TRANSPORTATION RESEARCH RECORD 1054

Transit Terminals: Planning and Design Elements

TRB
TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C. 1986

Transportation Research Record 1054
Price $7.20
Editor: Edythe Traylor Crump
Compositor: Lucinda Reeder
Layout: Theresa L. Johnson

mode
2 public transit

subject areas
11 administration
12 planning
13 forecasting
14 finance
15 socioeconomics
54 operations and traffic control

Transportation Research Board publications are available by ordering directly from TRB. They may also be obtained on a regular basis through organizational or individual affiliation with TRB; affiliates or library subscribers are eligible for substantial discounts. For further information, write to the Transportation Research Board, National Research Council, 2101 Constitution Avenue, N.W., Washington, D.C. 20418.

Printed in the United States of America

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

Transit terminals.

(Transportation research record, ISSN 0361-1981 ; 1054)
1. Terminals (Transportation)—Planning.
2. Terminals (Transportation)—Design and construction.
3. Pedestrian areas—Planning. I. National Research Council (U.S.). Transportation Research Board.
II. Series.
TE7.H5 no. 1054 380.5 s 86-16350
[TA1225] [385'.314]
ISBN 0-309-03970-3

Sponsorship of Transportation Research Record 1054

GROUP 1—TRANSPORTATION SYSTEMS PLANNING AND ADMINISTRATION
William A. Bulley, H. W. Lochner, Inc., chairman

Urban Public Transportation Section
John J. Fruin, PED Associates, chairman

Committee on Intermodal Transfer Facilities
Walter H. Kraft, Edwards & Kelcey, Inc., chairman
John S. Pavlovich, New York Metropolitan Transportation Council, secretary
Mark M. Akins, Colin H. Alter, Charles F. Arndt, Howard P. Benn, Gregory P. Benz, John P. Braaksma, S. Lee Carlson, Donald L. Dean, John J. Fruin, Lester A. Hoel, Barry J. Kaas, Jeaninne Kahan, Adib Kanafani, Hanan A. Kivett, Jerome M. Lutin, Bruce W. Mainzer, Debra A. Newman, Robert A. Olmsted, Ira N. Pierce, Richard R. Sarles, Wilfred Sergeant, Ronald A. Wiss, Harold I. Wright

Wm. Campbell Graueb, Transportation Research Board staff

The organizational units, officers, and members are as of December 31, 1985.

1054

Contents

Times Square Subway Complex Pedestrian Movement Analysis

JAMES H. HERENDEEN, JR., and MYUNG-HAK SUNG

ABSTRACT

Reconstruction of the Times Square Station is an integral part of the 42nd Street Development Project. The new development, planned for the sites above and adjacent to the subway station, creates the opportunity for complete reconstruction of the station. An analysis of pedestrian flows within the station was conducted to assist in selecting the design concept. The movement analysis task takes on a special significance because of the size, the number of possible entrance and exit points, and the number of alternative paths available to get from place to place within the station. The complexity of the station area is such that it precludes the use of existing station area models, including the UMTA Transit Station Simulation (USS) program. Highway network and assignment techniques were adapted and the Urban Transportation Planning System (UTPS) was used to simulate pedestrian networks and to project pedestrian volumes on discrete station elements. UTPS has proved to be valuable for analyzing alternatives and for providing pedestrian flow data that are needed to refine the design concepts. Information generated by UTPS helped to evaluate the overall performance of the alternatives with respect to each other and the existing station. It also pinpointed the location of the problem areas within each alternative.

Times Square Station, one of the three largest subway stations in New York City, was built over the three decades between 1900 and 1930 by three different private transit companies. This complex is currently the major interchange of four subway lines: the 7th Avenue Interborough Rapid Transit (IRT), the Broadway Brooklyn-Manhattan Transit (BMT), the Flushing IRT, and the 42nd Street Shuttle. The station contains an upper and lower mezzanine, the lower one stacked between the Flushing and 7th Avenue IRT lines, and is also connected to the 8th Avenue line and the Port Authority Bus Terminal through the 41st Street pedestrian tunnel. The station platforms are connected by a maze of concourses, stairs, ramps, escalators, passageways, and entrances.

Reconstruction of the Times Square Station is an integral part of the 42nd Street Development Project. The new development, planned for the sites above and adjacent to the subway station, creates an unprecedented opportunity for the reconstruction of the station. The design of the modernization is being prepared under the direction of the New York City Public Development Corporation (PDC) in cooperation with the project steering committee.

THE ASSIGNMENT

Development of reliable estimates of pedestrian flow volumes is an important task in the design of facilities for pedestrian use. In most cases, estimates of the number of users during a selected design period, perhaps by direction of movement, are sufficient to permit elements of the facility to be properly sized and designed. However, the movement analysis task for developing a design concept for the Times Square Subway Complex takes on a special significance because of its size, the number of possible entrance and exit points, and the number of alternative paths available to get from place to place within the station.

