even aesthetic criteria, while mimicking the process by which experts utilize years of experience to assess a problem; this is particularly useful in the case of complex design issues where closed-form, algorithmic solutions are not well developed.

CONCLUSION

A research effort, which describes the potential of computer-aided design methodologies in the development of transportation interface facilities, has been outlined in this paper. The research seeks to illustrate the potential advantages of an analysis system that is closely linked to, and that more directly accommodates, the design process. By improving comprehension of data as well as providing an interactive user environment, such a design system offers the potential for significant improvements in the transportation interface facility design process. These design features are becoming affordable as supermicrocomputer-based computer-aided design capabilities become available in a networked workstation environment. Indeed, one of the most important by-products of the growth in the microcomputer and computer graphics fields is the increasing accessibility of sophisticated tools for the practicing professional with an accompanying decline in the necessity for consideration of operating expense and initial capital outlays. Transportation professionals should remain keenly aware of the tremendous potential of micro- and supermicrocomputer technology and its utility in the transportation field, particularly as it attracts and makes more accessible sophisticated tools such as simulations to assist in the analysis of complex problems.

A report on the state of station design procedures included the observation that ". . . deeply embedded in the consciousness of transit riders . . . is that unpleasant, unrewarding, unaesthetic experience of getting off one somber train and waiting on a dreary platform for another. Inadequate planning has made the transfer no fun. One sometimes wonders how transit and transportation planners could have been more successful in achieving total error" (*1*). It is hoped that this singularly unappealing description will no longer be accurate as the art and science of pedestrian facilities design continues to evolve into a more sophisticated, objective, and productive process.

ACKNOWLEDGMENTS

The authors wish to acknowledge the assistance of John Ward and the Undersea Technology and Systems Department of the University of Washington Applied Physics Laboratory (APL). Previous interactive computer graphics research was sponsored in part by the APL. Valuable contributions to this research effort were also provided by Jerry Schneider, Scott Rutherford, and Joseph Garbini. This work was performed as part of a dissertation research effort.

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Publication of this paper sponsored by Committee on Intermodal Transfer Facilities.

A Posteriori Impact Analysis of a Subway Extension in Montreal

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An impact analysis of a subway extension in Montreal is presented. Opened in 1976, the extension began operating just before the summer Olympics and included two stations allowing easy access to the Olympic stadium. The analyses are based on large-scale regional origin-destination surveys carried out by the Montreal Urban Community Transit Corporation (the local transit operator) every 4 years since 1970. Because of the amount and nature of data as well as the programming package MADITUC (a Model for the Disaggregate Analysis of Trips on a Transit Network), it was possible to perform specific studies, identifying the main impacts of the extension. On a short-term basis, no urbanistic structuring effect was observed following the subway extension: general trends of population decrease and aging continued in the surrounding sectors. However, the extension had a positive influence on transit ridership. Transit users experienced significant reductions in travel time and a decrease in the number of transfers required. Nevertheless, the effect on modal split was limited in space and time, thus being very local. This attraction phenomenon appears to be significant only within a distance of 1.6 km from the subway line. After an initial increase, the market share for public transit began to decrease, sometimes reaching levels lower than those in the pre-extension period.

The subway system of the city of Montreal has been gradually extended since the inauguration in 1966 of the first 3 lines comprising 26 stations. One of the most important extensions was opened to the public in 1976, the year of the Olympic games hosted by Montreal. Line 1 was then increased by nine stations to the east (two of these stations provided easy access to the Olympic site); 2 years later, eight stations were added to the west on Line 1. Because of the data involved, this paper focuses on impacts caused by the eastern extension.

To legitimate large investment projects, transportation planners, in an era of evolving technology and information systems, are required to use more and better models to forecast relevant and most probable impacts of different scenarios. The present study [for more details, see Lavigueur et al. (*1*)] attempts to contribute to the still-limited knowledge of the impact of rapid transit lines. A posteriori, the predicted impact could be compared to the one that was really observed, thus enabling the authors to confirm, reject, or improve the hypotheses used a priori. Thus, the a posteriori analysis becomes the motor of the evolution of the techniques, principles, and hypotheses used in transportation systems planning.

This paper contains first a description of analytical methodology (data and tools); the general status of public transport in Montreal is presented followed by the identification of the influence zone of the eastern subway extension. Finally, multiple impacts are considered on the basis of a before-after comparison: demographic characteristics, modal split, travel attributes, central business district (CBD) accessibility, and benefits evaluation.

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PLANNING AND EVALUATION METHODOLOGY

The main purpose of the proposed analysis is derived from a distinctive point of view. Instead of examining all the possible impacts observed after the implementation of a subway extension—such as new residential or commercial developments, added value of adjacent lands—the experiment consists primarily of an evaluation exercise performed strictly under the same conditions (data and tools) as those considered available before the project. This tends to validate planning techniques and to evaluate several of the more commonly made hypotheses concerning the impact of subway extensions. The main opportunity of analysis comes from the fact that the 1976 eastern subway extension is surrounded by two large regional O-D surveys conducted in the fall of 1974 and 1978 by the MUCTC's Service Planning Department. Moreover, the 1978 trends can be validated by using the 1982 survey. All these surveys were of the telephone interview type with an average sampling rate of about 5 percent, including the coded and validated answers of 43,000, 55,000 and 75,000 households, respectively.

For each traveler interviewed the surveys provide socioeconomic data (such as age, sex, car ownership, etc.), the zones of origin and destination of every trip made and, for transit trips, the sequence of lines used (*2–5*). This detailed information on transit lines actually used will permit comparison, at a very disaggregate level, of the route and mode choices before and after the subway extensions. Supply-related data on public transport are those used in 1974 and 1978 for planning purposes; this level of resolution is sufficient for network simulation or capacity analysis for a peak period, but is still too crude for a precise evaluation of the operational costs involved. For comparative analyses, however, they provide a good representation of the supply issues during the 1974 and 1978 surveys. For instance, the 1978 MUCTC transit network is coded with about 140 lines (subway, train, bus), 2,000 nodes, 1,400 centroids of zones, and 5,000 transit links. Thus, the error margin may be considered well under 10 percent for large volumes, such as those involved in a subway analysis. To deal with these large data bases, two software packages were used: (a) the transit network planning package MADITUC for processing of network data (*6*), modeling of access links, computation of shortest paths according to a calibrated impedance function, and loading of the observed or simulated trips on the network; and (b) the statistical analysis system (SAS) for files manipulation—merging, sorting, new variable generation, statistical comparative analyses—and for graphical representation of results in reference to the territorial system.

PUBLIC TRANSPORT IN MONTREAL

The city of Montreal is located on an island in the St. Lawrence river, where it forms, with 26 other surrounding municipalities, the Montreal Urban Community (MUC). In the MUC territory (corresponding nearly to the island), the MUCTC is responsible for public transportation. Figure 1 shows the island and the locations of the subway network (1974–1978), the Olympic complex, and the CBD, which attracts an important part of work-related trips.

On the island of Montreal, public transport represents 37 percent of the motorized trips; this percentage becomes as high as 63 percent when considering trips to the CBD. During the morning peak hours, 385,000 passengers use the transit network (*9*). Because of its importance, the CBD is the center of the radial subway system; the surface transit network has a grid configuration.

INFLUENCE ZONE OF THE EASTERN EXTENSION

A study of the origins of the transit trips using the subway lines, all destinations considered in the O-D survey of 1978, provides a good characterization of the respective drainage (catchment) areas (Figure 2). Some zones are clearly attracted by both lines, one of them being chosen by the transit rider according to travel time and location of the destination. Subways are often considered by urban planners to have a strong impact on socioeconomic factors. These impacts are apparently not measurable over a short period of time.

The evolution of the demographic profile of the island of Montreal between 1970 and 1982 (Table 1) was marked by combined aging and urban sprawl, which have well-known corollaries: decrease of population and household size, increase of mobility and automobile ownership. Locally, these phenomena may act quite differently. A key issue of the impact analysis is to distinguish clearly between the effects of the subway extension and the historical evolution had the subway not been built. To summarize:

1. Urban sprawl affects principally the most densely populated sectors; even if the metro was implemented in these sectors, it did not succeed in reversing this population trend.
2. Household size, the most changing variable in modern times [e.g., Baltimore 1985 (*10*)], decreases everywhere, but slightly more near the subway Line 1, probably because of the massive numbers of young people (one- or two-person households from baby boom) reaching adulthood and purchasing property and the new accessibility to the CBD. Examining the available data, no significant change in this trend could be detected over a 6-year period.
3. During the last 15 years, automobile ownership has continuously increased, a trend slowed by the economic recession

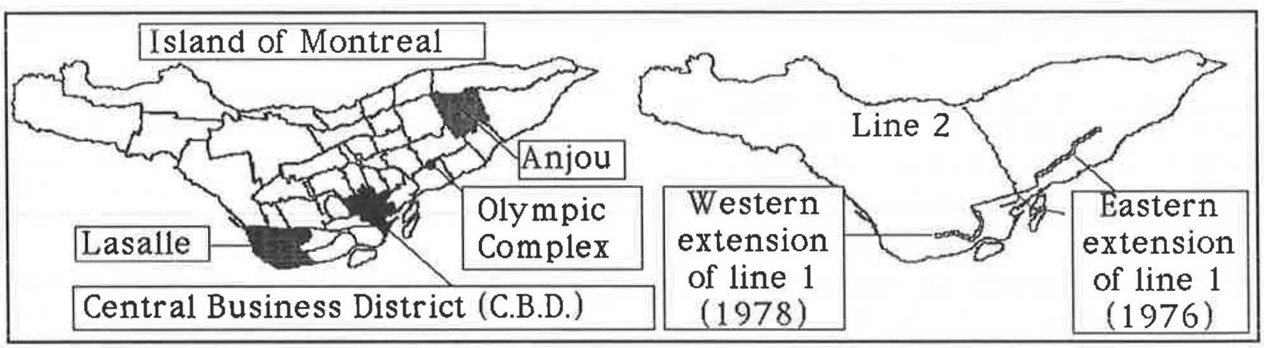

FIGURE 1 Line 1 extensions.

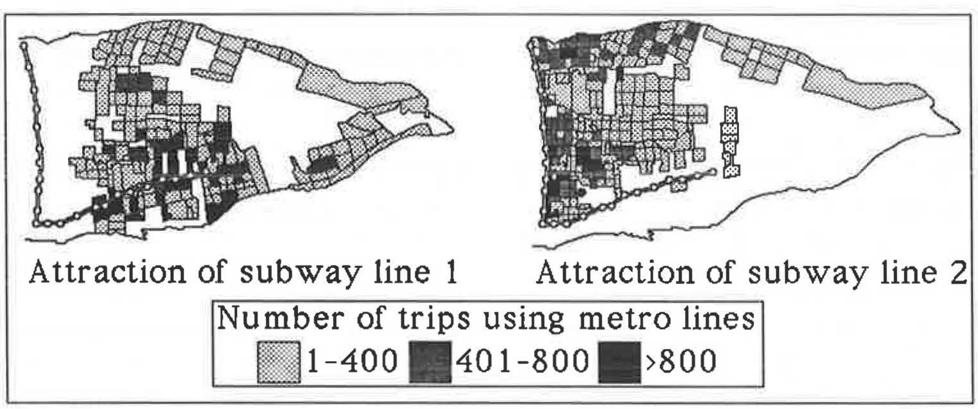

FIGURE 2 Areas of attraction of subway Lines 1 and 2.

TABLE 1 EVOLUTION OF THE POPULATION ON MONTREAL ISLAND

Year	Population	Decrease of Population (%)	Car Ownership (car/ persons)	Household Size	Density (persons/ km²)
1970	1,945,000		0.24	3.3	3,995
		1.0			
1974	1,926,000		0.28	3.0	3,955
		1.9			
1978	1,889,000		0.31	2.7	3,880
		5.9			
1982	1,777,000		0.32	2.5	3,650

of 1981. As with household size, a strong relationship exists with distance from the CBD, but the observed increases near the new extension are in all points similar to the average values of the entire MUC. This observation suggests that the extension had no discernible influence on automobile ownership.

4. An overall aging of the population on the island can be observed; the oldest sectors being those where the subway already existed in 1970. A similar evolution can be seen in the areas touched by the new subway extension between 1974 and 1978. This continuous trend suggests the subway extension had no influence on this population characteristic.

Thus, on the basis of the Montreal case, it may be concluded that if a subway has any structuring effect on urban (and maybe underprivileged) sectors, it may take at least 10 years before it can be measured.

TRANSIT TRAVEL DEMAND

The number of trips made by public transport has increased at a rate of 11 percent every 4 years since 1974, which is significant considering the population decrease in the MUC. According to an extensive study of mobility behavior in the Montreal area (*11*), both (average weekday per capita) total and transit trip rates have grown between 1974 and 1982 from 1.79 to 2.05 for total trip rate and from 0.52 to 0.66 for transit trip rate. The increase in transit use is not distributed uniformly over space (Figure 3).

The sectors located along the Line 1 extensions experienced high increases, but not as high as the zones at the east and west ends of Line 1 (58 percent in Anjou and 43 percent in Lasalle). During the 1974–1978 period, new housing development occurred, which might have attracted potential metro users not yet used to driving to work. It appears to be difficult to induce drivers to use the metro and as can be observed, modal changes were often of a temporary nature.

The new subway extensions have had a positive effect on transit ridership, but it may also be surmised from Chapleau and Girard (*11*) that transit benefited mostly from demographics: progression of specific age–sex cohorts (15 to 24 year olds, senior citizen's groups) in the nearest suburbs.

MODAL SPLIT

Share of the Market

The transit modal split was remarkably stable over the 1970–1982 period (around 37.0 percent of motorized trips), but it was significantly different between sectors. Based on the 1978 survey, it was observed that the new extensions resulted in a local increase in the market share. However, in 1982, this gain was partly lost and the market share decreased below the 1974 level in many zones. Data appear to prove that, as long as the network is stable, the market share tends to stabilize or decrease. A new metro line temporarily improves the market share in the adjacent zones, but the initial downward trend is resumed after a fairly short period.

The municipalities of Anjou and Lasalle were the most successful sectors with respect to the change in market share (Anjou: 1974 > 25.8 percent; 1987, > 32.4 percent; 1982, > 31.9 percent. Lasalle: 1974, > 29.5 percent; 1978, > 37.7 percent; 1982, > 36.4 percent), showing nevertheless decreasing shares between 1978 and 1982. It will be interesting to validate this trend with the new 1987 survey; although, it should be remembered that total ridership is still increasing, the relative loss being the result of increased mobility.

Radius of Influence of the Metro Line Extensions

The influence of the metro line extension was studied with the most disaggregate survey data; zones were grouped with respect to their distance from the nearest metro station. A net gain of approximately 5 percent was observed over a distance of 1.25 km (0.75 mi) followed by a steep decline, so that after 1.67 km (1 mi) the positive influence of the subway disappears (Table 2). The zone of influence for modal split appears to be limited to a band of approximately 1 mi on both sides of the metro extension.

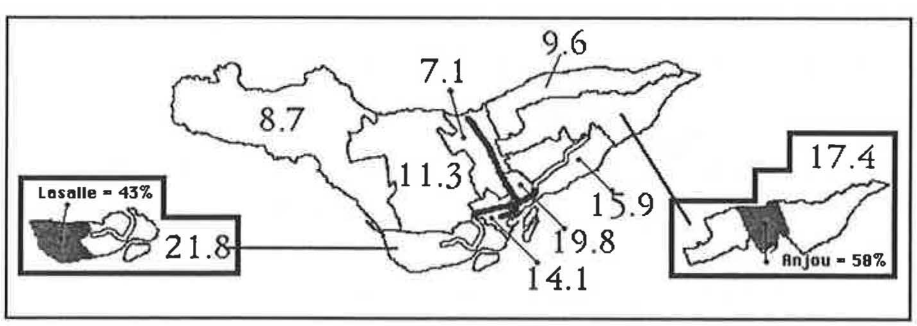

FIGURE 3 Rate of increase, number of trips per person between 1974 and 1978.

TABLE 2 MODAL SPLIT VERSUS DISTANCE FROM THE METRO LINE

	Distance		Modal Split (%)		Difference
Grouping	Km	Miles	1974	1978	(%)
A	0.00–0.42	0.00–0.25	39.9	44.7	4.8
B	0.42–0.83	0.25–0.50	37.7	43.6	5.9
C	0.83–1.25	0.50–0.75	38.4	43.5	5.1
D	1.25–1.67	0.75–1.00	41.2	42.9	1.7
E	1.67–2.08	1.00–1.25	38.9	37.9	−1.0
F	2.08–2.50	1.25–1.50	42.7	40.0	−2.7

TRAVEL DEMAND CHARACTERISTICS

The main contribution of subway implementation is speed substitution (commercial speed of the metro is about 35 to 40 km/hr versus an average of 15 to 20 km/hr for bus). Low headway and regularity also contribute to the reduction of travel time of subway users, often at the expense of an increasing number of transfers. From every transit trip observed in the 1974 and 1978 surveys, the MADITUC simulation model estimated travel attributes such as average travel time (which is, strictly speaking, an impedance function composed of walking access, waiting, in-vehicle times with appropriate weighting factors, in addition to transfer and modal penalties) and average number of transit lines taken by transit riders. Figures 4 and 5 show the differences between 1974 and 1978.

Normally, a subway implementation has a detrimental effect on the number of transfer users experiment. Here, because of the very nature of the line extension, the opposite has been observed. It appears that the users from the sectors adjacent to the metro extension needed fewer transfers and got to their destinations faster in 1978 than in 1974 in spite of longer trips. In summary, large areas have benefited from the service improvement and the consequent user cost reduction.

ACCESSIBILITY TO CBD

The main role of the Montreal metro is to facilitate accessibility to the CBD. The extensions confirm this role, and so far, have contributed a net 5 percent increase in modal split. As shown earlier, the CBD is served by Metro Line 1, which brings people from east and west, and Line 2 from the north. Shortest paths, with the same previously calibrated impedance function, were computed with the respective attributes of the 1974 and 1978 networks (line lengths, commercial speeds, headways). Results (Figures 6 and 7) represent calculations done for a CBD destination near each metro line; this last precaution was taken because of the importance of transfers. Good coherence is noted between areas of larger reductions in travel time and zones of influence of the subway extension already shown in Figure 2. Remarkably, the sector with the largest time savings is Anjou, where MUCTC recorded its best modal split results. Considering both destinations, these maximum savings were an estimated 25 to 30 min (in generalized time units). In the second case, the area experiencing this maximum gain is much larger, comprising almost the whole Anjou municipality. In order to identify the strengths and weaknesses of a metro extension scenario, this type of analysis offers the interesting

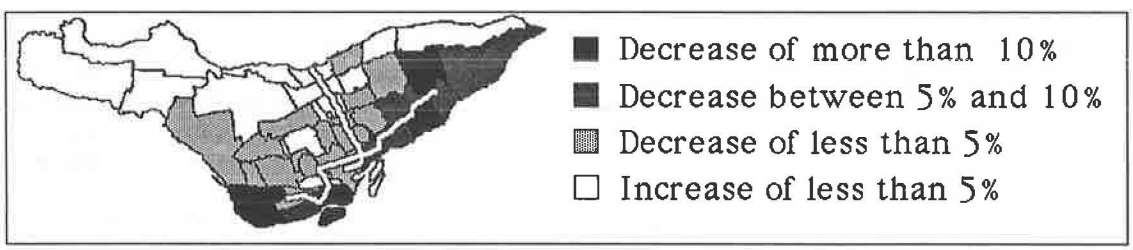

FIGURE 4 Evolution of average trip time between 1974 and 1978.

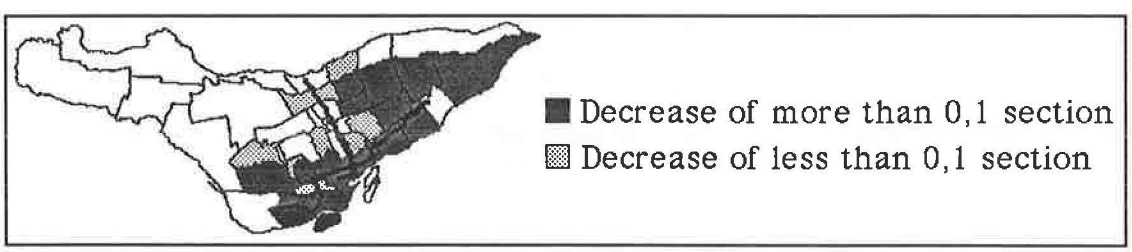

FIGURE 5 Evolution of number of lines used for a trip between 1974 and 1978.

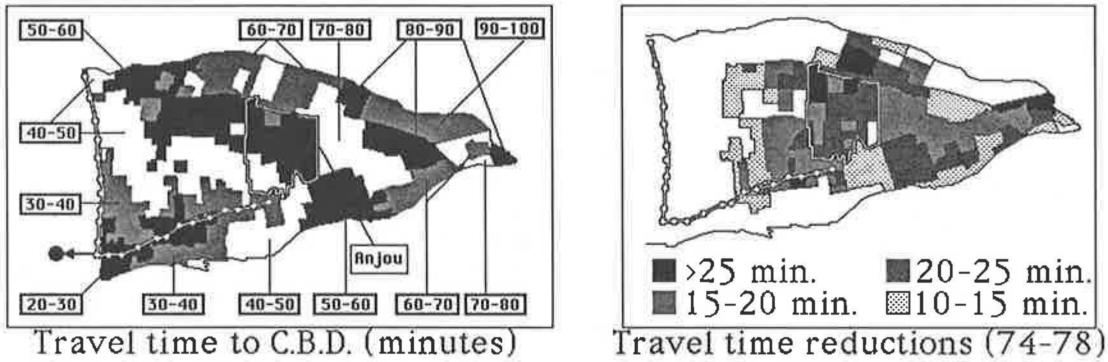

FIGURE 6 Access to CBD near Line 1.

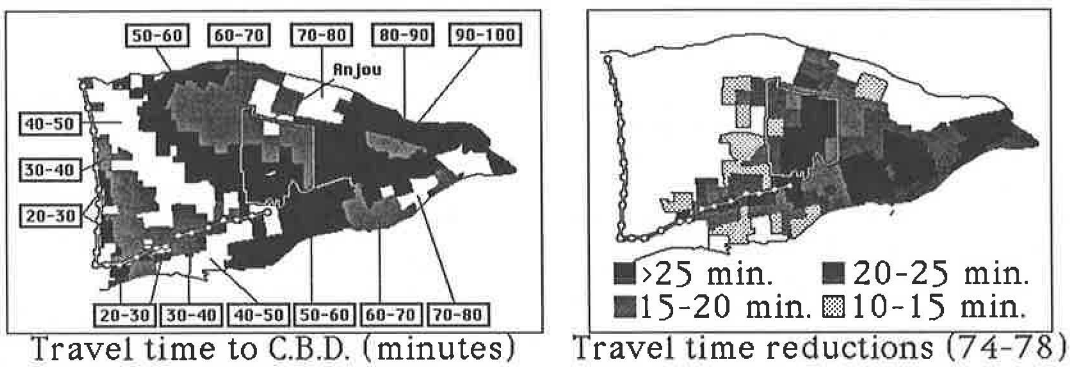

FIGURE 7 Access to CBD near Line 2.

possibility of measuring the spatial distribution of the time benefits. An a posteriori impact study allowed the authors to understand partly why residents of Anjou significantly increased their use of public transit.

TRAVEL BENEFITS' ESTIMATION

The present analysis is carried out on the whole network, in part to simplify the analysis but also because most trips are made on the subnetwork adjacent to the metro extension as well as on the remaining network. Travel time savings were obtained by loading the 1978 a.m. peak demand on the 1974 and 1978 transit networks, applying a calibrated "all or nothing" assignment model. Simulation indicated an overall reduction of 11,500 hr of generalized travel time during the weekday a.m. peak period, consisting mainly of significant time differences; for example, for all trips originating from the Anjou sector, the average time saving is 9.75 min per transit trip. In the neighborhood of the eastern subway extension, approximately 50 percent of these savings experienced by about less than 20 percent of the total demand can be observed.

Estimates of the operational resources (vehicle hours) computed with the network data used in the trip assignment model give the following for the surface network touched by the eastern extension: decrease of 270 vehicle hours for parallel bus routes, increase of 180 vehicle hours for perpendicular bus routes (feeding line 1) and an increase of 70 vehicle hours for other services in the east. The net gain is slim compared with the added costs of supplying resources for the corresponding lengthening of subway Line 1 (mostly tripling the metro vehicle hours because of the simultaneous east and west extensions).

Factors exterior to the analysis are worth mentioning. The extension of a subway line has, in any case, a detrimental effect on the utilization ratio (passengers-km/seats-km), if no short line is introduced. All things being equal, the maximum load point volume increases, requiring more vehicles that have to travel a longer distance to complete their circuit. At this point, for the a.m. peak period in 1978 compared with 1974, maximum link volume on Metro Line 2 dropped by 4,500 from 52,500, while maximum link volume on Metro Line 1 increased by 11,000 from 33,000. Finally on the surface network, the economy of buses is counteracted by another phenomenon: because of the improved regularity of metro service, transit riders have a tendency to reduce the spread of the peak period, accentuating the requirements of the feeder bus fleet and increasing the resources involved.

CONCLUSION

The MUCTC's O-D surveys allowed an analysis, on a before-after scheme, of the impacts of some transportation investments. A new survey is planned for the fall of 1987; 10 years later it is hoped that more medium-term impacts will be observed. From a planning point of view, precise historical supply data were not truly available or recoverable. When these projects were planned, more attention was given to the technology aspect (capacity analysis) instead of cost or productivity dimensions. This explains why the analysis was not capable of discriminating factors related to scale economies on resources usually obtained with rail transit investment projects.

Nevertheless, the multidimensional analysis conducted so far allows some conclusions to be drawn:

- Contrary to the beliefs of many urban planners, based on the Montreal case, subway extensions have no significant structuring effect on a short-term horizon: no distinct trend in demographics was noted around the new metro stations.
- Overall transit ridership has been positively maintained with the subway extension, owing essentially to the general increase in mobility.
- With respect to modal split, the opening of the extension had a stepping-up effect. Nevertheless, this gain declines over time. Six years later, the positive effect remained over only two municipalities (Anjou and Lasalle). The modal split has decreased in all other sectors to or below the level observed before the opening of the extension.
- The subway appears to have, on a short-term basis, a localized impact on transit use. The increase in market share for public transit is diminishing rapidly with distance from the subway stations. In fact, there was no gain outside a 1-mi area on both sides of the subway line. Transit users experienced significant reductions in travel times and needed fewer transfers to make a trip during peak hours. This last result is fortuitous for a subway implementation; here, it depends on the nature of the 1974 surface network: all those having direct access to the new Line 1 extension saved a transfer if the CBD was their destination. Other aspects have also been investigated but may not be validated because of the "weak" quality of operational data available for network situations existing more than 12 years ago. Since then, planners have learned to invest in data characterizing the supply side of urban transport.

Finally, the main result emerging from the Montreal case is that planners must refrain from relying too much on short-term benefits that result from a transit infrastructure. Real benefits appear to come from the dynamics of the urban demography, which would be more easily explainable. It is a conjecture to be validated in future research.

ACKNOWLEDGMENT

The authors would like to thank the MUCTC for the use of data from its O-D surveys for this study. Special thanks are extended to M. Claude Boucher, chief, Research Division, Network Planning Service, for his interest, comments, and contribution to the technical and editorial aspects of this paper. This research project has been partly sponsored by the Natural Sciences and Engineering Research Council of Canada and the FCAR fund of the province of Quebec and the Montreal Urban Community Transit Corporation. The authors are also grateful to the TRB reviewers for their useful comments.

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Publication of this paper sponsored by Committee on Rail Transit Systems.

Simulation Model of Shared Right-of-Way Streetcar Operations

ERIC J. MILLER AND PAUL D. BUNT

Described in this paper is the Queen Streetcar model, a large FORTRAN program currently under development that simulates light-rail vehicle operations on the Queen Route in Toronto. This service operates in mixed traffic and on a reserved right-of-way over a 21-mi route. There are 140 passenger stops and 38 traffic signals along the route, and three separately scheduled streetcar services operate over portions of the route. The model is designed to analyze the impact of a range of operating policies on the regularity of streetcar service. Specifically, the model is intended to allow examination of operating procedures and then permit comparison with alternate means of regulating service, such as alternative short-turn strategies; use of a centralized automatic vehicle monitoring system; and introduction of traffic signal priorities for transit vehicles, reserved rights-of-way, or larger capacity vehicles, or both. The model proceeds by computing the amount of time that each streetcar will spend in a logical set of "states" within each link within the network, where streetcar states include moving in a link, loading and unloading passengers at a stop, and so forth. The model simulates operations during a 2:00 to 7:00 p.m. weekday period using 5-sec time increments. At each 5-sec interval, each streetcar currently in the system is examined to determine if it will remain in its current state for at least another 5 sec or if it is about to go to its next state. If the latter is the case, the appropriate next state is determined, the amount of time that the car will spend in this state is computed, and the system records are updated accordingly. Major sources of randomness within the model include passenger arrival rates and boarding times, and delays as a result of interactions with other traffic within the shared right-of-way.

The Queen Streetcar model is a computer program that simulates light-rail vehicle operations on an urban street. The model was developed as part of a larger study of streetcar operations on the Queen Street route in Toronto that focused on the short-turning of streetcars as a method of regulating service headways (*1*). The objectives of this study were to (a) analyze the sources of headway irregularities, (b) assess the effectiveness of the existing short-turn procedures in controlling these irregularities, and (c) evaluate alternative means of service operation in order to reduce the need for invoking short-turning control methods. Such service options include modifications to the route structure, introduction of new sections of reserved right-of-way for streetcars, introduction of traffic signal priorities for transit vehicles, use of larger capacity vehicles, introduction of a centralized automatic vehicle monitoring system, adjustment to service schedules, and variations in current route-control procedures.

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This wide range of alternatives is indicative of the variety of factors that affects surface transit operations. In addition, streetcar dwell times are determined by random numbers of persons boarding or alighting at each stop. Traffic signals interrupt the streetcars' progress along a route. Finally, a variety of random delays related to queueing or pedestrian interference can occur during mixed-street traffic operation. These complex stochastic interactions, combined with the cost of collecting large amounts of field data and the lack of proven analytical methods, make a comprehensive analysis of alternatives such as those listed previously extremely problematic. Computer simulation was considered a valuable approach for evaluating these alternatives in greater detail.

Although the original need for the model was precipitated by the larger study of streetcar operations on Queen Street, the model development and testing ran past the study time allotment, with the result that direct simulation results were not included in the original study. The principal benefit of the model to this study was the analysis required to construct it. In the conviction, however, that a detailed simulation model is still the only comprehensive analysis tool possible to study the range of operating strategies that can affect streetcar service regularity, the authors have continued the development of the model. The structure and use of the model and its current development status are described . An overview of the model is presented [for a more detailed documentation, see Miller et al. (*2*)] and the results of applying it to a test base case is described.

GENERAL MODEL DESCRIPTION

The Queen Streetcar model was constructed specifically to replicate in detail certain aspects of the Queen Street Route in Toronto. This service operates both in mixed traffic and on a reserved right-of-way over a 21-mi route. There are 140 passenger stops and 38 traffic signals along the route. Three separately scheduled streetcar services operate over portions of the route, which passes through the downtown area where other vehicular traffic is significant. Because of the length of the route, streetcars enter and leave the line at two separate carhouses. In general, it is an extremely large and complicated operating environment to simulate.

In order to control the magnitude of the program development, the simulation model simplifies the real processes wherever possible. However, streetcar service irregularities result largely from the cumulative effects of a large number of random processes. To simulate these effects realistically, it was necessary to develop certain elements of the model in considerable detail. In constructing the model emphasis was directed to those details of operation that had been observed to have the greatest effect on streetcar running times and delays, notably, the passenger loading/unloading process, and delays at signalized intersections. By contrast, the model, which is written in FORTRAN 77, provides only a simplified simulation of general urban street traffic operations. It currently runs on a micro-VAX 11 computer under the Berkeley 4.2 UNIX operating system. A single run of the model takes approximately 5 min of CPU time to execute.

Overall Program Operation

The structure of the model is based on the representation of the streetcar route as a series of links, connected to form a loop. Simulation of the system performance is conducted by calculating the time required for each streetcar to progress through each link. The simulation begins at 2:00 p.m. and runs for 5 hr to cover the entire afternoon.

Streetcars are assumed to operate over each link, in the absence of delay, at predetermined speeds. They are, however, generally delayed by a series of events that include random arrivals of passengers at each stop and subsequent boarding and alighting activity; random midlink delays caused by such events as left turns at unsignalized intersections; and delays at signalized intersections as a result of a red light or a queue of vehicles in front of a streetcar waiting to enter the intersection. A streetcar schedule is provided, and each streetcar attempts to maintain a given schedule by slowing down or speeding up as appropriate.

The short-turn procedure is modeled by establishing "inspector locations" and monitoring the vehicle headways and loads as each streetcar passes these points. A set of criteria is provided to flag the need for a short turn, and a location for the short turn is selected from among a series of preset locations along the route. When a streetcar designated for a short turn reaches the appropriate location, it leaves the route and reenters service in the opposite direction according to instructions provided by the inspector. Data to assess system performance, such as vehicle headways and passenger loads, are collected continuously throughout the simulation at selected points along the route. This information and other summary statistics are compiled periodically, or at the end of the simulation and provided as output on completion of the program. Before execution of the program, input data are compiled in a series of off-line files and read into the program at the beginning of execution. These files include such information as streetcar schedules, passenger demand patterns, traffic signal timings, vehicular traffic flows, and the location of all streetcars at the beginning of the simulation run. In addition, user-defined parameters are provided as input to the program, either from another data input file or interactively from the computer terminal. These inputs permit easy variation of key parameters such as inspector locations, as well as selective output options.

Route Structure Representation

Figure 1 shows a map of the streetcar services using Queen Street. The model focuses on the longest and most heavily scheduled of these, the 501 Queen Route, which runs along Queen Street from the Neville Loop in the east, through the central business district, and along the Queensway to the Humber Loop in the west. This route is modeled in its entirety and serves as the basis for the link definitions used in the model. Each link in the system ends at either a passenger stop or a traffic signal and begins immediately downstream of the previous link. Every passenger stop defines a unique link. In addition, at traffic signal locations where there is no passenger stop, additional links are defined. Streetcars can only enter or leave the link network at specific points. Three types of entry/exit locations exist in the model: carhouses, short-turn locations, and off-line entry/exit points for the 502 and 503 routes discussed next.

The 502 Downtowner operates between the McCaul Loop in the downtown area and the Bingham Loop, overlapping on the Queen line between McCaul Street and Kingston Road, as shown in Figure 1. The 503 Kingston Road Tripper operates between York Street in the downtown area and the Bingham Loop overlapping on the Queen line between King Street and Kingston Road. Separate streetcar schedules are provided as input data for the 502 and 503 routes. On the overlap portions of the Queen line, the 502 and 503 routes are modeled in almost the same detail as the 501 Queen cars. The exceptions are that no adjustments to speeds are made to maintain their schedules and no short-turns are executed.

At the points at which the other routes depart from the Queen line, their operation is modeled in a simplified manner. While off-line, details of passenger service and delays to these services are approximated by estimating the time at which each streetcar returns to the Queen line and reenters with an estimated passenger load. The return times are estimated by computing a random travel time (uniformly distributed around the scheduled travel time) that is added to the scheduled departure time from the end point of the line (i.e., from the McCaul and Bingham Loops for the 502 Downtowner and from York Street and the Bingham Loop for the 503 Tripper). The number of persons onboard and their destinations at the time of reentry is directly estimated by the product of the return travel time and a load rate, which is provided as input data.