Table 1 contains a list of all possible access and egress points for the existing station. Between most pairs of points, there is more than one logical or reasonable path. Furthermore, those who want to enter or leave the subway complex have a choice of 20 station access and egress locations. Therefore, estimates of the volume of passengers who will want to use the station in the design period in some future design year provide only part of the information required to design improved pedestrian flow station elements. Reliable estimates of pedestrian flow volumes through each element in the subway complex must be developed if the design is to be functional.

The complexity of the station area precludes the use of existing station area models, including the UMTA Transit Station Simulation (USS) program. Highway network and assignment techniques were adapted and the Urban Transportation Planning System (UTPS) programs (1), including MBUILD, UMATRIX, HR, and UROAD, were used to simulate pedestrian networks and to project pedestrian volumes on discrete station elements. The analysis procedure was validated by comparing the actual pedestrian counts with the counts produced by the simulation procedures. The validated procedures were then applied, and pedestrian volumes were projected for the four different alternatives, including the existing system in the design year. The selected alternative was further evaluated by testing several different design concepts for specific components of the station. This is the first known application of highway assignment techniques to evaluate capacity and levels of service for pedestrian facilities.

ANALYSIS METHODOLOGY

In assessing the information requirements for developing design concepts for the Times Square Subway

---

Gannett Fleming Transportation Engineers, Inc., P.O. Box 1963, Harrisburg, Pa. 17105.

TABLE 1 Access and Egress Locations for the Times Square Subway Complex

Location No.	Description
1	Southwest corner of the 43rd Street and Broadway intersection
2	South side of Broadway midblock between 42nd and 43rd Streets
3	Northeast corner of the 42nd Street and 7th Avenue intersection (exit only)
4	Northwest corner of the 42nd Street and 7th Avenue intersection (two stairways)
5	Southeast corner of the 42nd Street and Broadway intersection
6	Southwest corner of the 42nd Street and 7th Avenue intersection
7	West side of Broadway midblock between 41st and 42nd Streets
8	Northeast corner of the 41st Street and 7th Avenue intersection (two stairways)
9	Northwest corner of the 41st Street and 7th Avenue intersection
10	Southwest corner of the 41st Street and Broadway intersection
11	Southeast corner of the 41st Street and 7th Avenue intersection (exit only)
12	Southwest corner of the 41st Street and 7th Avenue intersection
13	Northeast corner of the 40th Street and Broadway intersection
14	Northwest corner of the 40th Street and Broadway intersection
15	Southeast corner of the 40th Street and Broadway intersection
16	Southwest corner of the 40th Street and Broadway intersection
17	Southeast corner of the 40th Street and 7th Avenue intersection
18	South side of 40th Street just west of 7th Avenue
19	South side of 40th Street midblock between 7th and 8th Avenues (exit only)
20	The 41st Street passageway at the station for the 8th Avenue IND line
21	Track 1 platform for the 42nd Street shuttle
22	Track 2 platform for the 42nd Street shuttle
23	Track 4 platform for the 42nd Street shuttle
24	Uptown platform for the Broadway BMT
25	Downtown platform for the Broadway BMT
26	Uptown platform for the 7th Avenue IRT
27	Downtown platform for the 7th Avenue IRT
28	Flushing IRT platform

Complex, and in evaluating the nature of the problem of developing estimates of the information, the analogy between the prediction of vehicular traffic volumes on individual elements of a highway and street network became obvious. In the highway and street network case, estimates are first derived for the volume of traffic between each origin-destination pair. Paths are then identified between the origins and destinations, and the volumes for each origin-destination pair are assigned to the elements that comprise the paths. The sum of the volumes assigned to an element for each origin-destination pair is the estimate of total volume on that element.

This entire process has been computerized and is available from the Urban Mass Transportation Administration in the form of a battery of computer programs referred to as UTPS. Although application of UTPS to a pedestrian flow network requires adjustments in the methods of describing the characteristics of the elements of the pedestrian network, such adjustments are easily made and readily understandable.

In the UROAD program of the UTPS, highway speed and capacity are determined by facility type (a maximum of six facility types), by area type (a maximum of five area types), and by the number of lanes (a maximum of nine lanes). To adapt the UROAD program, pedestrian facilities within the study area were divided into six different facility types: walkways, platforms, ramps, stairs, escalators, and entry and exit facilities. Each facility type was further categorized by using an area type code and a number of lanes code. For example, Facility Type 1, walkways, was divided into four different area types: walkways within the station, sidewalks, street crossing, and centroid connectors. Area Type 1, Facility Type 1, was further partitioned by the number of lanes representing the width of the walkways. After definitions were developed for the various facility types, area types, and number of lanes, the travel speed and capacity of each link type were determined by using the level-of-service definitions developed by Fruin (2).