As shown in Figure 1, the system divides into five natural sections. Section 1 is the Queensway portion of the 501 route, which operates over a reserved right-of-way. Section 2 is served by the 501 route operating within a shared right-of-way (Sections 3, 4, and 5 are also shared rights-of-way). Section 3 has both 501 and 502 cars operating within it, whereas Section 4 is served by all three routes. Finally, Section 5 is again served only by the 501 route. Each link is thus labeled by its section number in order to keep track of the different service levels. In particular, passenger origin-destination flows are computed on a section-by-section basis so that the model can load passengers onto appropriate cars (e.g., a westbound passenger in Section 4 destined for Section 3 will be permitted to board a 501 or a 502 car, but not a 503 car because the latter does not serve Section 3).

At the start-up of a simulation run, a given number of streetcars are already on the network, distributed according to their individual schedules. As the simulation proceeds, additional streetcars, termed swing cars, enter the system from the two carhouse locations, corresponding to the increase in

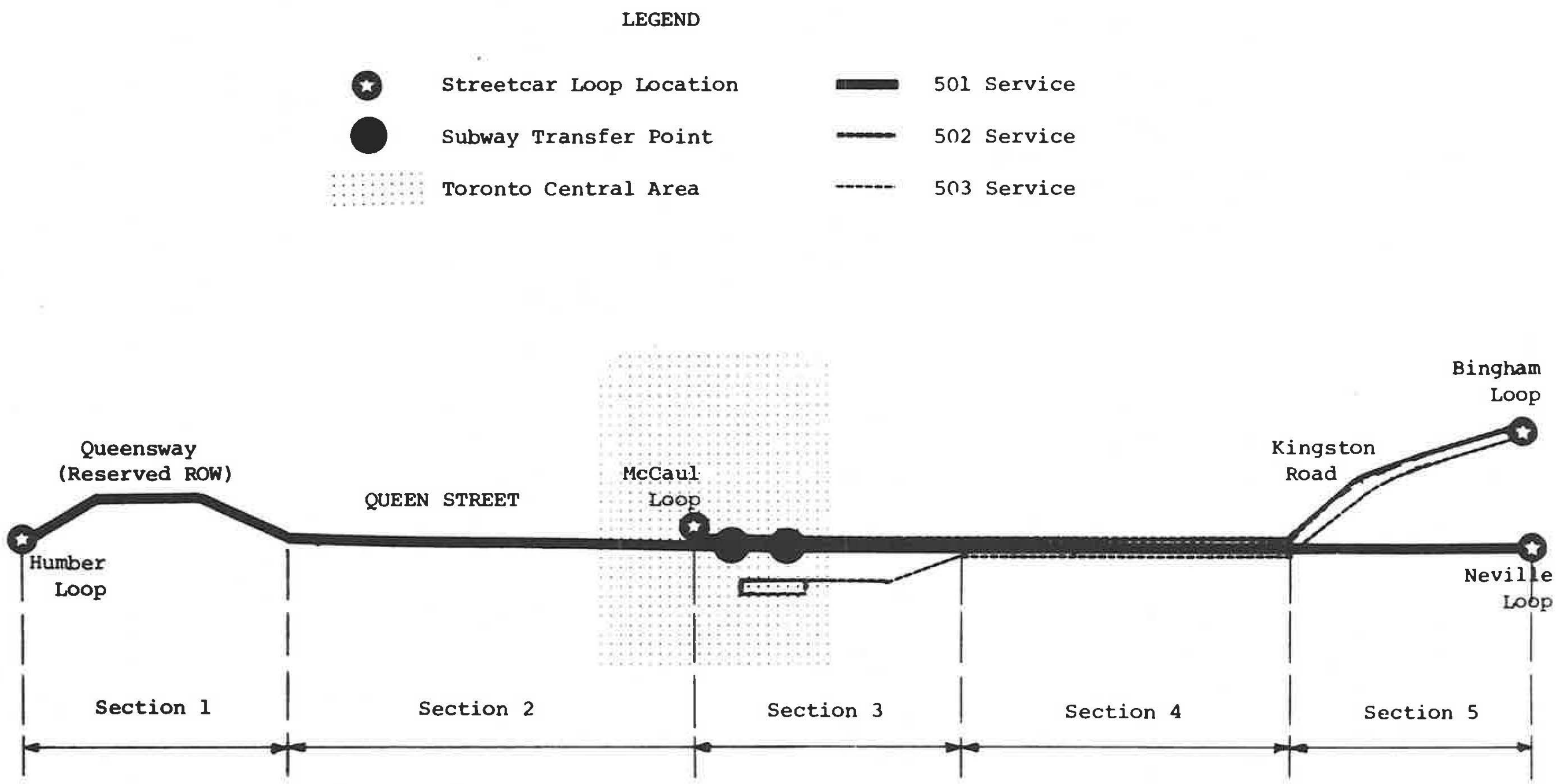

FIGURE 1 Queen Streetcar system.

service during the peak period defined by the schedule. Similarly, streetcars exit to the carhouse locations when their scheduled service ends.

During the course of the simulation, a variable number of short-turns are executed as directed by the inspector submodel. Streetcars leave the network at the end of specific links and reenter in the other direction at the beginning of another link. There are a total of 8 potential short-turn locations, four east and four west of downtown.

Adjustments to streetcar speeds to maintain the schedule are calculated according to time checks at specific timing points along the line, labeled T-points. Each streetcar compares its departure time with the schedule and adjusts its speed to the next T-point accordingly. For convenience, the T-points are also designated as locations for collecting streetcar performance data such as vehicle headways and passenger loads. To complement these locations, where the spacing between T-points is wide, additional user-specified data collection stations, labeled O-points, are included in the model.

Simulation Procedure

Simulation of streetcar performance is based on the calculation of time required for each streetcar to travel through consecutive links in the network. This time is divided into three major activities: moving between stops, loading and unloading passengers, and waiting to clear a traffic signal. On completion of these activities in one link, a streetcar moves downstream to the next link.

Operation of the system as a whole, including the progress of each streetcar, the entry and exit of cars to and from the line, and the short-turn execution, is updated throughout the simulation in time-steps of 5-sec intervals. At each time-step, all links are searched sequentially to determine if there are one or more streetcars either within the link or about to enter or leave the link.

Rather than move each streetcar forward in detailed 5-sec steps, however, progress is monitored by holding each car in a discrete state for a certain number of time increments. When this time expires, the next appropriate state is determined and the length of time the streetcar will remain in that state is calculated. The link review in each time increment then simply checks to determine if any state changes are due at this particular time. The streetcar states defined for use in the model generally correspond to the three major activities referred to earlier. In addition, other temporary or transitional states have been defined to facilitate the programming and the accounting tasks. A full list of the possible streetcar states is provided in Table 1.

The pattern of passenger arrivals at each passenger stop is simulated coincident with the modeling of the streetcars' progress through the network. At the time a streetcar arrives at a passenger stop, the time elasped since the last streetcar arrived at the stop is computed. This time interval is used by the passenger demand submodel to generate a number of passenger arrivals grouped according to their destination section. The passenger loading/unloading submodel then computes the number of passengers that will board this particular streetcar and the time required to do so.

TABLE 1 STREETCAR SYSTEM STATES

State	Activity
1	Having entered a link, a streetcar is moving toward the end of the link with a known arrival time (there are no streetcars ahead in the same link)
2	Loading/unloading at a stop at the end of the current link
3	Upon completion of loading/unloading (or in the absence of a stop), a streetcar is waiting at the end of a link to exit the link (delays include traffic signals, queues, etc.)
4	A transitional state that takes no time and is used for determining the streetcar's next movement, that is, to the next link, out of service, off-line, or to a short-turn loop
5	A streetcar in service but temporarily removed from the Queen line (for 501 cars, they are being short-turned; for 502 and 503 cars, they are traveling on separate route sections)
6	A transitional state for a streetcar that has entered a link and is moving toward the end of the link but with an unknown arrival time because at least one other streetcar is ahead in the same link

Model Sub-Components

The logic of the main components of the model is described in this section. The presentation has been tailored for ease of description, and the subtitles do not necessarily correspond to the structure of the subroutines in the program code itself. More complete documentation of the main program and the individual subroutines is provided by Miller et al. (*2*).

Moving Between Stops

An initial running speed is assigned to each streetcar at the simulation startup according to the section in which the streetcar is located. As the streetcar moves from one section to another, this base running speed is altered. Adjustments to the base running speed are made continuously throughout the simulation for each streetcar according to the schedule adherence monitored at the T-points. This streetcar speed and the length of the link are then used to compute the free running time of the streetcar in the link (i.e., the time the streetcar would arrive at the end of the link in the absence of delay).

Midlink delays to each streetcar can result from such events as left-turns by other vehicles in front of the streetcar at unsignalized intersections, pedestrian crossings, and parking maneuvers of other vehicles. The model groups all such occurrences together and calculates whether or not a delay will occur in each link. The occurrence of a midlink delay is first randomly determined, and, should the outcome be positive, a random delay length is then generated. Both the probability of occurrence and the distribution of delays are provided as input data.

Whether or not a queue exists at the end of the link is determined by the traffic flow entering at the beginning of the link ahead of the streetcar, the size of any residual queue at the traffic signal at the end of the link, and the presence of other streetcars already in the link. If there are no other streetcars in the link, the streetcar is considered to be in State 1, the size of the head queue in front of the streetcar is computed, and the time required to dissipate the queue is simulated. If another streetcar is present, the entering streetcar is considered to be in State 6, whereupon it is advanced only part way into the link. When all other streetcars have finally departed, the entering streetcar effectively reverts to State 1, and the final arrival time at the end of the link is computed (queueing delay calculations are discussed further in the next section).

The running time, mid-link delay time, and queue delay time are added to produce an arrival time for the entering streetcar at the end of the link.

Passenger Loading and Unloading

The passenger demand submodel generates arrival of passengers in two parts. Average arrival rates over 30-min periods are provided for each passenger stop as input data. The number of passengers arriving at a stop is computed according to these mean arrival rates and the time interval between streetcars reaching the stop, assuming that passenger arrivals are Poisson distributed. In addition to this continuous arrival distribution, it was considered necessary to account for observed "surge" loads of passenger arrivals corresponding to transfers from other transit services at stops on major intersecting transit routes. This is simulated in a manner similar to the midlink delays. A random occurrence is generated according to a preset rate, and, in the event of a positive outcome, a random load is generated, again within a defined distribution.

When the total number of arriving passengers has been computed, they are divided into destination groups according to section, based on observed sectional origin-destination distributions. Five separate queues of waiting passengers are therefore maintained at each stop, each being incremented or decremented according to arrivals and boardings. The passenger loading/unloading model is used to compute the amount of time a streetcar spends in State 2, termed passenger service time. Boarding and unloading times are computed separately, the latter being further divided into front and rear door unloading times. The total passenger service time is the greater of either the rear door unloading time or the sum of the front door unloading time plus the boarding time.

The number of persons onboard each streetcar is updated by the model at each stop. The total number of passengers onboard is stored separately for each destination section. At any given stop the number of persons who unload is determined by the section of the route on which the stop is located, the number onboard destined for that section, and the overall destination of unloading patterns within the section (provided as input data). Unloading times are simply calculated as the product of the number of persons alighting and a user-specified average time per passenger. The distribution of unloading passengers between front and rear doors is based on an assumed distribution of seated and standing passengers onboard the streetcar as it arrives at the stop.

Boarding times are calculated in a sequence of steps. The number of passengers wishing to board is first calculated depending on the number of persons in the five destination queues of waiting passengers, the streetcar route (501, 502, or 503), and, if the car is designated for a short-turn, the short-turn destination. The number of persons who actually board is then calculated depending on the remaining space on the streetcar after unloading is completed. In the event that there is insufficient room to board all waiting passengers, the number who actually board is drawn proportionately from the five destination queues.

With the number of persons boarding known, the boarding time is then computed as a random variable dependent on this number as well as the number of persons already onboard the car at the completion of unloading. It is assumed that variability in loading times is higher for small numbers of persons boarding and that average boarding time per person increases if more than a full seated load is already onboard. Once the initial passenger service time has been computed, a second iteration of the passenger loading calculation may be made. During the period that passengers were first unloaded and loaded on arrival of the streetcar, additional passengers may arrive at the stop wishing to board. If another streetcar is immediately behind, the arrival of this second wave is ignored, based on the assumption that these passengers will board the trailing car. If there is not a trailing car, and there is still room onboard the car at the stop, these additional passengers, or a portion of them, will also be loaded onto the streetcar with a corresponding extension of the passenger service time.

Other Street Traffic

The operation of streetcars on an urban street in mixed traffic slows running speeds considerably. In addition, the randomness of the delays that occur is a major source of variability in streetcar service. The list of potential types of delays is almost unlimited. Moreover, on a high frequency route with heavy passenger loadings such as the Queen line, interaction between streetcars running on a fixed track and other street traffic is complex. Because vehicular traffic is prohibited by law from passing a streetcar with open doors at a passenger stop (where there is no passenger platform), a loading streetcar will delay other vehicular traffic. Streetcars delay traffic, which creates a queue, which in turn may delay a following streetcar, and so forth.

The approach used to simulate this process in the Queen Streetcar model is to estimate traffic-related delays from the viewpoint of each individual streetcar only, on a link-by-link basis. Calculation of these delays depends on the model of traffic signal operations and the process of vehicle arrivals and departures into and from a link.

The model of traffic signal operations closely resembles the real world by simulating the actual timing plans used by the Metropolitan Toronto Roads and Traffic Department through the central traffic computer. These timing plans are provided as input data and include directional split phases, changes in timing plans through the 5 hr of simulation, and all are time coordinated through the specification of signal offsets. The only simplifications are that time is measured in 5-sec steps (rather than as a proportion of cycle length) and that no allowance is made for clearance intervals (amber or all red periods). Signals facing a streetcar are either effectively red or green.

Vehicle arrivals into a link are assumed to accumulate at constant rates, which are provided as input data. To model time variations in flow, the rates are altered each 30 min of simulated time. These rates are compiled directly from traffic count data at all signalized intersections provided by the roads and traffic department. Variations within a 30-min period are not modeled and disturbances to the arrival flow caused by upstream traffic conditions are ignored. The arrivals correspond to the estimated proportion of the traffic volumes in the left lane only (i.e., the lane in which the streetcars travel).

Vehicle arrival rates are used to compute the number of vehicles ahead of a streetcar as it enters a link (i.e., the head queue). If the last streetcar is still within the link, the queue remains unaltered until that streetcar departs. No allowance is made for traffic in the left lane to pass a streetcar ahead. If the previous streetcar has departed, then the time required to dissipate the queue is calculated. If there is no traffic signal at the link end (i.e., a passenger stop only), then the queue is assumed to discharge immediately. Otherwise the queue dissipation time is computed by means of a model of the vehicle departure process at a traffic signal.

Vehicle departures are modeled as two separate cases: before the streetcar arrival at the link end and after it has arrived. A streetcar is considered to have arrived when the head queue has shrunk to a size of two vehicles or less. It is assumed that a queue of two vehicles will not prevent the streetcar from proceeding with the load/unload process in State 2 directly.

In the first vehicle departure case (head queue greater than 2), the vehicles are discharged at the traffic signal according to a constant saturation flow rate built directly into the model. The time required to reduce the queue to at most two vehicles is computed in combinations of partial and, if necessary, whole signal cycles, according to the green time in each cycle. The streetcar is considered to have arrived at the link end at that point in time and will change to State 2. Any residual green time in the last signal cycle is then used to discharge either one or both of the remaining head queue vehicles.

On completion of the initial passenger service time in State 2, the streetcar changes to State 3, and a series of checks are made to determine if it can then proceed to the next link or if it will be delayed by either additional arriving passengers or by traffic-related factors. If there are additional passengers, the streetcar reverts to State 2 and continues loading as previously described.

Possible traffic delays result when the traffic signal is red, there is a small remaining head queue of one or two vehicles, or the next link is full. If the link is full, the model holds the streetcar in State 3 and checks each 5-sec time step to determine if enough space has been created to allow the streetcar to proceed. If the signal is red, the streetcar simply waits for a green signal. If there is a remaining head queue, then the second type of vehicle departure time is calculated. In all three cases, no additional passenger loading is assumed.

The second vehicle departure case is intended to model the effect of delays as a result of left-turning vehicles at a signalized intersection immediately before the streetcar's departure from the link (other left turns before the streetcar arrival at the link end are accounted for in the saturation flow rate used to dissipate the head queue down to two vehicles or less). Because there are at most two vehicles in the queue, there are either 0, 1, or 2 left-turning vehicles, with the actual number of left-turners determined by a sequence of Bernoulli trials applied to each vehicle in turn. If there are no left turns the delay is zero. If there is one left turn, the model assumes that 30 percent of the next green phase is required to clear the queue, whereupon the streetcar can then depart if there is any green time left. If there are two left turns, it is assumed that the entire green time is needed to clear the queue, and the streetcar is delayed until the next cycle. In any case, it is assumed that the two-vehicle queue will clear within the current cycle so that the streetcar will be delayed no longer than the beginning of the next green phase. An advanced green split phase or separate left-turn phase in the signal timing plan is treated simply as additional green time for the queue to clear.

The overall effect of this method of modeling traffic-related delays is to simulate the delays that occur as a result of other traffic on the basis of streetcar performance. Although the other traffic factors are assembled in various components, the processes are largely deterministic. With the exception of midlink delays, randomness in the delays because of these factors is entirely the result of randomness in the progress of the streetcars. The model also assumes implicitly that there are no road capacity problems deriving from the other traffic volumes alone. In the absence of streetcars, all traffic arrivals will clear at each traffic signal every cycle with no spillover of queues into upstream links. Only if a streetcar arrives and encounters a long passenger service time will queueing create congestion difficulties on the network.

Short Turn Model

The short-turning procedure is a control strategy directed by inspectors on the line for the purpose of regulating service headways. Streetcars are directed off the line at certain loop locations and instructed to reenter in the opposite direction of travel at specific times in order to place the reentering streetcar between two other cars that are widely separated. Passengers who are destined to stops further down the line and transfer to a trailing car are thus inconvenienced by having to get off the short-turning car. Because of passenger inconvenience and disruption to the vehicle schedules caused by the short-turning procedure, criteria are established by management to guide the inspectors in making short-turn decisions. In practice, inspectors use considerable judgment in applying these criteria. Because analysis of the short-turning procedure was the principal focus of the main study, the model tries to duplicate that procedure as closely as possible. Any computer simulation of a process involving human judgment, however, does have certain limitations. The model establishes certain rules and procedures that are followed rigidly. In practice, there is a variety of nonquantifiable circumstances that may cause an inspector to deviate slightly from these rules. Analysis of the simulation results is therefore restricted to examination of the effects of the rules and criteria rather than to the procedure as it is more widely applied.

The occurrence of a large gap between successive streetcars on the line is the basic cause of a decision to short-turn. The model identifies this condition by monitoring vehicle headways at locations identified as inspector locations. A critical gap size is defined as input data, which, when exceeded, flags the need for a short-turn. From that time forward, a search procedure is followed to find one or more streetcars behind the gap to be selected for short-turning. This search procedure is executed by continuously monitoring the status of streetcars as they pass the inspection locations and comparing their status with estabished criteria. The number of short-turning vehicles required for a certain gap is a function of the size of the gap. This number is selected in order to reduce the resulting gaps between successive cars to an average equal to the nominal headway on the route.

The eligiblility of a streetcar for short-turning is determined by the following criteria:

1. Must be a 501 Queen car;
2. Must not already be designated as a short-turn car;
3. Must not be scheduled to go out of service during the current run;
4. Must not have a large headway in front of it;
5. Must have no more than a critical passenger load onboard (provided as an input parameter);
6. Another 501 Queen car must be behind in the same link or, if the link is short, in the link behind;
7. Must be able to reach a short-turn loop location in sufficient time to turn around and reenter service in the gap; and
8. Two consecutive cars may not be short-turned.

If no such vehicle can be found, the search to find cars to fill that gap is abandoned. Gaps greater than the minimum criteria are stored in a file and serviced sequentially. When no further short-turn cars can be found for the gap on top of the list, it is removed and the next gap is serviced, if possible.

Possible locations for the short-turn are determined by estimates of the travel time from the inspector's location to the available downstream short-turn loops. Suitable short-turn locations are therefore determined by the inspectors' positions. The short-turn location is selected in order to insert the short-turning car onto the line at the earliest time. This corresponds to the location closest to the end of the line from which the car can fill the gap in the opposite direction at the earliest opportunity.

For a selected short-turn vehicle and location, the reentry time is chosen by determining aim-points. If the gap is small enough so that only one short-turn car is required, the aim-point corresponds to that point in time when it is estimated that the center of the gap will pass the short-turn loop location. This is determined from travel-time estimates between short-turn loop locations and the end of the line. If the gap requires more than one short-turn vehicle, the aim-points are determined by dividing the gap by the number of short-turns. The aim-points for a certain gap are serviced sequentially. This procedure permits multiple short-turns for a given gap to occur at two or more available locations. Short-turns are then executed in the model in the following steps:

1. A streetcar successfully found for short-turning at a determined short-turning loop is labeled (this label then subsequently affects boarding patterns onto the car as described previously);
2. At the link immediately upstream of the short-turn location, all passengers on-board the labeled car are off-loaded;
3. When the streetcar exits from the link immediately upstream of the short-turn location, it is directed off the line for a preset turnaround time (provided as input data);
4. The streetcar reenters the line into the beginning of the appropriate link at the time corresponding to the selected aim-point, or if that time has passed, as soon as possible;
5. The streetcar's schedule is redefined to be "on-time" at the aim-point time.

Model Evaluation

Validation and further development of the model is currently proceeding. To date, of the range of operating strategies that the model was designed to test, only the existing short-turn operating procedures have been examined in any detail. Other test cases, including the use of larger capacity, articulated streetcars and passive traffic signal priorities, have been constructed but not yet fully tested. The validation tests that have been performed to date on the Queen Streetcar model are summarized next. These tests consist of four runs using combinations of two initial 2:00 p.m. system states and two initial random number seeds. In all other respects, the inputs are identical for the four runs and are intended to represent base case or normal operating conditions. Comparisons of the simulation results obtained from these four runs are presented with observed statistics for Queen Street operations. These comparisons include passenger flows, streetcar travel times, loading counts, delays, and short-turn performance. The simulated travel times between time-points (T-points) averaged over the four base runs are given in Table 2. Overall, half-trip times between 4:00 and 6:00 p.m. are quite close to the travel times observed by the Toronto Transit Commission in its elapsed time surveys conducted in the fall of 1983. Similarly, the overall correspondence between simulated and observed times on a section-by-section basis is also generally good. The deviations from observed performance that do exist are likely because of the assumption of constant bidirectional sectional running speeds for the entire 2:00 to 7:00 p.m. simulation. Incorporation of running speeds that are sensitive to time of day and direction would undoubtedly rectify this problem. Table 3 gives observed and simulated flows for eastbound passengers during the 4:00 to 7:00 p.m. period, where the observed passenger flows were derived from TTC Riding Count Surveys conducted in the fall of 1983. To more accurately represent typical passenger volumes, the average flows from the four base runs are presented in the table. Total simulated passenger origins and destinations, by section, are quite close to the observed volumes, with similar results being obtained for westbound flows and the 2:00 to 4:00 p.m. period.

The September 1984 vehicle loading counts at selected locations formed the basis for checking simulated vehicle loadings between 4:00 and 6:00 p.m. Observed and simulated vehicle loadings at the selected location are given in Table 4. Simulated average vehicle loadings between 4:00 and 6:00 p.m. are close to those observed. The simulated loading distributions are, however, noticably skewed at the central locations as evidenced by the standard deviation about the mean and the percentage of vehicles with very light and very heavy loads. One factor that contributes to this high variance in vehicle loads is the short-turning strategy currently used in the model, which results in a large proportion of the short-turns being executed at the inner locations (i.e., Church-Victoria eastbound and Bathurst and McCaul westbound).

To illustrate the impact of this short-turning strategy on vehicle loadings, consider the Church eastbound location. The large percentage of vehicles eastbound at Church Street with very light loads (27.6 percent) and very heavy loads (29.8

TABLE 2 SCHEDULED, OBSERVED, AND SIMULATED RUN TIMES BETWEEN T-POINTS

(a) Average Simulated Run Times for Queen Streetcars (Min.)

Section	2-4 p.m. EB	2-4 p.m. WB	4-6 p.m. EB	4-6 p.m. WB	2-7 p.m. EB	2-7 p.m. WB
Humber Loop-Roncesvalles	7.0	7.8	7.0	7.8	7.0	7.8
Roncesvalles-Ossington	9.0	9.2	9.0	10.0	9.0	10.0
Ossington-Bathurst	5.0	4.5	5.0	4.2	5.0	4.0
Bathurst-Spadina	2.3	2.0	3.0	2.0	3.0	2.0
Spadina-McCaul	2.0	2.0	2.0	2.5	2.0	2.0
McCaul-Yonge	5.2	4.0	6.5	4.0	6.0	4.0
Yonge-Broadview	10.0	10.7	11.0	13.0	10.0	11.7
Broadview-Connaught	8.0	8.3	8.3	8.5	8.0	8.0
Connaught-Kingston	2.8	2.0	3.0	2.0	3.0	2.0
Kingston-Neville Loop	8.0	8.0	8.2	7.8	8.0	8.0
Humber Loop-Neville Loop	59.3	58.5	63.0	61.8	61.0	59.5

(b) Scheduled, Observed and Simulated Run Times Between T-Points Eastbound 4:00 to 6:00 p.m.

Section	Scheduled	Observed	Simulated 1	Simulated 2	Simulated 3	Simulated 4
Humber Loop to Roncesvalles	8	7	7	7	7	7
Roncesvalles to Ossington	8	9	9	9	9	9
Ossington to Bathurst	6	5	5	5	5	5
Bathurst to Yonge	10	11	12	11	12	11
Yonge to Broadview	10	9	11	11	11	11
Broadview to Kingston	9	11	11	11	12	11
Kingston to Neville Loop	9	12	8	9	8	8
Humber Loop to Neville Loop	60	64	63	63	64	62

Section	Scheduled	Observed	Simulated 1	Simulated 2	Simulated 3	Simulated 4
Neville Loop to Kingston	9	8	8	8	8	7
Kingston to Broadview	9	10	10	11	11	10
Broadview to Yonge	10	10	12	13	14	13
Yonge to Bathurst	10	12	8	9	8	9
Bathurst to Ossington	6	5	4	4	4	5
Ossington to Roncesvalles	8	8	10	10	10	10
Roncesvalles to Humber Loop	8	8	7	8	8	8
Neville Loop to Humber Loop	60	61	62	63	63	59

Note: Observed Run Times were calculated from TTC Elapsed Time Surveys, Oct. 1983.

percent) is partly attributable to the relatively large number of westbound short-turns at Bathurst Street (four in the 4:00 to 6:00 p.m. period) and McCaul Street (two in the 4:00 to 6:00 p.m. period). The short-turned vehicles enter service eastbound with no passengers onboard and travel a relatively short distance to Church Street where they are observed to be lightly loaded. The streetcars that are not short-turned westbound pick up a larger than expected number of passengers on their eastbound return trip, especially over the section from Roncesvalles to Bathurst. This tends to inflate the percentage of heavily loaded vehicles at Church Street. A similar argument holds with respect to the high loading variance at Bathurst Street westbound resulting from the large number of short-turns occurring at Church Street eastbound.

The model classifies streetcar delays under three general headings: passenger service time, queueing and signal delay, and other running delay. Passenger service time is simply the time required to load and unload passengers at a stop. Queueing and signal delays are those that impede the streetcar from reaching the stop at the end of the link or block it from entering the next link. Other running delays are associated with midlink delays such as left-turning vehicles, parking maneuvers, and pedestrian crosswalks. The simulated streetcar delays are summarized by section and time period for one of the test runs in Table 5. The model's performance in simulating streetcar delay is one area that has not been evaluated to date. A major obstacle in assessing the model's performance in this area is the lack of available data on actual streetcar delays in a format comparable to the model outputs. It is encouraging to note, however, that the simulated delays appear reasonable given the limited data available from previous TTC Speed and Delay Surveys (October 1983 and September 1984). The short-turn model and the current criteria that a car must meet to be signed for a short-turn are discussed in the General Model Description in Section 2. The model's performance for the four base runs is summarized in Table 6. Considerable variation exists across the four base runs in the number and size of the gaps observed and the inspector's ability to find short-turn cars. On average, the inspector is able to find only one-half the number of cars required to completely fill the observed gaps.

TABLE 3 OBSERVED VERSUS SIMULATED PASSENGER FLOWS (EASTBOUND 4:00 TO 7:00 P.M.)

Eastbound 4:00 to 7:00 p.m.

Origin / Dest'n	Section 1	Section 2	Section 3	Section 4	Section 5	Section[3] 7	Total	Difference Sim. vs. Obs.
Section 1	302[1] 359[2]	495 513	198 190	42 34	5 1	-	1042 1097	+5.3%
Section 2	-	1125 1045	1194 1161	887 866	204 196	-	3410 3268	-4.2%
Section 3	-	-	1270 1267	1232 1238	808 797	539 539	3849 3841	-0.2%
Section 4	-	-	-	884 905	369 357	221 218	1474 1480	+0.4%
Section 5	-	-	-	-	245 241	-	245 241	-1.6%
Total	302 359	1620 1558	2662 2618	3045 3043	1631 1592	760 757	10020 9927	-0.9%
Difference Sim. vs. Obs	+18.9%	-3.8%	-1.7%	-0.1%	-2.4%	-0.4%	-0.9%	

1. Observed: Based on TTC Riding Count Summaries - October 1983
2. Simulated: Average from the four simulation base runs.
3. "Section 7" represents the Kingston Road catchment area served by the 502 and 503 streetcars.

TABLE 4 VEHICLE LOADING SUMMARY, 4:00 TO 6:00 P.M.

Location		Mean	Std. Dev.	% 25	% 80
		Eastbound			
Church	-obs.	48	17	6.0	3.3
	-sim.	58	41	27.6	29.8
Broadview	-obs.	49	22	11.5	10.5
	-sim.	53	32	27.5	27.5
Kingston	-obs.	29	17	43.1	1.0
	-sim.	23	18	56.8	0.0
		Westbound			
Bathurst	-obs.	60	28	11.9	29.2
	-sim.	57	41	30.4	30.4
Parkside	-obs.	40	22	30.3	4.0
	-sim.	36	28	44.7	7.9

Note: Observed vehicle loadings are based on the Vehicle Loading Survey, Sept. 1984

Simulated vehicle loadings are those produced in Run 1.

TABLE 5 STREETCAR DELAYS

Section	2:00 to 4:00 P.M.			4:00 to 6:00 P.M.			6:00 to 7:00 P.M.		
	PST	Q+S	Other	PST	Q+S	Other	PST	Q+S	Other
				Eastbound					
1	2.7	4.4	0.7	7.4	12.9	2.8	5.0	14.7	3.9
2	8.9	8.8	3.6	15.4	14.9	6.2	11.9	17.1	4.3
3	11.1	8.2	2.5	20.7	22.6	5.9	14.9	20.2	5.2
4	9.9	4.9	3.8	19.5	9.9	6.8	13.1	12.7	5.1
5	7.6	3.1	4.4	16.0	9.0	8.6	13.7	10.5	6.5
				Westbound					
1	9.2	4.3	0.7	16.9	7.0	3.2	12.0	11.8	4.1
2.	8.2	6.9	2.3	19.3	16.3	5.5	11.9	22.5	4.1
3	10.2	8.8	3.2	17.7	22.1	4.4	10.0	32.3	4.4
4	7.9	7.8	3.9	12.5	12.1	6.6	6.8	18.2	5.3
5	3.8	4.6	2.7	8.7	10.3	7.8	5.3	14.6	6.6

Note: Streetcar delays are expressed as a percentage of total section travel time.
PST — Passenger Service Time.
Q+S — Queueing Plus Signal Delay.

TABLE 6 SUMMARY OF SHORT-TURN MODEL PERFORMANCE

Inspector Location	Run No.	Gaps Observed	Short-Turns Required	No. of Cars Short-Turned	Gaps for Which No Cars Were Short-Turned
Eastbound: Victoria	1	19	34	10	12
	2	13	27	17	2
	3	14	35	14	5
	4	13	31	17	2
	Avg	15	32	15	5
	2x	12	24	24	0
Westbound: Simcoe	1	16	30	17	4
	2	16	38	21	5
	3	14	34	16	5
	4	15	34	20	4
	Avg	15	34	19	5
	2x	16	31	26	3

One-third of the gaps go unattended as the inspector cannot find suitable cars to short-turn in time to meet the returning gap in service. The distribution of short-turn locations for the four base model runs is given in Tables 7 and 8. The large majority of short-turns was executed at the four inner short-turn locations. In practice, inspectors direct most of the short-turning cars to the outer locations to restore service regularity as quickly as possible.

The number and location of short-turns predicted by the model is a reflection of the input criteria used to judge a car's suitability for short-turning discussed earlier. The model undoubtedly adheres more rigidly to the criteria than do inspectors in the field. During the 4:00 to 6:00 p.m. period, for example, average vehicle loads at the inspector locations were in excess of 50 passengers; therefore, few cars in the model were eligible to be short-turned, whereas under real conditions, inspectors might be expected to relax this rule. Further, the criteria that there must be a 501 car close behind made the task of finding a suitable short-turn car more difficult. To test the model's sensitivity to this criterion, Run 2 was rerun with the trailing car criteria removed (this run is labeled Run 2x). The substantial improvement in the model's short-turning performance is given in Table 6. Not only was the eastbound inspector able to short-turn all the required cars, but he was able to direct the short-turns to the outer locations. Similar, although less dramatic, improvements in the westbound inspector's performance are also observed.

TABLE 7 EASTBOUND SHORT-TURN LOCATIONS FOR THE FOUR BASE MODEL RUNS

	Location			
Run No.	Church	Parliament	Connaught	Kingston Road
1	9	0	0	1
2	11	4	1	1
3	7	3	1	3
4	11	4	1	1
Total	38	11	3	6
Percent	65.5	19.0	5.2	10.3
2x	0	4	5	15

TABLE 8 WESTBOUND SHORT-TURN LOCATIONS FOR THE FOUR BASE MODEL RUNS

	Location			
Run No.	McCall	Bathurst	Shaw	Sunnyside
1	2	5	1	8
2	9	7	1	4
3	5	6	4	1
4	6	5	5	4
Total	22	23	11	17
Percent	30.1	31.5	15.1	23.4
2x	1	10	4	11

SUMMARY

A large FORTRAN simulation model of streetcar operations within a complex shared right-of-way operating environment has been described in this paper. The model is currently operational, but requires further validation and fine-tuning before it can be used to analyze alternative streetcar operating policies. In particular, an improved set of short-turn criteria that result in more realistic short-turn patterns must be developed, and the traffic delay components of the model must be validated in greater detail than has so far been done. Nevertheless, the results obtained to date are very encouraging. With further development, it is the authors' intention to test the other strategies that the model was constructed to address, including alternate short-turn strategies and the introduction of traffic signal priorities for transit vehicles, reserved rights-of-way, and larger capacity vehicles. With an analysis tool such as the Queen Streetcar model, these and other possible operating strategies can be examined and compared in a comprehensive manner, leading, it is hoped, to a better understanding of the trade-off involved in improving light rail transit performance.

ACKNOWLEDGMENTS

The model presented in this paper was developed as part of a study funded by the Toronto Transit Commission. The authors would like to thank the members of the study's Steering Committee, P. A. Wenning, B. J. Drew, A. R. Sharron, and E. von Zittwitz for their time and advice. Appreciation is also expressed to the Divisional Superintendents, J. Gordon and D. Carmichael, as well as the line inspectors and planning staff for their patience in explaining TTC procedures and practices. In addition, the authors thank the streetcar operators for their candid comments about their work environment when interviewed. Finally, the authors thank Efi Goldstein, Ian Carmichael, and Ed Brencis for their assistance in programming the model.