Further, travel speeds were represented in the description of station elements as 10 times actual speeds, and distances as 100 times actual distances. As a result, estimates of travel times and speeds produced by the computer process must be divided by 10 to obtain the actual times and speeds. On station elements where two-way flows are permitted, that is, all elements except escalators and exit-only locations, the width of the facility had to be apportioned to the flow by direction. This is not required for highways on which lanes are dedicated to one direction only, but in a pedestrian facility the effective width for a given direction will vary with the directional split throughout the day. In interpreting the assignment results, judgment must be used in determining whether sufficient capacity exists for both directions of flow. Volume estimates for various station elements need no adjustment however.

Although the analogy between the prediction of pedestrian flow volumes on elements of a pedestrian network and the prediction of vehicular flow volumes on a highway network is striking, it is not complete. There are two major differences in the problem to be solved for pedestrian flow facilities that are not adequately addressed by the highway network analysis procedures. The model is unable to predict the impact of channelization of flow versus the mixing bowl effect that occurs in areas where many conflicting movements meet. The model is also incapable of accounting for the effects of orientation and the ease of pathfinding. The travel time estimates are, thus, not sensitive to these pedestrian facility characteristics. The shortcomings of the process, while failing to account for some of the likely differences between alternatives in terms of travel times and travel speeds, will not influence the estimates of pedestrian flow volumes. The predicted flow volumes are the most important product of this analysis because the number of people using the various elements of the facility will be used to size and design these elements.

In the following sections of this paper a brief description is given of the data that were collected and compiled for this study, the procedures for projecting travel demands for the design conditions, and the results of the analyses. The ways that the analysis procedures influenced the development of design concepts are then presented, followed by the conclusions reached as a result of the movement analysis.

DATA COLLECTION AND MODEL VALIDATION

Pedestrian flow volume data were collected over a 2-week period in November 1982. Counts were recorded in 5-min increments from 7:30 a.m. to 9:30 a.m. and from 4:30 p.m. to 6:00 p.m. (3). These counts were then used to identify morning and evening peak-hour flow volumes on each element within the station.

To complete the description of present pedestrian flows in the Times Square Subway Complex, it is necessary to determine the volumes of people that want to transfer between trains and the volumes that want to travel between the trains and the surrounding area. The trip table given in Table 2 was developed from sample data collected during a transit user survey conducted in 1978 (4), expanded to estimate the origin-destination characteristics of all Times Square Station users, and adjusted based on the pe-

TABLE 2 Times Square Subway Complex Modernization Project—Existing Trip Table (1982) Morning Peak Hour (8:00 to 9:00 a.m.)

Destination / Origin	Station Platforms						Zones Surrounding Times Square														
	7 IRT NB[a]	7 IRT SB	B BMT NB	B BMT SB	F IRT	SHUT	122	124	PABT 129	130	133	134	139	140	142	154	161	162	163	164	Total
1 7 IRT NB[a]			346		1,205	1,525	12	115	148	207	91	51	462	184	7	22	24	12	7	7	4,425
2 7 IRT SB			446	1,671	2,723	2,565	21	184	238	338	149	82	754	298	12	36	41	21	13	9	9,601
3 B BMT NB	405				52	959	12	137	381	789	377	21	2,990	592	81	239	89	57	216	159	7,556
4 B BMT SB	302	228			52	135	3	57	153	324	155	6	1,222	241	34	97	38	22	89	64	3,222
5 F IRT	621	1,596	0	17		0	72	184	880	953	602	46	1,491	578	67	292	21	46	283	102	7,851
6 SHUT	771	1,949	116	171	0		0	86	0	835	272	56	1,162	165	0	56	25	63	81	18	5,826
7 122	23	20	3	7	94																147
8 124	23	25	13	37	1,135	114															1,347
9 PABT 129	623	622	166	499	933	57															2,900
10 130			14	44	308	239															605
11 133					94																94
12 134			3	10																	13
13 139			3	10	88																101
14 140	34	37																			71
15 142																					0
16 154																					0
17 161																					0
18 162																					0
19 163					94																94
20 164					50																50
TOTAL	2,802	4,477	1,110	2,466	6,828	5,594	120	763	1,800	3,446	1,646	262	8,081	2,053	201	742	238	221	689	359	43,903

[a] See Table 3 for definitions of origins and destinations.

destrian volume data collected in 1982. Definitions of the zones are given in Table 3 and Figure 1.

The trip table presented in Table 2 is for the morning (8:00 a.m. to 9:00 a.m.) peak period. An analysis of the pedestrian-flow volumes collected in 1983 indicated that there was little difference in the volumes between the morning and evening peaks. This indicated that the morning peak-hour flows adequately represent typical peak-period flow conditions. Thus, the remaining analyses were conducted using the morning peak-hour trip table.

TABLE 3 Description of Zones Used in Trip Tables

Zone No.	Designation	Description
1	7 IRT NB	Northbound platform of the 7th Avenue IRT line
2	7 IRT SB	Southbound platform of the 7th Avenue IRT line
3	B BMT NB	Northbound platform of the Broadway BMT line
4	B BMT SB	Southbound platform of the Broadway BMT line
5	F IRT	Platform of the Flushing IRT line
6	SHUT	Platforms of the 42nd Street shuttle line
7	122	Zone 122[a]
8	124	Zone 124
9	PABT 129	Port Authority Bus Terminal and Zone 129
10	130	Zone 130
11	133	Zone 133
12	134	Zone 134
13	139	Zone 139
14	140	Zone 140
15	142	Zone 142
16	154	Zone 154
17	161	Zone 161
18	162	Zone 162
19	163	Zone 163
20	164	Zone 164

[a] Zones defined for use in conjunction with the Metropolitan Transit Authority's Midtown Underground Pedestrian Connections Study as illustrated on the map shown in Figure 1.

The existing morning peak-hour trip table was assigned to the existing Times Square Subway Complex pedestrian network using the UROAD program. The results of the assignment (i.e., the predicted volume of pedestrians on each element in the network) were compared to the morning peak-hour flow volumes compiled from the 1982 survey. Table 4 contains the results of this comparison.

It should be noted that validation results within 5 percent by facility type are considered to be excellent. Volume predictions on major station components can be expected to be within 15 percent of the counts. For minor elements, large variations sometimes occur, especially where volumes are low and where alternative paths exist. Care must be exercised in the interpretation of the computer results in these areas.

It is very difficult to check the accuracy of the system totals such as the total number of hours of travel and the average travel time per person. The travel times appear reasonable based on limited field observations, but no comprehensive data on travel times are available. Tests conducted for this project indicate that variations of one to two percent frequently occur in these numbers when very minor changes in system elements are made. This leads to the conclusion that the system totals used to compare the alternatives are accurate to 2 percent relative to other alternatives.

In addition to the testing of the computer modeling process, the results of the data collection and analysis were used to evaluate the existing station. Points of congestion were identified and verified by field observations. Correlations between computer predicted trouble spots and observed points of congestion and delay within the station were excellent. Recommendations for improvements were made. The results of this evaluation formed the basis for developing alternative design concepts.