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Publication of this paper sponsored by Committee on Rail Transit Systems.

Stray Current Control Within DC-Powered Transit Systems

RAY E. SHAFFER

An overview is presented on the historical aspects of stray currents created by dc-powered transit system operations and their control. The relatively recent resurgence in the interest and the construction of dc-powered transit systems has emphasized the necessity for control of stray currents. This is particularly significant for new systems being built in areas where the utilities and other facilities were not designed with consideration for the need for stray current control measures. The theoretical aspects of the reasons for stray currents and the methods available for their control are presented along with practical applications within new and old systems as part of revitalization programs. The results obtained have shown that stray current control is practical. Although certain aspects of stray current control are common within all dc-powered transit systems, the variations within the transit systems and the areas they serve require that systems be treated individually to determine the level of stray current control required and the best means of achieving this level.

The concept of detrimental corrosive effects that can result from stray earth currents emanating from dc-powered transit facilities was recognized soon after the start of operations for this type of transit system in the late 19th and early 20th centuries. This corrosive effect on metallic structures created by the dc traction currents, often referred to as electrolysis, remains to this day and has received renewed emphasis within the last two decades with the building of new dc-powered transit systems and the rebuilding of parts of older systems.

In those areas in which new systems are being constructed, the effects of stray currents become particularly important because the utility facilities have not been built to facilitate the control of stray currents. The increased costs to the utilities to address the stray current effects could be appreciable, and a case for reimbursement by the transit system could be made if significant levels of stray current effects exist. In areas in which stray currents have been experienced in the past, rebuilding of the transit system facilities provides a means for reducing these effects and thus reducing the maintenance requirements for the utility companies and others that operate underground metallic facilities. In either case, responsibility for control of the magnitudes of stray currents to reasonable levels rests with the transit system; as with many similar situations, it is accepted practice that the utility operators, or others, should not be put in distress by transit system operations without there having been a reasonable and prudent effort made to control stray currents during the design, construction, and operation of new transit facilities.

The theoretical concept of the effects of the electrolytic interchange of dc current between a metallic structure and its environment is well understood for the more common metals of construction, such as those used for utility facilities and structures, including those owned and operated by the transit system. A dc current flowing from the electrolyte to the metallic structure will provide a protective effect to that structure; it tends to reduce the corrosion rate that existed before to the introduction of the current. (*Note*: All reference to current flow polarities is in the conventional sense as opposed to the electronic flow used in scientific research.) This protective effect is the basis for cathodic protection that can be used to control corrosion of metals immersed in an electrolyte by proper engineering and consideration of the many factors involved. Certain metals, for instance, lead and aluminum, are amphoteric and can be corroded by current flow from the electrolyte to the metal if the rates are excessive. Thus, in the area in which the stray current passes from the electrolyte to the metallic structure, the structure may receive beneficial effects, especially if it is steel, cast iron, or copper. At a location on the metallic structure where the current passes from the structure to the electrolyte, corrosion will occur. The rate of the corrosion depends on the metal. For instance, one ampere of dc current passing electrolytically from the metal to the electrolyte for 1 year will result in the dissolution of approximately 20 lb of iron, 75 lb of lead, 22 lb of copper, and 6.5 lb of aluminum. The effects of this corrosion process are quite apparent on many streetcar rails embedded in roadways where current discharge has recurred over the years, resulting in the corrosive destruction of the bottom rail flange, tie plates, and spikes. This corrosion process can be even more dramatic on pressured structures, such as pipelines.

Although the mechanism of electrolysis corrosion from stray currents has not changed from the start of dc-powered transit operations in the 1890s, other aspects of the problem have changed. The power requirements for transit operations have changed, with accelerating currents (for a typical 750 V system) for heavy rail trains reaching 10,000 to 15,000 amp; the light rail vehicles (LRV) having accelerating currents of around 1,000 amp compared with 400 amp for President's Conference Committee vehicles; and the new LRV's are quite often operated in consists of up to four vehicles. The concept of the traction power substation has changed for the better with the advent of solid state, automatic controlled units; stations can be placed more appropriately throughout the system as opposed to the use of the rotary converters at a centralized location covering large areas. The introduction of continuously welded rail has reduced the problem associated with negative return continuity that occurred because of broken rail bonds and rail joints every 40 ft.

PSG Corrosion Engineering, Inc., 110 Essex Ave., Narberth, Pa. 19072.

On the utility side, there has been a tremendous change from the days of essentially a cast iron, low pressure gas system to a steel, often higher pressure system that by federal law must have a corrosion control system, which generally means being cathodically protected. The presence of stray traction or other earth currents greatly increases the testing, maintenance, and number and type of facilities required for compliance. The construction of other utilities and civil structures have also changed in concept, resulting in structures that are much more prone to failure because of relatively low levels of corrosion. The older structures could, and of course still can, withstand higher levels of transit system stray currents without catastrophic results, the newer structures cannot, in many cases, tolerate the same levels. This general concept also applies to many of the transit system structures in addition to those operated by utility companies and others.

Before the relatively recent interest (late 1960s) within the United States in the construction of new dc-powered transit systems and rebuilding some portions of some of the old facilities, relatively few areas of the country had what could be considered significant stray current effects from dc-powered transit systems. These areas were limited to those within or near cities such as Boston, Chicago, Cleveland, New Orleans, New York, Philadelphia, and Pittsburgh. The stray current problems incurred by the utilities and others within these areas have been discussed by corrosion engineers through local coordinating committees and through technical societies such as the National Association of Corrosion Engineers (NACE). With this background information, the corrosion engineers for the utilities within the areas where new transit systems were contemplated became quite alarmed and, in many cases, formed groups to present a common front relative to the possible problem of stray current control. Transit system designers and operators were put on notice that the utility operators and others would not tolerate the stray current conditions that had occurred and still existed in the older systems in many of the cities. Their alarm and concern were justified by the experience from these older systems.

Review of the stray current problems associated with the old systems revealed the following general problems:

1. Traction power substations too widely spaced, or conversely, a single substation used to cover too large an area.
2. Common traction power ties between surface streetcar lines and high-speed subway or elevated lines, and in some cases, negative ties between high-speed lines.
3. Grounding points within the system, such as at yards, maintenance facilities, and traction power substations.
4. Use of elevated and portions of subway structures as part of the negative return system and connections between abandoned streetcar rails and the negative buses of substations.
5. Inability of the transit operators to maintain continuity on operating surface streetcar rails.
6. Direct embedment of the streetcar rails into the paving, providing low resistance, electrical contact with earth.
7. Changes made within the traction power distribution system, which affects stray current conditions causing different modes of stray current effects, resulting, in some cases, in the need for more than one stray current mitigation system.

With these problems in mind and considering that sufficient transit system resources are not normally available to correct these conditions as a separate project, it is absolutely necessary that appropriate action be taken during rebuilding work within the transit system to assure that stray current control matters are properly addressed. Otherwise, it may be another 40 or 50 years before the next realistic opportunity arises and, as noted, those adversely affected by stray currents are no longer taking a passive attitude toward acceptance of the burden of stray current control when corrective actions could have been taken as part of some other work within the transit system.

The basic reasons for stray earth currents from dc-powered transit systems are essentially the same today as they were at the beginning of the 20th century; however, changes have occurred. Figure 1 shows a simplistic schematic circuit that illustrates the basic factors within the traction power system that results in the creation of stray currents. It is the general rule, with some exceptions of course, that the positive distribution circuits are so well insulated from earth that they are not a significant portion of the stray current problem. With the insulating hardware currently available, this is probably more true today than it has been in the past. The positive portion of the traction power system generally contributes insignificant amounts of stray currents compared to the basic problem associated with the negative return system and is normally not a significant factor in stray current control.

In this simplified circuit (Figure 1), there is one substation feeding one load through a positive feeder conductor with a negative feeder conductor, which in most but not all cases is the running rails. Because a current (I_T) is required to operate the vehicle and the resistance of the negative return conductors cannot be zero, a voltage (E_N) will be developed within the negative return conductors, resulting from the product of I_N and R_N (I_N will equal I_T if I_S is zero). This voltage (E_N) will result in a stray current flow (I_S) depending on the values of R_L and R_S; the stray current flow being calculated from the relationship $I_S = E_N/(R_L + R_S)$. To put some of these factors into perspective, consider the following:

R_N—four rails of 115 lb/yd weight in parallel will provide a resistance of about 0.0022 ohms/1,000 ft of two track system;

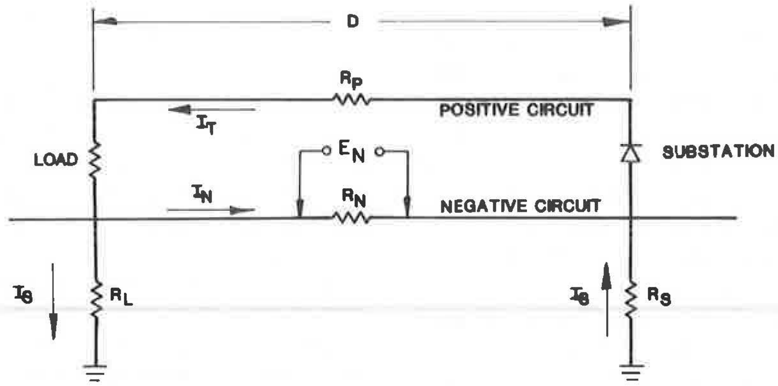
I_T—can vary, depending on system, from 1,000 to 13,000 (or more) amp;

d —will vary from 3,000 to as much as 15,000 ft on some systems.

Table 1 gives a summary of the values of E_N that will exist under the conditions described. The calculated voltages are based on perfect rail continuity.

TABLE 1 VOLTAGE DEVELOPED WITHIN THE NEGATIVE RETURN SYSTEM AS A FUNCTION OF DISTANCE AND LOAD CURRENT

		E_N – Volts, d (ft)				
		1,000	2,000	3,000	4,000	5,000
I_T (amp)	1,000	2.2	4.4	6.6	8.8	11.0
	3,000	6.6	13.2	19.8	26.4	33.0
	5,000	11.0	22.0	33.0	44.0	55.0
	8,000	17.6	35.2	52.8	70.4	88.0
	12,000	26.4	52.8	79.2	105.6	132.0



D DISTANCE BETWEEN SUBSTATION AND LOAD

R_N RESISTANCE THROUGH NEGATIVE CONDUCTORS (PRINCIPALLY RAILS)

R_P RESISTANCE THROUGH NEGATIVE CONDUCTORS (CONTACT RAILS OR OVERHEAD)

R_L NEGATIVE SYSTEM TO EARTH RESISTANCE AT LOAD END

R_S NEGATIVE SYSTEM TO EARTH RESISTANCE AT SUBSTATION END

I_T TRAIN OPERATING CURRENT

I_N CURRENT RETURNING THROUGH NEGATIVE CONDUCTORS

I_S CURRENT RETURNING THROUGH EARTH

FIGURE 1 Simplistic circuit illustrating the major components that affect the levels of stray currents generated by a dc-powered transit system.

The values of R_L and R_S (negative system to earth resistance) will govern the values of stray current (I_S) for the various values of E_N.

The values of R_L and R_S can vary over many orders of magnitude; some representative examples are as follows:

Type a: Newly constructed transit system with well-insulated track and insulating fasteners, 500 ohms/1,000 ft of track.

Type b: Timber tie and ballast construction (not insulated).
- *b1*: new, 4 ohms to several hundred ohms per 1,000 ft of track with an average in the range of 20 to 30 ohms/1,000 ft.
- *b2*: old, 0.3 to 30 ohms/1,000 ft of track (highly dependent on type of ballast, maintenance, and condition of ties).

Type c: Embedded, joint usage with automobile traffic.
- *c1*: in portland cement concrete, 0.1 to 0.2 ohms/1,000 ft of track
- *c2*: in asphaltic concrete, 1.0 to 3.0 ohms/1,000 ft of track
- *c3*: intentionally insulated, 50 to about 300 ohms/1,000 ft of track (limited data to date)

Type d: Connections to grounding systems.
- *d1*: maintenance facilities, 0.03 to 0.05 ohms.
- *d2*: diodes or solid connections at substations.
  - *d2a*: Power neutral connected, 0.03 to 0.05 ohms.
  - *d2b*: Power neutral not connected, 1.0 to 3.0 ohms.

These values should not be used as design parameters; however, they do represent a range of values the author has witnessed and can be used for preliminary estimating purposes.

Thus the possible combinations of R_L and R_S cover a very wide range. Using an illustrative value of I_T = 5,000 amp, d = 3,000 ft, E_N = 33.0 V (a relatively common occurrence within modern transit systems), the values of I_S can vary as indicated in the examples given in Table 2. This comparison illustrates the influence of negative system-to-earth resistance on the magnitudes of stray earth currents, all other factors being equal.

TABLE 2 STRAY EARTH CURRENT VARIATIONS AS A FUNCTION OF NEGATIVE SYSTEM-TO-EARTH RESISTANCE

	I_S (amp)	Percentage of Load Current
Type a throughout	0.050	0.001
Type a and b1	0.095	0.002
Type a and d2a	0.198	0.004
Type b1 throughout (at 20 ohms)	1.24	0.025
Type b1 and d1	4.95	0.10
Type c2 throughout (at 2.0 ohms)	12.4	0.25
Type c1 throughout (at 0.2 ohms)	124.0	2.5
Type c1 and d2a	309.0	6.2

The range of possible variations is, of course, quite dramatic, and of particular significance is that the maximum current represents only 6.2 percent of the load current. However, even though the percentage appears relatively small, the propensity for electrolysis damage is great because of the actual magnitudes of currents involved. As a point of comparison, some old type streetcar systems have stray current characteristics with upwards of 50 percent of the traction power station outputs returning directly through stray current mitigation bonds and recorded situations whereby operating currents for vehicles at some locations within the system become all stray current. It must be remembered that these situations were generally associated with lower operating currents than present day systems.

To further illustrate the concept of stray current accumulation and therefore the effects on utility or other structures, consider the basic condition shown in Figure 2, which illustrates the condition shown in Figure 1, except that the stray earth current pattern and therefore the creation of voltage gradients within the earth path are illustrated. Shown in Figure 2 are several factors to be emphasized:

1. The voltage (or earth) gradient will be a function of the soil resistivity, the length over which the gradient is measured, and the magnitude of the current. As a general rule, the only control is on the magnitude of current. However, if the stray current problem exists or is anticipated, some control of the electrical length of a metallic structure can be exercised by the use of insulating joints or other means. For existing structures, the cost of installing insulating joints can be very high. There is no practical means of controlling the resistivity of a large volume earth environment.

2. The maximum earth gradients per unit length are going to occur where the current levels are most concentrated; that is, in the vicinity of the track or other location of traction power interchanging with earth. For the simplistic example in Figure 2, this would occur at E_{E2} and E_{E3}. Thus the most severe effects are most likely to occur near the operating transit system. This results in the need for special consideration for the metallic structures in the immediate vicinity of the track or other low resistance ground points, or both (substation ground, yard/maintenance facility, etc.). As a general rule, if the earth gradients within the vicinity of the transit system are held to reasonable levels, the remote effects (Item 3) will also be reasonable.

3. Earth gradients will also exist at remote locations, such as E_{E1}, especially if the length (Item 1) is great. Thus an electrically continuous pipeline remote from the track but covering a long distance, such as between the load and the substation, may also be significantly affected. The major controllable factor in this case is also the level of stray currents.

The level of earth gradients, and therefore an estimate of stray current magnitudes, can be obtained on an operating system by studying the earth gradient patterns as illustrated by E_{90} to E_{270} at various locations. These gradients can be related to transit system operations by direct correlation or by studying of general patterns and characteristics over several days.

Experience shows that, in general, the most severe effects from stray currents will occur near the transit system. However, experience also shows that where conditions of high-level stray currents or transit systems, or both, exist over wide areas with continuous negative and positive buses, the remote effects of

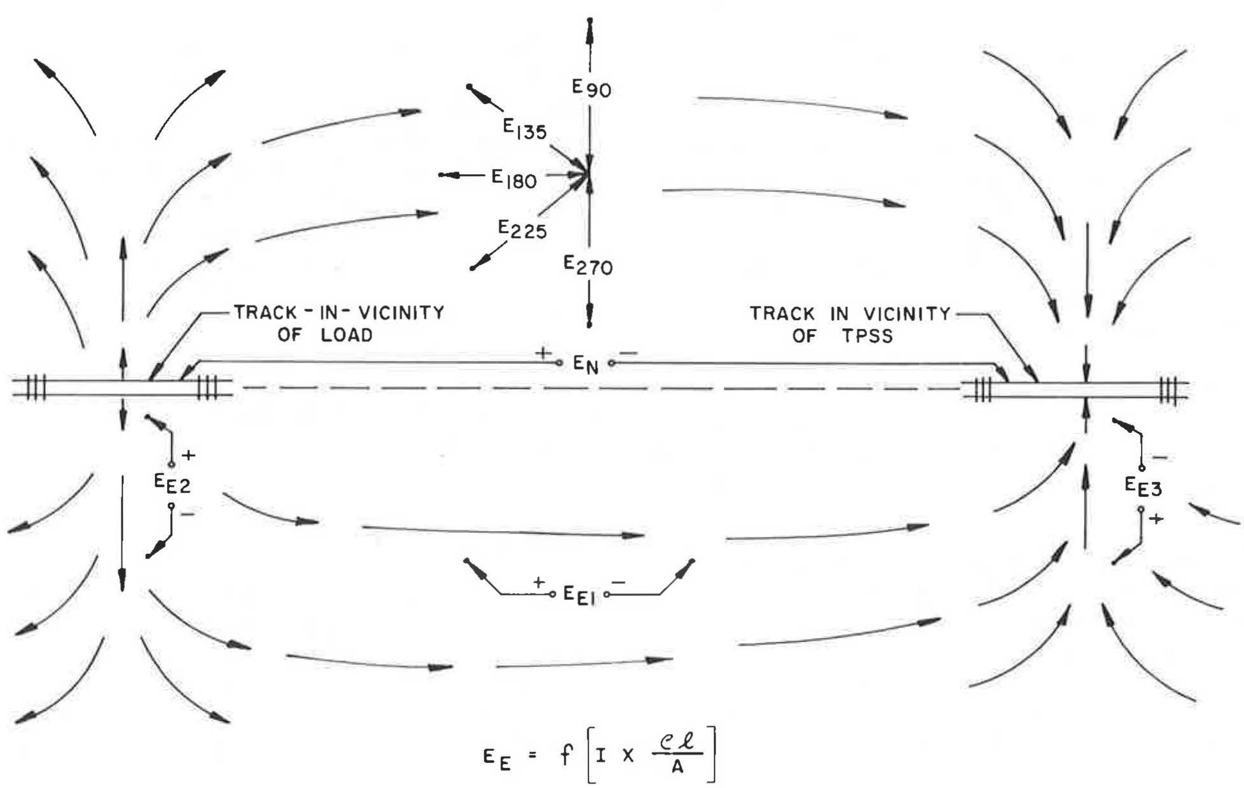


FIGURE 2 Earth gradients created by stray currents from dc-powered transit systems.

stray currents can also be significant. It is not unusual to observe these effects on long, cross-country transmission systems 20 to 30 mi from the transit system. It must also be noted that these effects are often attributable to other structures that may pass close to the transit system and, in some cases, may operate a stray current drainage facility to the transit system. However, the lower the levels of stray earth currents, the smaller will be the effects on other structures. An analysis of the various components shown in Figure 1 and their influence on the magnitudes of stray earth currents is reviewed relative to actions that can be taken to reduce these magnitudes.

1. Increase the system operating voltage. This would allow for a reduction in operating current to provide the same power to the vehicle. The practicality of this is being continuously evaluated; to date, however, the maximum voltage used in this country on heavy or light rail has been 1,000 V, with the majority of the newer systems using 750 V and many of the older systems using 600 V. (This action will not be effective if the substation spacing is correspondingly increased along with the system voltage.)
2. Decrease the distance between substations and thereby decrease the value of R_N. A dramatic change has occurred in this aspect of stray current control, because the use of self-contained solid state rectifier units with remote/automatic control provides an economic means for the use of more substations at closer distances. Nevertheless, there are practical limits to this method of improving stray current conditions.
3. Reduce the resistance within the negative return conductors. This has been accomplished in recent transit system construction by the use of heavier, continuously welded rails. However, analysis of most systems indicates that further reduction in the resistance of the negative return conductors by using parallel negative feeder cables is not justified economically because of the small incremental improvement for the expenditure required. Further significant improvements are unlikely in the future.
4. Restrict the distance in which a particular substation or group of substations can participate in load sharing within the system. This requires the introduction of power segregation points on both the positive and negative at select points throughout the system. This procedure will reduce stray current conditions, especially during light load periods. It will also restrict the energy-saving factors associated with regeneration during light load periods and must be closely studied for the particular system relative to operational constraints.
5. Increase the resistance-to-earth of the negative return conductors. The single most important factor in this respect is the increase in resistance-to-earth of the running rails and appurtenances and elimination of intentional ground connections.

Work on Item 5 to improve the negative system-to-earth resistance is the area within which improvements in stray current control will provide the most benefits in the near future. The ultimate approach to electrical isolation of the negative from earth has been used with excellent results on some types of systems where a separate insulated conductor is used for the negative (similar to construction of the positive), such as those used for trolley coaches with dual trolley wires, linear induction motor-powered-systems, and rubber-tired subways with dual contact rails. The practicality of this approach on more conventional heavy and light rail systems should not be overlooked in the analysis for future projects.

The simplistic schematic in Figure 1 does not represent an actual modeling of a transit system for stray current analysis purposes. The actual model will have numerous substations, generally all feeding common positive and negative buses, and the track-to-earth and negative conductor (track) resistances will form a distributed network similar to that shown in Figure 3 for a portion of a transit system. Also shown in Figure 3 are the track-to-earth voltage and the stray current level per unit length profiles that would occur for the situation shown, assuming uniform resistances for R_E and R_T. Using this distributed network approach, an analysis is conducted early in the system design studies, shortly after the basic traction power configuration has been decided, to determine the stray current levels that can be expected with the design factors proposed. Generally, this will include information on system operating voltage, power/current characteristics for the vehicle(s), locations of passenger stations and other points of heavy loading, and the configuration of the yard/maintenance facility. Also, at this point, the track configuration will have been established relative to type of track construction, such as areas of direct fixation fasteners, tie and ballast, grade crossings, and embedded construction along streets.

A schematic representation of the system is then prepared that will be used to analyze the stray current levels and characteristics that can be expected under various conditions such as load locations, selected substations out of service, low-resistance grounding connections at the shop or other areas, and by varying the track-to-earth resistance.

The information generated from this analysis is then used to determine the levels of stray currents that will result from various levels of track-to-earth resistances within the areas of different track construction. This information, along with information on the types of transit structures to be used, the density and type of utility structures within the area of influence of the stray currents, and the soil resistivity characteristics, provides a basis for decisions on the levels of stray currents that will be tolerable. Thus, this information allows the determination of the level of electrical isolation required for the negative conductor system and the corrosion control measures required for the fixed facilities. Variation of other factors, such as relocating or installing an additional substation, can occasionally be justified based on the results of the analysis. The significance of the track-to-earth resistance in controlling stray earth currents cannot be overemphasized. Some experience on new transit system construction has indicated the following generalized results.

DIRECT FIXATION

The proprietary and assembled fasteners on the market and in use at present will provide track-to-earth resistances in the range of 500 ohms/1,000 ft of track under relatively dry and clean conditions. This resistance quickly degrades when moisture or dirt films are allowed to develop on the exposed surfaces of the insulating materials. This is particularly prevalent in subways where the passage of each train creates a mist from any water that has accumulated. Generally, this moisture is also

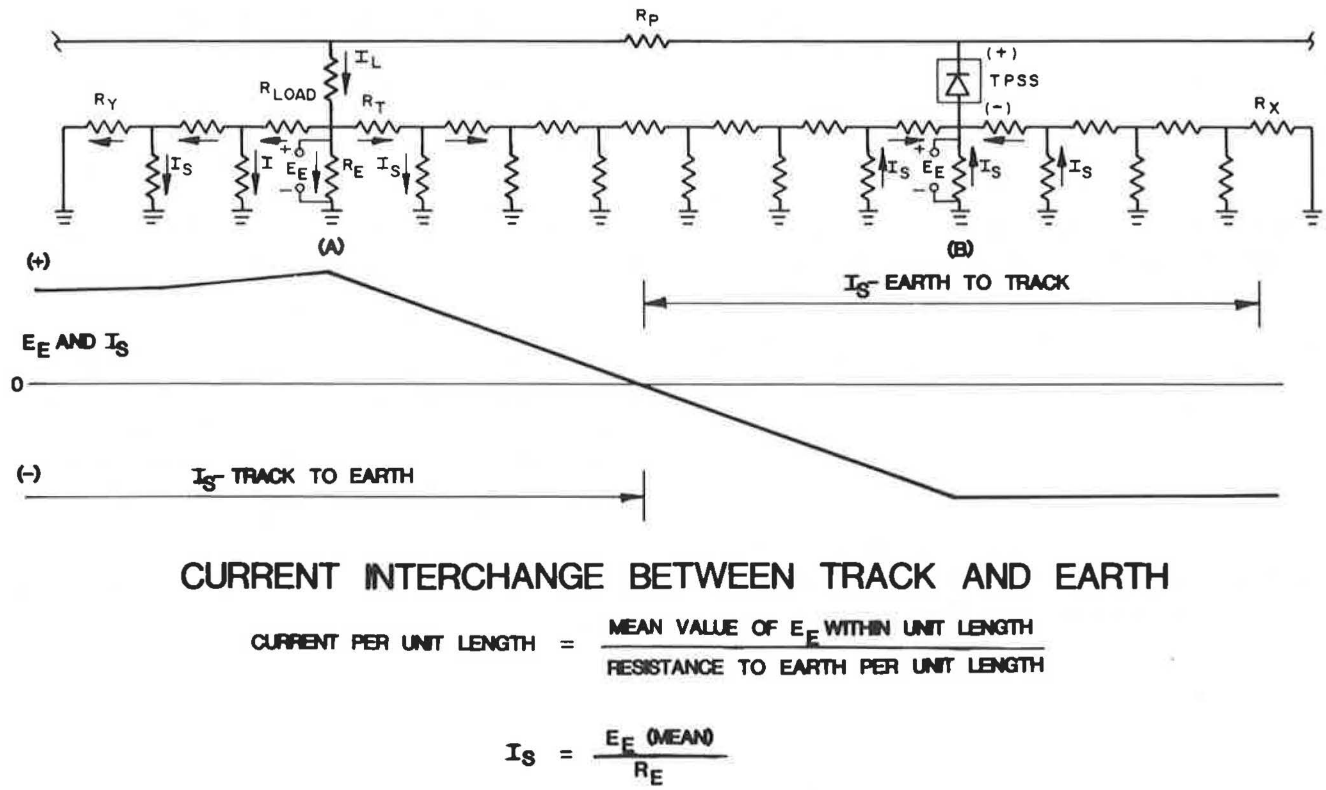


FIGURE 3 Distributed network schematic representation of transit system for stray current analysis.

very low in resistivity. This aspect of the electrical effectiveness of direct fixation fasteners must be reviewed carefully during design to ensure that proper characteristics are obtained, depending, of course, on the in-service track-to-earth resistance levels required.

TIE AND BALLAST CONSTRUCTION

Timber tie and ballast construction has shown variable results, depending on the amount of rainfall that occurs and the weather conditions before and during testing. Experience has shown such large swings in effective track-to-earth resistances and therefore stray current magnitudes that this type of construction cannot be relied on to perform at required levels, if this level is above about 10 ohms/1,000 ft of track. The only exception to this would be in areas of extremely low rainfall where the increase in stray currents may be acceptable during short periods of rainfall. Experience has also shown that ballast cleanliness and tie conditions are extremely important. The use of insulated fasteners on timber ties has not gained widespread use to date. However, one transit system under construction will be using insulated fasteners and other existing systems are considering their use. Theoretically their use should be entirely acceptable.

This author's experience on concrete tie track-to-earth resistance has been limited to the Pandrol system using the embedded shoulder, steel clip, insulating tie pad, and clip insulator. The resistance-to-earth characteristics of this system run approximately on 500 ohms/1,000 ft of track or greater under relatively dry conditions, decreasing to the 300 ohms during rain, which is excellent performance. It must be emphasized that these values are based on limited data; to date it has not been practical to obtain long-term, in-service data on specific track sections. However, experience does indicate that concrete ties with insulated fasteners can perform very well relative to requirements for track-to-earth isolation for stray current control. Review of other types of insulated fasteners for concrete ties indicates that they should perform well in this service; however, the author has no personal experience and has found no reference to such fasteners in the published literature.

EMBEDDED TRACKWORK/GRADE CROSSINGS

Achieving electrical isolation of embedded trackwork is presently the most experimental of the three major classes of trackwork construction. However, it is also quite likely the most critical for stray current corrosive effects on utility structures because of their proximity within embedded areas. There are four types of electrical isolation of embedded track:

- The rails are placed in troughs formed in poured concrete, and an insulating compound is used to electrically separate the rail from the concrete. Only limited in-service data are available within the United States; however, an arrangement of this type used in Calgary reportedly has been successful.
- Rails with timber ties are placed on well-drained ballast, with the entire track structure encapsulated in asphaltic concrete. This method has been effective when used in dry areas with utility relocation or replacement, or both, with nonmetallic materials within the transitway.
- An insulating membrane is placed on the bottom and along the sides of the concrete track slab forms before pouring

of the slab, thus encircling the slab on the bottom and sides. In-service data are not available, although several variations of this type are being built.

- Rails are installed on a continuous insulating pad on top of a concrete track slab; the top of the bottom rail flange and the top of the concrete are coated with a high-resistivity insulating coating. The entire track is then embedded in asphaltic concrete. This method was reported to have been effective in controlling stray currents immediately after the start of revenue service, although no follow-up information has been obtained.

The variations associated with electrical isolation of the embedded trackwork results from the many variations that exist in this type of track construction.

SUMMARY

Research and product development programs for the field of stray current control within the transit industry should concentrate on the following basic considerations:

1. Use of an electrically isolated negative feeder system with resistance-to-earth characteristics similar to that commonly achieved for the positive distribution circuit.
2. Methods for reducing the surface leakage effect common to direct fixation rail fasteners.
3. Methods for achieving effective, long-term electrical isolation for embedded trackwork and road crossings.
4. A practical, cost effective method for insulating rails from timber ties, including special trackwork.

The stray current control measures that have been or are being included in transit system construction have been effective. As with most relatively new concepts of this type, they have not been perfect. It is the responsibility of the transit system operators to keep others within the industry informed of the in-service results obtained on the measures used if the industry is to learn the best methods of stray current control to be employed in future construction projects.

Publication of this paper sponsored by the Task Force on Rail Transit Design.

The Direct Fixation Fastener—Its Past and Its Future in Rapid Transit

ROBERT F. GILDENSTON

When compared to most other trackwork components, direct fixation fasteners are relatively new products in transit applications at North American transit authorities. In the past, some difficulties have been experienced by procuring operators as well as fastener suppliers in specification compliance and effective part design. With the introduction of newer, more technically advanced direct fixation fasteners at various authorities, a reevaluation of the older style of specifications and testing procedures is necessary to avoid past difficulties and provide a more effective qualified product to the authorities. Past procurement practices and proceedings in general are reviewed with suggestions for possible improvements to balance trackwork and the vibrational requirements in specifications for direct fixation fasteners.

Within rail transit there has been constant and continuing misuse of the phrase direct fixation fasteners (DFFs). On some occasions it has come to mean everything from flexible clips, clip and shoulder assemblies, to clips on thick rubber and steel assemblies. Rather than attempting to correct any inherent misuse of the term by manufacturers, consultants, and authorities, it is simpler to identify what most trackwork personnel have come to understand as a direct fixation fastener.

The direct fixation fastener is a system composed of clips with a thick elastomer and steel body unit that holds the rail to tie or concrete slab, provides electrical isolation, and has an additional function of providing major vibration, shock, and noise reduction to the track-car system as a whole. It was conceived and designed for use in a rapid transit system for these purposes. It is this type of multifunctional direct fixation fastener system that is discussed in this paper (Figure 1).

The major point of the DFF that sets it apart from the standard steel tie plate is that one of its primary functions is maximum vibration, shock, and noise control for the entire track-train system. This is accomplished through the use of elastomeric elements acting as a spring-mass system between the rail flange and the support base. Studies have shown that fasteners with stiffnesses in the range of 50,000 to 120,000 lb/in. are required to reduce vibration in the critical frequency ranges of 10 to 100 Hz.

In discussing direct fixation fasteners, a second major point must be considered: the fastener system must function as an integral part of the total trackwork system. Vibration and trackwork requirements can be made compatible in order to provide the best advantages to both areas. There is no conflict between the vibration and the trackwork requirements for DFFs if the specifications allow the fastener designer to use existing proven design concepts.

Lord Corporation, Erie, Pa.

In the past, difficulties in fastener procurement have usually been caused by a lack of understanding of the intent of various specific tests within the specifications, which created inherent conflicts between vibration and the trackwork concepts. Although realistically it is impossible to write a perfect specification, especially for what has now become a multifunctional part, far fewer problems will be encountered when basic fastener concept requirements are better understood. To better understand fastener concept requirements, how they are viewed by transit authorities must first be determined.

The usual authority requirements for DFFs include

1. Low life-cycle cost and reduced fastener maintenance.
2. Improved passenger and wayside comfort.
3. Maintenance of a high fastener reliability level for maximum operational state of the total system.
4. Maximum electrical isolation for maintaining signal strength and reducing stray current.
5. Reduced maintenance of other trackwork components and train subsystems.

Although these requirements are general and would be satisfactory to any authority, their implementation into a procurement document requires a series of steps.

The first and one of the most vital steps is in the procurement of the DFFs. The three types of procurement processes have been described by Hanna (*1*) and of these the two-step process is the most effective in obtaining a low life-cycle cost fastener. It has been the one-step or low-bid type of procurement that in the past has resulted in poor quality fasteners and design submissions and subsequent procurements not intended by the specification writer.

In contrast, the reviews and prequalification within a two-step process, however, provide ample framework for eliminating suppliers that do not meet or conform to the criteria and intent of the specifications. The only further improvement that should be made in the two-step process is that all suppliers should be required to test at a single independent laboratory. This will eliminate the wide-ranging results now being received from different laboratories using different test equipment and methodology. As it now stands, it is impossible to directly compare results received from direct fixation fasteners tested at different laboratories to make any valid sole source prequalified procurement. In summary, true low life-cycle costs can only be achieved when sufficient time is allowed for all the necessary procurement steps, specifications written for a specific type of fastener, and valid laboratory comparative testing available in a two-step procurement process.