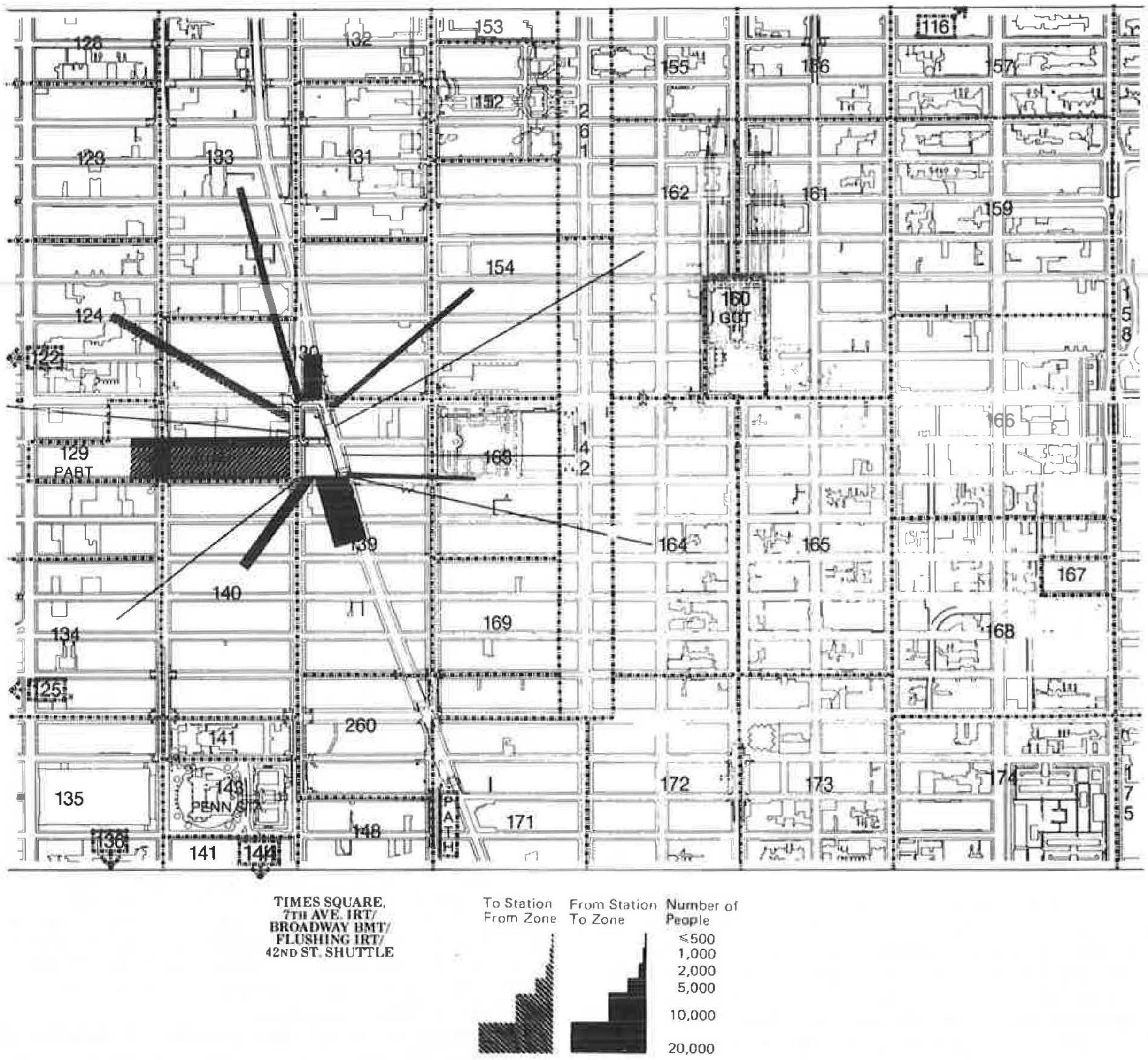


FIGURE 1 Map showing subway station origin and destination zones.

TABLE 4 Predicted Volume Versus Actual Count Summaries by Facility Type—Morning Peak Hour Existing Trips in the Existing Station

Facility Type	Predicted Volumes (P)	Actual Count (A)	P/A
Walkways	431,100	532,200	0.81
Ramps	37,700	37,000	1.02
Stairs	102,400	111,300	0.92
Escalators	4,300	4,200	1.02
Entrances and exits	21,200	20,800	1.02

Note: Total person hours of travel per morning peak hour = 4,219; total number of trips in the peak hour = 43,903 person trips; average travel time per person in the peak hour = 5.8 min.

FUTURE DEMANDS

The proposed improvements to the Times Square Station should be designed to accommodate not only the volumes of pedestrians that currently use the station but also those that are expected to use the station in the future. To predict future passenger use of the station, it was first necessary to identify the conditions for which the station should be designed. Then, the impact of these conditions on trip-making activity could be estimated.

In discussions with representatives of the New York City Department of City Planning, the New York City Transportation Authority, the Metropolitan Transit Authority, and the New York City Public Development Corporation, it was decided to assume the following conditions would exist in the design year:

1. All development currently planned for the Times Square area would be completed, including the 42nd Street Development Project, the Portman Hotel, and the Durst Site Development.
2. Changes in the current configuration of subway stations in the Times square area would result in the extension of the paid zone to include the 8th Avenue and 6th Avenue subway stations at 42nd Street.
3. General growth and increased density of activity in Manhattan would result in a 13 percent increase in subway users.

The trips were partitioned into three categories to account for the impacts of these assumptions:

1. People moving between the surrounding development and the subway station;

2. People transferring between the 8th Avenue line and other lines in the station and those transferring between the 6th Avenue line and other lines in the station; and

3. People transferring among the Shuttle, the Broadway BMT, the 7th Avenue IRT, and the Flushing IRT.

Future pedestrian trips between the subway complex and the surrounding developments were estimated using information developed and acquired as a result of the work on the Midtown Underground Pedestrian Connections study (3). Currently, 26,048 people use the Times Square Subway Complex to go to or to leave from developments surrounding the complex, including the Port Authority Bus Terminal in the morning peak hour. When planned developments are completed, this volume is expected to increase to 33,596, an increase of nearly 30 percent.

Projections of interline transfers between 8th Avenue and the remaining lines had to be based on estimates of what will happen when the 8th Avenue Paid Zone is connected to the Paid Zone for the rest of the complex, a modification that will take place in the near future. The New York City Transit Authority has estimated that 550 people would transfer from the Flushing line to the 8th Avenue line and 400 would transfer from the 7th Avenue line to the 8th Avenue line in the morning peak hour under existing conditions. These volumes were increased by 13 percent to 622 and 452, respectively, to represent future conditions. The number of people who would transfer between the current station complex and the 6th Avenue line was judged to be insignificant, and therefore, no adjustments were necessary in the trip table for this assumed change.

The remaining portion of the trip table (the interline transfers among the shuttle, the 7th Avenue IRT, the Broadway BMT, and the Flushing IRT) was increased by 13 percent to account for the general growth in the subway system utilization. The existing morning peak-period interline transfer volume of 17,855, therefore, increased to 20,194.

The total increase in trip-making activity between present conditions and the design conditions is expected to be 25 percent from about 44,000 currently to about 55,000. The resulting future trip table is contained in Table 5. Descriptions of the zones are contained in Table 3.

During the analysis of the pedestrian volume counts that were compiled in November 1982, it was noted that flows were not steady over the entire peak hour. Surges lasting as long as 15 min frequently occurred during which time the flows were 20 to 30 percent greater than for the remainder of the peak hour. It was also known that the daily volume of passengers is not constant. Transit use tends to increase on days when the weather is inclement and during peak shopping days in December, for example.

A third trip table was prepared for use in tests of alternative station design concepts to estimate the impacts of these surge or unusually high flow volumes on station performance. Each cell in the trip table was multiplied by 1.25 to represent a 25 percent increase in trip-making activity. Twenty-five percent was selected as an appropriate value based on observed variations in pedestrian flow volumes in the station area. Results of testing alternatives with this trip table will also indicate the ability of the alternative design concepts to accommodate unexpected increases in pedestrian flow volumes that might occur in future years.

TESTING ALTERNATIVES

The testing of alternatives involves the assignment of future trips to the networks that represent the

TABLE 5 Times Square Complex Modernization Project—Future Trip Table (Design Conditions) Morning Peak Hour (8:00 to 9:00 a.m.)

Destination	Station Platforms						Zones Surrounding Times Square																
Origin	7 IRT NB[a]	7 IRT SB	B BMT NB	B BMT SB	F IRT EB	SHUT	122	124	PABT 129	130	133	134	139	140	142	154	161	162	163	164	Total
1 7 IRT NB[a]			391		1,363	1,725	12	115	227	623	108	51	522	184	7	22	24	12	7	7	5,400
2 7 IRT SB			504	1,890	3,080	2,901	21	184	818	1,016	178	82	851	298	12	36	41	21	13	9	11,955
3 B BMT NB	458				59	1,085	12	137	507	1,459	405	21	3,086	592	81	239	89	57	216	159	8,662
4 B BMT SB	342	258			59	153	3	57	205	598	167	6	1,261	241	34	97	38	22	89	64	3,694
5 F IRT	702	1,805	0	19		0	72	184	1,582	1,374	620	46	1,551	578	67	292	21	46	283	102	9,344
6 SHUT	872	2,204	131	193	0		0	86	28	982	278	56	1,183	165	0	56	25	63	81	18	6,421
7 122	23	20	3	7	94																147
8 124	23	25	13	37	1,135	114															1,347
9 PABT 129	636	635	171	512	962	59				2,302	98		330								5,705
10 130	72	72	38	116	463	251			360												1,372
11 133	27	26	9	27	152	5			134												380
12 134			3	10																	13
13 139	10	10	7	20	109	2			50												208
14 140	34	37																			71
15 142																					0
16 154																					0
17 161																					0
18 162																					0
19 163					94																94
20 164					50																50
TOTAL	3,199	5,092	1,270	2,831	7,620	6,295	120	763	3,911	8,354	1,854	262	8,784	2,058	201	742	238	221	689	359	54,863

[a] See Table 3 for definitions of origins and destinations.

alternatives being considered. In this study, the existing system and the design guidelines (5) alternative were tested first. Scheme Nos. 1 and 2 were then developed to mitigate the problems identified as a result of the first tests.

Much of the effort involved in the development of alternatives focused on the creation of a station complex that reflects the importance and significances of Times Square. Specific attention was paid to the elimination of narrow, dark passageways, opening the station up to light and air from street level, and the creation of underground connections among the new buildings of Times Square. However, care was exercised to ensure that congestion and delays were avoided by the number and the size of the facilities serving each major movement.

The analysis of the tests on the existing system and the design guidelines began by identifying those station elements or links that had volume-to-capacity ratios of 1.00 or more. A further check was made of the volume in the other direction. The two-way volume-to-capacity ratio was then computed. If the two-way volume was found to exceed the capacity of that station element, it was identified as a problem area. This process was necessary because of the method used to assign or proportion the widths of the various station elements to directions of flow. Design options were then developed to improve passenger flow conditions at the problem area. Solutions included widening stair cases, entranceways and ramps, adding escalators and stairways, and realignment of certain facilities to improve pedestrian flows.

The summary results of the tests are given in Table 6. The total travel time in hours is the summation of the travel time spent by each pedestrian moving through the station in the morning peak hour. It does not include time spent waiting for a train. The average travel time per person in minutes is the average time spent by pedestrians moving through the station, again excluding waiting time on the platforms. In both of these categories, lower numbers imply more efficient operation of the station.

The other three categories of system performance measures deal with the number of station elements or links that fall within different level-of-service

originally developed to describe vehicular traffic conditions on highways. Fruin (2) later applied similar concepts to the flow of pedestrians. As volumes increase, freedom to maneuver and to select a desired travel speed decrease until capacity is reached. When capacity is reached, travel speeds are low, and small disruptions can cause flow to cease altogether for short periods of time. Level of service A represents the least congested conditions. Level of service C is generally considered as the appropriate design criterion. Level of service D is considered acceptable, although not desirable. Level of service E represents conditions at or near capacity, that is, when the station element or network link is carrying as much volume as it can possibly handle. Level of service F represents the conditions that occur when speeds decrease, densities increase, and flow volumes decrease because congestion is so severe.