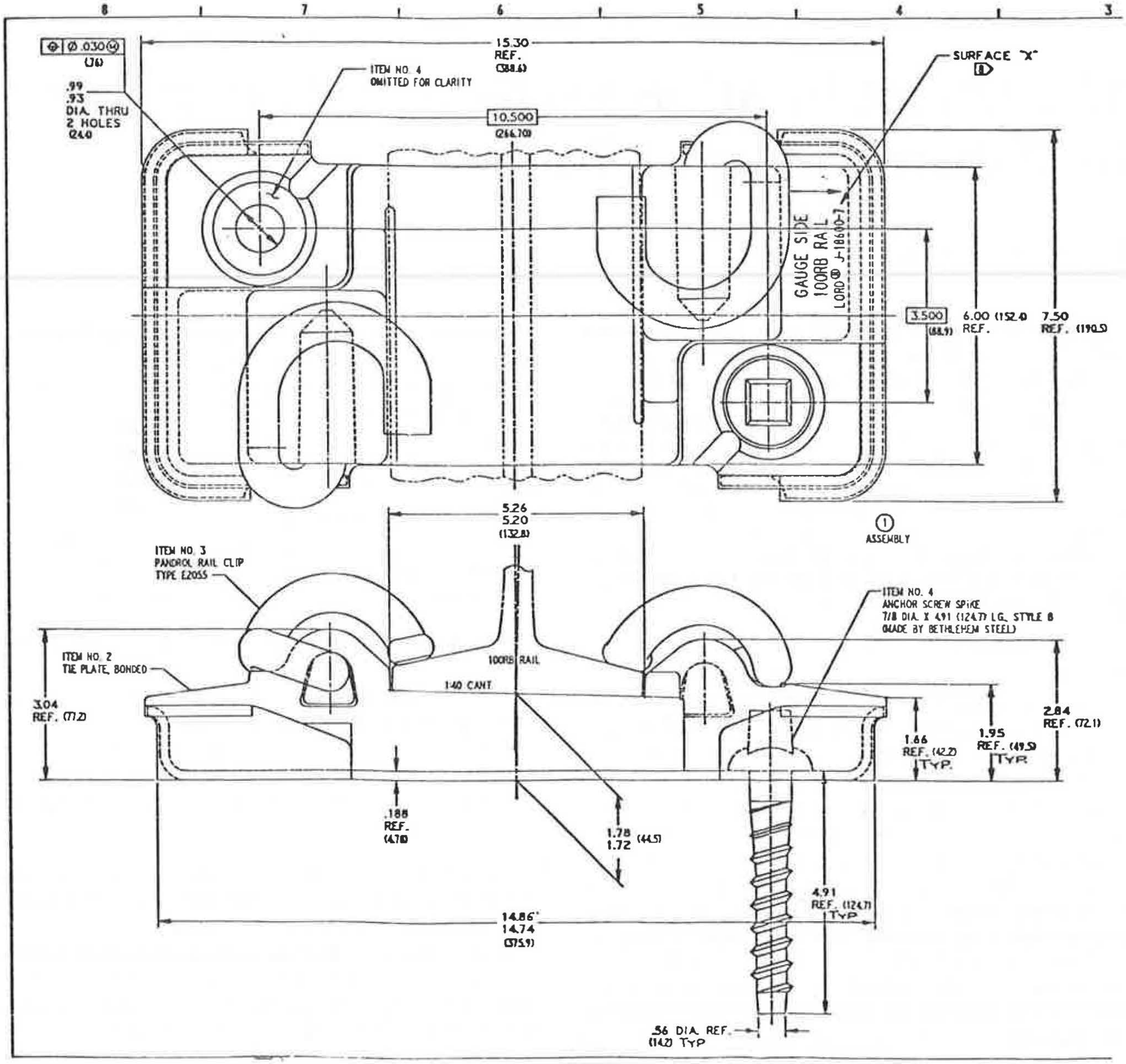


FIGURE 1 Typical direct fixation fastener.

Underlying all of the procedural efforts in fastener procurement is the fact that any DFF system installed will have to be inspected and maintained over its estimated life of 30 to 50 years. A number of authorities have direct fixation fasteners that will now require excessive hours of maintenance in order to conform to normal accepted trackwork standards. Although the reasons are varied, they can in most cases be traced to the procurement document itself. Any low first cost for DFFs will be overshadowed by constant and significant maintenance expenditures.

In this time of withdrawal of federal support for operating expenses, it is obvious that a low first cost for a fastener that has a high life-cycle cost will have a severe financial effect on an authority in the future. It should be noted that within the formation of any new authority, possible input from the maintenance group on design features may be limited because of lack of personnel at the time of the DFF procurement. In this case the responsibility must rest with the consultant and other authority groups to anticipate inherent maintenance requirements and subsequent maintenance costs within any submitted design.

Although a low first cost does not necessarily indicate a high life-cycle cost, it must be recognized that once a bid is opened, within the review of the low bid submission, the proposed DFF must have a significant design defect to be rejected. Because the value of a significant design defect is subjective, and the possibility of design correction is also open to subjective evaluation, the reviewer can be subject to both professional and legal difficulties with a negative decision on the submission of the low bidder. Recognizing these complications, some DFF suppliers will submit a low-cost design below specification, knowing that an initial rejection usually does not occur, and by delaying the furnishing of fasteners, exceptions and deviations to the technical specifications must be granted to ensure the system is built on schedule. The solution to this problem again goes back to the two-step procurement system.

The improvement of passenger and wayside-occupant comfort by reducing the effects of vibration and noise, at first glance, appears to be a minor point and something that must be tolerated by an authority. Nothing is further from the truth. Attendance at a community interface group meeting when a new system is being proposed will provide insight into the real concerns—noise and vibration. On a new system, substantially more time, money, and effort are expended trying to overcome the impression that all rapid transit systems are noisy than are actually extended on direct fixation fasteners. Given the inputs constantly received by actual ridership, movies, and TV as to what the old transit systems sound like, it is understandable why everyone wants a transit system as long as it does not run next to their house (Figure 2). On existing systems, any expansion of the present system into new areas is faced with the same problem of community acceptance as any new system. The wayside occupant and onboard passenger on older systems show a significant decrease in their tolerance and acceptance of noise and vibration. The direct fixation fastener's ability to retrofit older existing trackwork systems is now being used by some authorities.

It must be noted that the DFF system affects the noise and vibration levels experienced not only by the wayside occupant but also the onboard passenger and thereby serves a dual function. This is a critical point especially where any system is confined at grade by buildings or is below grade in tunnels where the wayside occupant and the onboard passenger are subjected to radiated and reradiated noise. Again, one of the major reasons for direct fixation fasteners is vibration and noise reduction working within all of the various aspects of the trackwork system.

In maintaining high levels of system operations and availability, there are many short- and long-term considerations. In the short term, the specifications must provide that the fastener quality and design integrity are sufficient to meet system needs without premature replacement. Given that all authorities have only a limited window of availability for track repair, any substantial change-out requirement because of fastener problems can become not only costly but a logistical nightmare for an authority once the system becomes operational. It is not reasonable to expect the DFF supplier to guarantee the fasteners for extended periods of time without total knowledge of maximum trackwork load system factors. It is reasonable to expect guarantees from manufacturers as to the workmanship and quality of production manufacturing even if the specification also requires production testing. It is actually the consultant and the authority working through proper specification and testing that will ensure that the fastener system maintain ongoing operational levels and track availability.

In the long term it is generally recognized that slab track in combination with DFFs is a low life-cycle arrangement. Some of this revolves around the point that the DFF in most recent configurations requires little or no maintenance. Compared to ballasted track, which will require ongoing maintenance with work crews and specialized equipment, two DFFs can be changed out by one man with a torque wrench and jack in a matter of a few minutes. When the long-term factor of ballast cleaning or significant quantities of tie replacements are considered, the operational service levels of the future system operation could be interrupted in a significant way.

When the electrical requirements placed on direct fixation fasteners are examined, are the multifunctional aspects to which it must perform understood? Although not all systems use track for signal circuits, the problem of stray current control appears to be more prevalent. Because authorities differ on their requirements, tests and testing criteria vary greatly. Recently, authorities have been viewing electrical surface tracking and air gap between charged and ground potential portions of the fastener with greater interest. The present difficulty occurs because within the specified dc and ac testings, no uniform method has been formulated that can be performed in a laboratory to duplicate contaminant build-up on the DFF. Wheel and

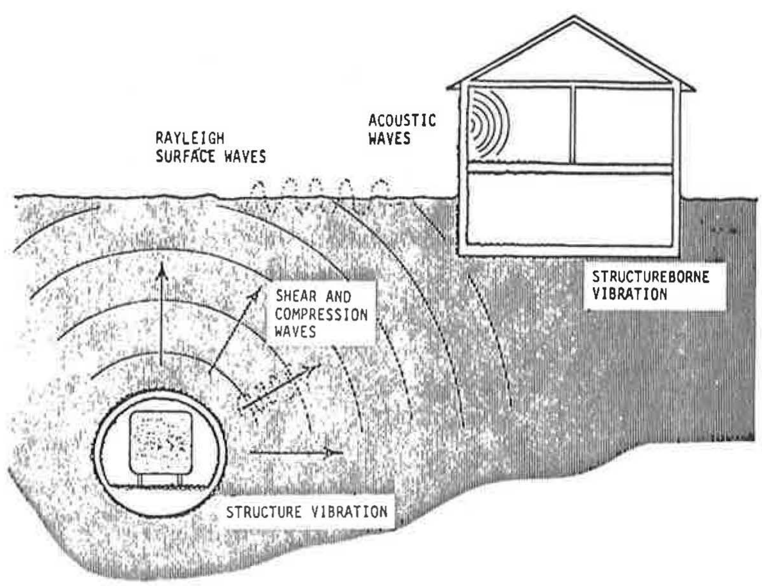


FIGURE 2 Example of vibration propagation.

rail metallic particles and other environmental contaminants on the fasteners can cause significant signal loss and stray current and, without some uniform testing method, subjective evaluation of the fastener design must continue to be relied on. It should be noted that bonded fastener designs are far less prone to tracking because of significantly longer surface paths and elimination of particle trapping design voids.

One of the benefits of soft direct fixation fasteners that has been totally overlooked is the possibility of reduced track and train design costs. The fastener system inherently changes the train-track system by providing a compliant support system that reduces shock and vibration inputs to the car, its equipment, and passengers. To date this author is not aware of any change to equipment specifications that recognizes this reduction in shock and vibration input and the subsequent possible cost reductions as a result of changes in car equipment design. Also, looking below the fastener base, this author is also unaware of any design reduction in track support systems that might be caused by reduced shock loading or lower vibrational levels going to any of the various types of structures involved. A review of track-train dynamics as they apply to direct fixation fastener track could possibly bring significant cost reductions to track and train design.

The design decision requirements and procedural processes necessary for effective DFF procurement have been discussed in broad terms. Underlying and supporting this process is the basic specification and testing document, which will ultimately determine the design of the fastener, its operating characteristics from both the trackwork and vibrational standpoints, maintenance requirements, life expectancy, and cost. When the basic requirements of a standard steel tie plate in trackwork is compared with the multifunctional requirements of a DFF in rapid transit trackwork, it is easy to understand why two-step procurement with a good specification foundation is an absolute necessity.

Although direct fixation fasteners have been in use for some time, basically only one general specification has been used by most authorities (Figure 3). With the exception of the vertical load test and the dynamic-to-static test requirements, the major point of fastener vibration requirements went unrecognized within the specification, which dealt almost exclusively with the trackwork requirements for fasteners.

As with any new product used in trackwork that must be proven safe and effective, it was understandable that this would be of greatest concern during the early period. There has never been any reported accident or derailment attributed to DFFs; therefore, it can be assumed that the trackwork requirements of the specifications for safety have performed well. However, this does not preclude the possibility of DFF failure in the future because of poor basic design. It should also be understood that bonded fastener designs are not totally dependent on their metallic components to maintain trackwork integrity but have an additional safety feature of the elastomeric bonding. As observed at one authority, failed metallic components of fasteners did not result in catastrophic gauge widening because of the restraint provided by the fastener bonding feature.

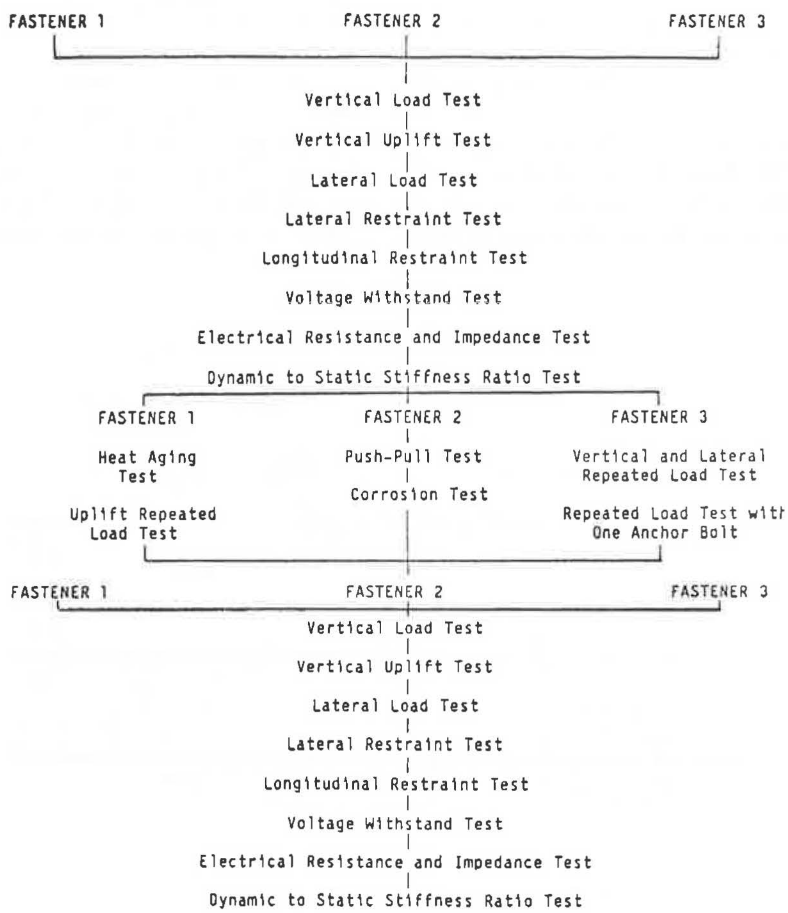


FIGURE 3 Fastener test sequence.

With the addition of new authorities in the United States and Canada and the use of this same basic specification as a core document, difficulties arose. Test loadings kept increasing to ensure that successive procurements would result in a stronger and better fastener. Unique design features desired by authorities were placed into specifications with little regard for other testing requirements and overall design impact. The original reasons for the individual tests and the test acceptance criteria results became vague and subject to arbitrary decisions that varied with each authority. The vibrational design portion of the specification and any testing requirements continued to remain low, and there was no recognition of possible new improved designs increasing vibration control and reducing noise, nor could they be proposed or tested under the existing specifications.

Finding the direct fixation fastener industry in a position of having to reassess procurement methods and specifications, a return to wood ties in ballast with cut spikes might be tempting. Thankfully, certain authorities such as the Washington Metropolitan Area Transit Authority (WMATA) have required a new specification core document that begins to recognize a better balance between trackwork and vibrational requirements for direct fixation fasteners. The foundation for this new specification is based on tests performed by the U.S. Department of Transportation Transportation Systems Center (TSC) in actual trackwork at WMATA (Figure 4). This test basically showed that while improving the vibrational characteristics of DFFs by further softening them both vertically and laterally above what was called for in prior specifications, trackwork characteristics were also improved without excessive gauge widening. The previously perceived track loadings, based on data from stiffer DFFs that were perceived to be valid and then subsequently required in the old test specifications, were not valid. Instead, with soft vertical and lateral fasteners, actual loading on the individual fasteners is greatly reduced. This forms the basis for a new core specification and brings into balance the vibrational and the trackwork requirements (Figures 5 and 6). In addition, the new specification still retains many of the basic prior trackwork testing requirements in order to continue to ensure integrity and safety in trackwork.

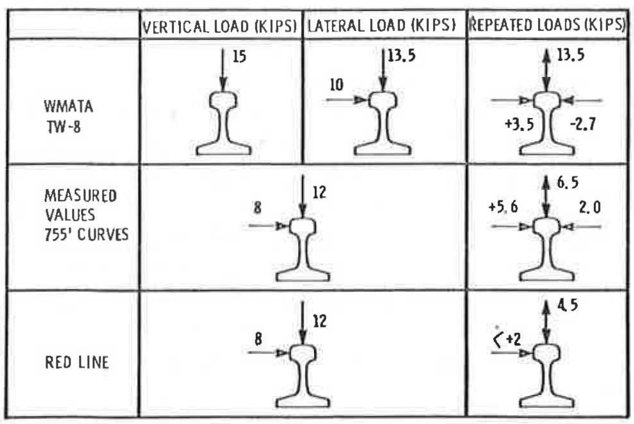


FIGURE 4 Comparison of WMATA fastener acceptance specifications and measured values.

Although some would argue that this new type of specification and the data values are site- and authority-specific, it is the concept that is universal and the specific data values that are site-specific. The difficulty of obtaining data values at operational authorities is minimal when compared with improved performance benefits and lowered life-cycle costs to the system. For those authorities still in planning and preconstruction stages, it would be valid to draw data from an operational system with similar car and track configurations for specification data values. To continue with the old specification, which is formed on an incorrect data base, is costly and results in far less than optimum total system performance.

As stated previously, the new specification for soft vertical and lateral fasteners still retains many of the previous tests required for trackwork integrity. It must be noted that these tests also must be reviewed for their overall compatibility with soft vertical and lateral direct fixation fasteners within the specification. In the old testing specifications, some tests such as the lateral load or lateral restraint test, or both, were performed to ensure that excessive gauge widening did not occur during operation. Although the testing intent from the trackwork standpoint was valid, it resulted in manufacturers' stiffening the fastener designs laterally. This stiffening, in almost all cases, also resulted in a design with a vibrational short circuit laterally in the anchorage area, causing subsequent loss of maximum vibration isolation, which was contrarily the basic reason for the DFF application.

		SPRING RATE AND DEFLECTION TEST		REPEATED LOAD TEST			TOTAL RESPONSE LOAD
	CASE	1	2	3	4	5	
VERTICAL CURVE V	A	-870	-520	-1044	-1298	-862	LBS
	B	+20	+12	+24	+30	+20	KIPS
	C	+13	+7.8	+15.6	+19.5	+13.1	KIPS
LATERAL CURVE L	D	-340	-510	-408	-850	-850	LBS
	E	+8	+12	+9.6	+20	+20	KIPS
	F	+3.1	+4.7	+3.7	+7.8	+7.8	KIPS
NO. OF CYCLES OF EACH CASE PER 100 CYCLES OF REPEATED LOAD TEST.				98	1	1	

FIGURE 5 Test load values.