Specific definitions of levels of service A through F are provided for walkways, stairways, and queuing areas. These definitions basically follow and correspond to the general description of levels of service for highways presented earlier. Thus, the analogy between the prediction of highway and street network flow conditions and the prediction of pedestrian network flow conditions extends to this part of the analysis. From the description of the level-of-service concept, it is evident that the better the level of service, the better an individual station element or network link performs. Also, the fewer the number of links operating at or below a selected level of service, the better the overall performance of the alternative.

The summary results given in Table 6 indicate that Scheme No. 1 performs better than the other alternatives. The measures of total and average travel times show that Scheme Nos. 1 and 2 perform substantially better than either the existing system or the design guidelines. There is very little difference between Scheme Nos. 1 and 2 based on the total time spent by pedestrians traveling in the system or the average travel time per pedestrian. Scheme No. 1 does, however, perform slightly better than Scheme No. 2 in terms of the numbers of links that operate at or below the various selected levels of service. Scheme No. 1 performs better in this regard than any other alternative except that Scheme No. 1 has two more links than Scheme No. 2 for the number of links at level of service C or below for the future trip table.

CONCLUSIONS

Scheme No. 1 was found to be better than any other alternative based on the travel time spent by pedestrians moving from place to place within the station complex and on the number of congested links. Changes introduced as a result of the analysis of flows in the existing station and those projected for the design guidelines improved the overall performance of Scheme Nos. 1 and 2, with Scheme No. 1 performing somewhat better than Scheme No. 2. The results of

TABLE 6 Summary of Computer Simulation Results

System Performance Measures	AM Peak Hour Trip Table	Existing Station	Design Guidelines	Scheme No. 1	Scheme No. 2
Total travel time in hours	Existing	4,219	NA	NA	NA
	Future	5,390	5,305	5,134	5,048
	Surge	7,178	6,909	6,462	6,506
Average travel time per person in minutes	Existing	5.77	NA	NA	NA
	Future	5.89	5.80	5.61	5.52
	Surge	6.28	6.04	5.65	5.69
Number of links at level of service "C" or below	Existing	96	NA	NA	NA
	Future	124	106	69	67
	Surge	180	148	99	105
Number of links at level of service "D" or below	Existing	44	NA	NA	NA
	Future	64	72	30	34
	Surge	96	92	50	62
Number of links at level of service "E" or below	Existing	24	NA	NA	NA
	Future	25	45	14	18
	Surge	55	56	30	34

Note: NA = not applicable.

tests conducted to determine the impact of unusually high flows that are expected to occur during bad weather or on days of peak activity also illustrate that Scheme No. 1 is better able to handle the additional traffic. These results support the selection of Scheme No. 1 as the preferred scheme. The results of the movement analysis of Scheme No. 1, particularly the flow volumes, were used to refine elements of the selected scheme. Further tests were conducted to demonstrate the effects of suggested design changes.

The use of the UTPS computer programs for predicting pedestrian flow volumes has proved to be valuable for analyzing alternatives and for providing pedestrian flow data that are needed to refine the preferred design concept, Scheme No. 1. Information generated by the UROAD program helped to evaluate the overall performance of the alternatives with respect to each other and the existing station. It also pinpointed the location of problems within each alternative.

ACKNOWLEDGMENTS

The Times Square Subway Complex Modernization Project is being conducted by William Nicholas Bodouva & Associates and Vollmer Associates in a joint venture under the direction of the New York City Public Development Corporation. Gannett Fleming, under the aegis of Corddry Carpenter Dietz and Zack, an affiliated partnership, is a subcontractor on the project responsible for transportation planning and pedestrian flow analysis. A project steering committee consisting of the following agencies and groups has been established to provide direction and coordination to the design consultants: New York City Public Development Corporation (PDC); New York City Department of City Planning (DCP); Times Square Redevelopment Corporation (TSRC); New York State Urban Development Corporation (UDC); Metropolitan Transportation Authority (MTA); New York City Transit Authority (NYCTA); Park Tower Realty Inc.; Housing Innovations Inc./Planning Innovations Inc.; Cooper, Eckstut Associates, _ex officio_; and Allee King Rosen & Fleming, Inc., _ex officio_.

The authors wish to thank these groups and representatives for their assistance in collecting the data needed to perform the Pedestrian Movement Analysis of the Times Square Subway Complex and in the analysis and interpretation of the results.