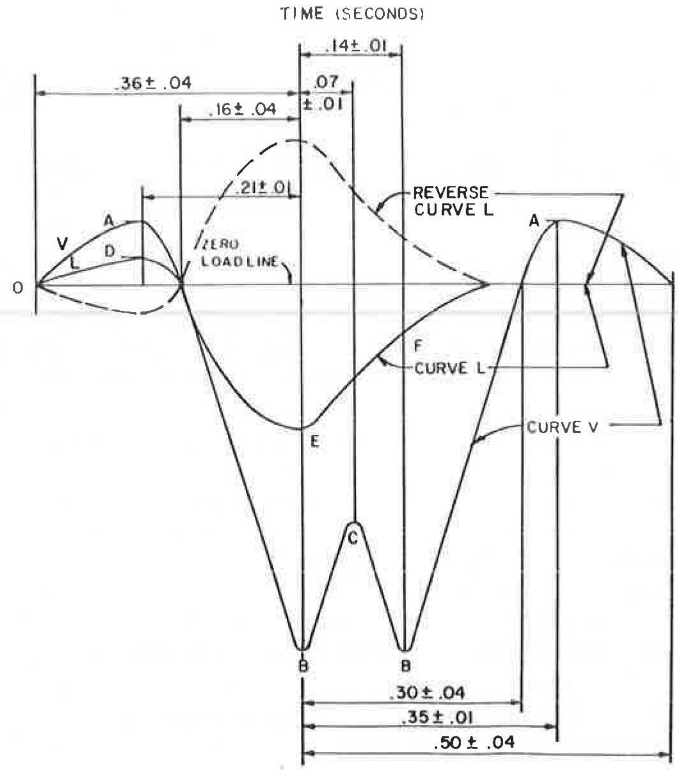


FIGURE 6 Test load sequence.

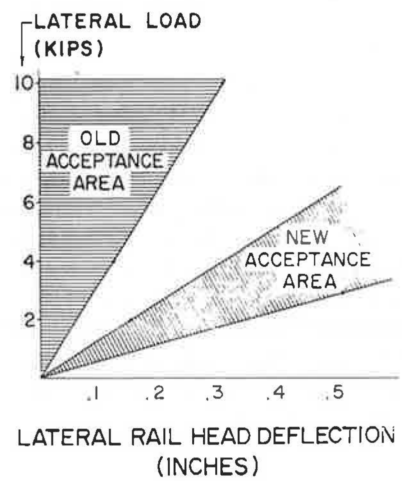


FIGURE 7 New versus old lateral static load acceptance criteria.

On review of the TSC/WMATA in-track testing of soft lateral fasteners with greater load distribution over greater numbers of fasteners, rail head motion and gauge, when loaded to the values that occur with this type of DFF application, remains within acceptable trackwork standards. Relating this to specifications, old data high load tests taken from stiffer fastener measurements with limiting motion acceptance criteria are not needed; what is needed are controlled maximum lateral stiffness requirements taken from in-track soft fasteners to allow greater load distribution patterns within the trackwork system (Figure 7). With this type of system, the necessary trackwork integrity is maintained while the vibrational reduction achieved from the DFFs is greatly improved.

It is also necessary to point out that the soft vertical and lateral fasteners in almost all cases require a somewhat larger space envelope for elastomeric materials in order to provide the necessary fatigue properties. Design of direct fixation fasteners is complex with many interdependent criteria that are partly predetermined by the technical and testing portions of the specifications. There is no problem in obtaining comparable fatigue life for soft versus stiff direct fixation fasteners if the specifications allow the necessary parameters.

A general review must be conducted of all of the static tests when moving to the new testing specification required of the soft vertical and lateral DFFs. It is reasonable that any authority or its designated consultant can work with the suppliers as a whole to accomplish such specification reviews. Although this has been done in the past, it normally occurred after the specifications were prepared. What is specifically needed now is this total interface among the parties before preparation of the specification document.

One level below the specification and tests required are the test laboratory and equipment. There exists an anomaly within all fastener test equipment in that few, if any, laboratories can duplicate actual in-track conditions and loadings. The size of test equipment and associated massive costs to set up and duplicate exact track operation and loads would be exorbitant in relationship to the information derived for fastener procurement. Also, it would probably stop all improvements to existing designs and end all new design efforts at the manufacturers because of the excessive cost. It would appear that a group of four fasteners is the maximum practical testing limit capability, recognizing that this only approximates in-track rail load distribution conditions to the fasteners (Figure 8). It then

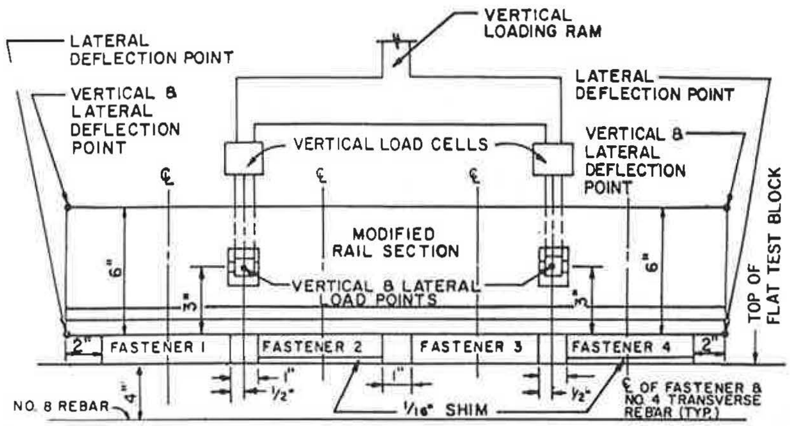


FIGURE 8 Machine setup for fastener test.

follows that data received from certain tests will only give approximate values for evaluation and should be recognized as such. Far too often, specification test data from laboratory testing were erroneously assumed to simulate what would actually occur under actual track conditions. Many of these tests were only intended to show relative performance of various DFFs from different supplier sources and different designs. An example of such tests having relative data would be the dynamic-to-static test required in many specifications. The number generated by this test is material dependent and should only serve as a relative guide for the efficiency of the elastomeric material in its vibration-reduction function. The resultant can be stated within the specification in a maximum number format for elastomeric material acceptance criteria; however, other factors such as plate masses, elastomer thickness, and design features may have more bearing on the final performance efficiency of the DFF in overall vibration reduction.

CONCLUDING REMARKS

It might be concluded from the preceding discussion that procurement of direct fixation fasteners is difficult to accomplish. Although this has been true in certain cases in the past, the growing knowledge of DFFs and their requirements continues to increase in the transit community. The direct fixation fastener with its multifunctional role in the rapid transit trackwork system and specifically the newer soft vertical and lateral DFFs simply requires more time in the preprocurement stages. The strength of rapid transit systems depends on the continuing improvement of existing products and methods and the continuing introduction of new concepts. Funding pressures now more than ever demand cost-effective improvements if North America is to remain in the forefront of technical leadership.

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Publication of this paper sponsored by Task Force on Rail Transit Design.

Conversion of Rapid-Transit Trains to One-Person Operation

JOSEPH A. HOESS

In recent years the federal government has pursued a policy of reducing its operating assistance to transit agencies. This policy has resulted in ever-increasing pressure on heavy-rail rapid-transit systems to develop more cost-effective operating procedures. One approach to improving cost-effectiveness is to reduce the rapid-transit train crew to a single operator. Although such reductions have taken place on a number of European systems, and all new U.S. systems have incorporated one-person operation, older U.S. systems continue to use two-person operation of multiple-unit trains. Battelle Columbus Division in conjunction with the National Cooperative Transit Research and Development Program, recently conducted a study of one-person operation of multiple-unit trains for improving the cost-effectiveness of heavy-rail rapid-transit systems. On the basis of the study findings, it is judged that while there are many problems to be resolved, conversion of many of the six older U.S. rapid-transit systems with two-person operation of multiple-unit trains to one-person operation is technically feasible. Such conversion will generally follow an evolutionary process. That is, rather than systemwide conversion of all services and lines at one time, systems will most likely convert those services or lines that are most compatible to one-person operation first, followed by conversion of less compatible services or lines over time. The most compatible services include new lines, lines or services with new or rehabilitated cars or facilities, and off-peak service.

In 1969 the Lindenwold Line of the Port Authority Area Transit Corporation (PATCO) began operation under full automatic control, except for doors and public address announcements, with one-person operation of all trains. It was the first instance of one-person revenue operation of multiple-unit, heavy-rail rapid-transit trains in the United States. Since Lindenwold, five additional heavy-rail rapid-transit systems have gone into revenue service in the United States—all with one-person operation of trains. The systems are as follows:

- BART–Bay Area Rapid Transit District (San Francisco),
- WMATA–Washington Metropolitan Area Transit Authority (Washington, D.C.),
- MARTA–Metropolitan Atlanta Rapid Transit Authority (Atlanta),
- MDTA–Metropolitan Dade County Transportation Administration (Miami), and
- MTA–Mass Transit Administration of Maryland (Baltimore).

Thus, over the past 18 years, six new heavy-rail rapid-transit systems have begun operation in the United States. Every one of these new systems has one-person operation of all trains. Further, this development is not limited to the United States; it has occurred worldwide. Although all new U.S. systems use one-person operation of trains, essentially all of the older, heavy-rail rapid-transit systems continue to require a second crew member onboard each multiple-unit train. These systems include:

- CTA–Chicago Transit Authority (Chicago),
- GCRTA–Greater Cleveland Regional Transit Authority (Cleveland),
- MBTA–Massachusetts Bay Transportation Authority (Boston),
- NYCTA–New York City Transit Authority (New York City),
- PATH–Port Authority Trans-Hudson Corporation (New York City), and
- SEPTA–Southeastern Pennsylvania Transportation Authority (Philadelphia).

Some of the older systems run single-car trains with one crew member onboard. Also, recently SEPTA began operation of two- and five-car trains with one-person crews. In the fall of 1983, SEPTA reopened its 1.9 mi Ridge Avenue spur to the Broad Street subway with one-person operation of the two-car trains operated on that spur. In September 1984, SEPTA converted the five-car trains operated on its Broad Street Express service from two- to one-person operations. SEPTA continues to operate all of its Broad Street local and Market-Frankford line trains with two-person train crews.

APPROACH

The principal effort of the Battelle-National Cooperative Transit Research and Development Program study involved visits to 16 heavy-rail rapid-transit systems in the United States and Europe to solicit their opinion and obtain information on the issues, problems, and solutions to problems associated with conversion of heavy-rail rapid-transit systems to one-person train operation. That work was supplemented by a review of the literature to identify definitive documents on the many topics of interest to the study. The following systems were visited:

1. The six older U.S. heavy-rail rapid-transit systems listed previously;
2. Four of the newer U.S. one-person operation systems listed previously (i.e., BART, MARTA, PATCO, and WMATA.); and

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3. Six European metro systems:

- BVG—Berliner Verkehrs–Betriebe (Berlin, West Germany);
- HHA—Hamburger Hochbahn A. G. (Hamburg, West Germany);
- LT—London Transport Executive (London, England);
- RATP—Régie Autonome des Transports Parisiens (Paris, France);
- SL—AB Storstockholms Lokaltrafik (Stockholm, Sweden); and
- VAL—Vehicle Light Automatic (Lille, France).

The first five European systems are heavy-rail rapid-transit systems that either have or are in the process of converting to one-person train operation. The Lille system, which began operation in May 1983, claims to be the first fully automated, unmanned transit system operating in an open urban environment.

FINDINGS

Management personnel at all of the U.S. and European heavy-rail rapid-transit systems visited that are presently operating one-person train crews on multiple-unit trains are happy with that mode of operation and have no desire to convert to two-person train operation. They are satisfied with the safety, security, and operational performance of their systems and stated that they have no major or limiting problems. With respect to the labor issue, all of the newer systems that began operation from the first day of service with one-person operation of multiple-unit trains encountered no major labor opposition to one-person operation. All of the older systems, except BVG in Berlin, that converted their entire system or only specific lines or services to one-person operation have encountered strong union opposition. To date, union opposition has sometimes delayed but never stopped conversion to one-person operation where it has been attempted. BVG in Berlin encountered little labor opposition at the time of its conversion because of a labor shortage in Germany (i.e., mid-1960s).

Three of the six U.S. two-person operation systems visited (CTA, GCRTA, and SEPTA) are very interested in conversion to one-person operation of multiple-unit trains. SEPTA has already converted two special services on its Broad Street line to one-person operation. Management personnel at the other three (MBTA, NYCTA, and PATH) stated that they have no plans for conversion at this time.

System management and union personnel interviewed at the six U.S. two-person operation rapid-transit systems visited were asked their opinion as to the major issues or problems that must be resolved in converting from two- to one-person operation of multiple-unit trains. A single list of individual system responses was compiled. The issues or problems judged to be most important are listed first. The ranking takes into consideration the frequency of citation and relative priority placed on the issues or problems by the six systems in question, plus the overall judgment of the research team based on the findings of the total study. The ranked listing of issues and problems follows:

- Car side door safety;
- Labor union opposition;
- Fire prevention and control;
- Emergency evacuation between stations;
- Reduced train operational performance resulting from increased time to recover from equipment failures and increased station dwell time;
- Security, including perceived security;
- Communication among passengers on train and train operator and passengers on station platforms and central control;
- One less onboard crew member to provide passenger information and assistance and detect problems;
- Between-car and end-door safety;
- Onboard fare collection;
- Operator training;
- Incapacitation of train operator;
- Increased operator stress; and
- Loss of position to which to assign medically disqualified train operators.

In addition to the preceding issues and problems, there is some concern that new cars are still being delivered without provisions for future conversion to one-person operation. Also, while in most cases the reduced labor costs associated with one-person train operation should exceed the costs of conversion from two- to one-person operation, some systems are concerned that the costs of improving equipment reliability and upgrading facilities will in some cases offset such savings.

A detailed discussion of solutions successfully applied by existing one-person operation systems to each of the issues or problems listed previously is presented in *National Transit Research and Development Program Report 13: Conversion to One-Person Operation of Rapid-Transit Trains*.

CONCLUSIONS

On the basis of the findings of the study, it is concluded that

1. *Many systems have been successfully converted.* Many heavy-rail rapid-transit systems, including older systems, lines, or services, have been successfully converted from two- to one-person operation of multiple-unit trains. These include the European systems visited and the limited SEPTA services.
2. *Problems still exist.* It should not be inferred from Conclusion 1 that there are no problems associated with conversion of the older U.S. two-person operation systems to one-person operation. The systems, lines, or services converted to date generally have reliable rolling stock with full-width or convertible full-width operator cabs and provisions, such as mirrors or closed circuit television (CCTV), to assist the train operator in seeing the car side doors, particularly at curved station platforms. Athough new one-person operation systems in the United States have demonstrated satisfactory door operation for trains up to 700 ft long (i.e., BART), these systems generally have straight, unobstructed station platforms. Many of the older U.S. two-person operation systems have less reliable rolling stock; antiquated facilities; curved, obstructed, and crowded station platforms; and more severe security problems, thus increasing the difficulty of conversion.
3. *Solutions are available to most problems.* Potential solutions to most of the problems at the older U.S. two-person operation systems have been successfully demonstrated at European or other U.S. one-person operation systems. These solutions are discussed in the final report.

4. *Conversion will follow an evolutionary process.* Conversion of many of the older U.S. heavy-rail rapid-transit systems with two-person operation of multiple-unit trains to one-person operation is technically feasible. Such conversion will generally follow an evolutionary process. That is, rather than systemwide conversion of all services and lines at one time, systems will most likely convert those services or lines, or both, that are most compatible to one-person operation first, followed by conversion of less compatible services or lines, or both, over time. The most compatible services include new lines, lines or services that have new or rehabilitated cars or facilities, or both, and off-peak service with shorter trains, fewer passengers, and longer headways. This process is presently being followed by SEPTA and London. The most likely exception is GCRTA, which operates a single heavy-rail line (Red Line) with all island platforms except one. GCRTA management plans to convert to all right-hand running in approximately 3 years. By that time, all of the older cars should be retired. All of the newer cars and cars on order have convertible full-width cabs with the operator's console on the left-hand or platform side of the cab for right-hand running. At that time, it should be rather straightforward to convert the total system to one-person train operation. On the other hand, NYCTA may never choose to convert its crush-loaded, 10-car, 600-ft-long, rush-hour trains to one-person operation.

5. *Transit employees will not be laid off.* Personnel and labor relations management people interviewed at all of the systems visited stated that train crew members displaced as a result of conversion to one-person train operation would either be used to improve service by running shorter, more frequent trains, assigned to other job classifications, or absorbed through normal attrition; they would not be laid off. An evolutionary process for conversion to one-person train operation will minimize the problems encountered with this approach.

6. *Eventual reduction in staff would be less than 14 percent.* The percentage of employees classified as train conductors varies from 9 to 14 percent at U.S. two-person operation rapid-transit systems. It is unlikely that any eventual reduction in staff as a result of conversion to one-person operation would be so large. Additional employees will most likely be required in the following areas:

- Security/police department;
- Maintenance;
- Ad hoc platform attendants (i.e., at busy stations during peak hours); and
- Supplemental crew members or wayside coverage persons at critical locations during peak commute hours.

7. *Economic assessment of each specific conversion is required.* Before proceeding with conversion of a specific system, line, or service to one-person operation, a comprehensive assessment of the economic worth of the conversion is required. For such an assessment, investment or capital costs include all of the costs required to convert that specific system, line, or service from two- to one-person operation. Likewise, the future savings (or losses) resulting from that investment include the sum of all the differences in operating and maintenance costs between the two- and one-person operation versions of the specific system, line, or service over its useful life. Detailed listings of the cost elements that must be considered in a site-specific economic analysis are presented in the final report.

ACKNOWLEDGMENT

The research summarized in this paper was conducted by Battelle Columbus Division as part of the National Cooperative Transit Research and Development Program, which is sponsored by the U.S. Urban Mass Transportation Administration, U.S. Department of Transportation, and administered by the Transportation Research Board. The author was the principal investigator. Paul J. Murphy, Human Resource Consultant, also participated in the study. Finally, this study would not have been possible without the assistance and cooperation of the many (100) transit system management and union officials who graciously agreed to meet with the project team and contribute their experience and expertise to the project.

Publication of this paper sponsored by Committee on Rail Transit Systems.