REFERENCES

1. Urban Transportation Planning System Reference Manual. Office of Technical Assistance, URT-41, Urban Mass Transportation Administration and the Office of Highway Planning, HHP-22, FHWA, U.S. Department of Transportation, Dec. 1982.
2. J.J. Fruin. Pedestrian Planning and Design. Metropolitan Association of Urban Designers and Environmental Planners, Inc., New York, 1971.
3. Skidmore, Owings & Merrill. Midtown Underground Pedestrian Connections Study. Project 1-01-18621-0-0. New York City Metropolitan Transportation Authority, 1982.
4. Transit Sufficiency Study. Report C-671. New City Transportation Authority, 1979.
5. Cooper, Eckstut Associates. Design Guidelines for the 42nd Street Development Project. New York State Urban Development Corporation, New York City Public Development Corporation, and the New York City Department of City Planning, 1981.

PC-Based Pedestrian Flow Simulation Model for Grand Central Terminal

GREGORY P. BENZ, JOHN S. CHOW, and JEROME M. LUTIN

ABSTRACT

A pedestrian flow simulation model was developed to test and evaluate the proposed underground pedestrian network for Grand Central Terminal's North End Access Improvements. The simulation model runs on a personal computer (PC) using the LOTUS 1-2-3 spreadsheet program. Based on the results of the simulation, planners modified the design to increase the capacities of certain passageways and to develop a more cost-effective design solution. Also, the model was used to test nearly a dozen construction-phasing options to respond to capital funding availability and passenger flow needs. The model, although not as sophisticated as some previous simulation programs, proved to be a useful and cost-effective tool in the design process. It uses widely available, inexpensive personal computer hardware and software. The pedestrian flow simulation model, its essential components, and how it was used as a design tool are described in this paper. The advantages and disadvantages of this type of approach are discussed in the conclusion.

The design of a new underground pedestrian passageway system is underway for historic Grand Central Terminal in New York City. Metro-North Commuter Railroad Corporation of the Metropolitan Transportation Authority is planning the North End Access Improvements to shorten the travel time for commuters and to reduce pedestrian congestion within and around the terminal. More than 150,000 rail commuters and subway riders will benefit from the improvements each day. A pedestrian flow simulation model that was developed to test and evaluate the proposed facilities is described in this paper. The simulation model runs on a personal computer (PC) using the LOTUS 1-2-3 spreadsheet program. Based on the results of the simulation, planners modified the design to increase capacities of passageways and to develop more cost-effective design solutions. The model also was used to test nearly a dozen construction-phasing options to respond to capital funding availability and passenger flow needs.

The model, although not as sophisticated as some previous simulation programs, proved to be a useful and cost-effective tool in the design process. It uses widely available, inexpensive personal computer hardware and software.

The pedestrian flow simulation model, its essential components, and how it was used as a design tool are described in this paper. The advantages and disadvantages of this type of approach are discussed in the conclusion.

BACKGROUND OF THE PROJECT

Grand Central Terminal is located in Midtown Manhattan at 42nd Street and Park Avenue (see Figure 1). It serves as a "stub end" terminal for trains arriving from the north. The terminal is the southernmost point on Metro-North's Harlem, Hudson, and New Haven lines, and it also serves long distance Amtrak service to upper New York State and the midwest. The only way for pedestrians to reach the train platforms is by walking through the main concourse at the south (downtown) end of the platforms, as shown in Figure 2.

When Grand Central Terminal was opened in 1913, the southern orientation of its exits served its commuters well because virtually all of Manhattan's development was south of the terminal. However, over the past 70 years, dense office building development has occurred to the north of the terminal. This shift in land use means that 57 percent of all morning peak-hour Metro-North riders are headed for destinations north of the terminal--between 42nd and 60th Streets in Midtown Manhattan. Most (94 percent) of those riders walk to their destinations (1).

The terminal was designed to handle southbound pedestrian flows out of the terminal, but the majority of the people are now headed northbound. This shift has created several problems. One problem is backtracking--northbound passengers exiting trains must first walk south off the platforms and into the main concourse before they can reverse direction and walk north (see Figure 3). Another problem is the congestion and delay created at the exits, corridors, and vertical circulation facilities used by these northbound passengers.

A solution to these problems is to build new exits leading from the north ends of the underground train platforms directly to the street. The North End Access Improvements will provide this direct access (see Figure 4). Conceptually, the North End Access Improvements will superimpose a grid of two north-south and two east-west walkways over the existing platforms, allowing most passengers to reach the new northern exits.

Two nonrevenue tracks will be covered over and converted into north-south walkways, or spines, that will run from the main concourse of Grand Central Terminal at 43rd Street northward to 47th and 48th Streets. The new north-south spines will replace tracks 22 and 31, currently used for maintenance, on the upper level. (Grand Central Terminal's tracks and platforms occupy two underground levels. The upper level tracks are numbered 11 through 42, and the lower level tracks are numbered 101 through 116.)

Two east-west cross passageways will tie into the north-south spines to allow passengers from virtually all platforms to reach the spines. The two cross passageways will be constructed at a new level be-

---

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

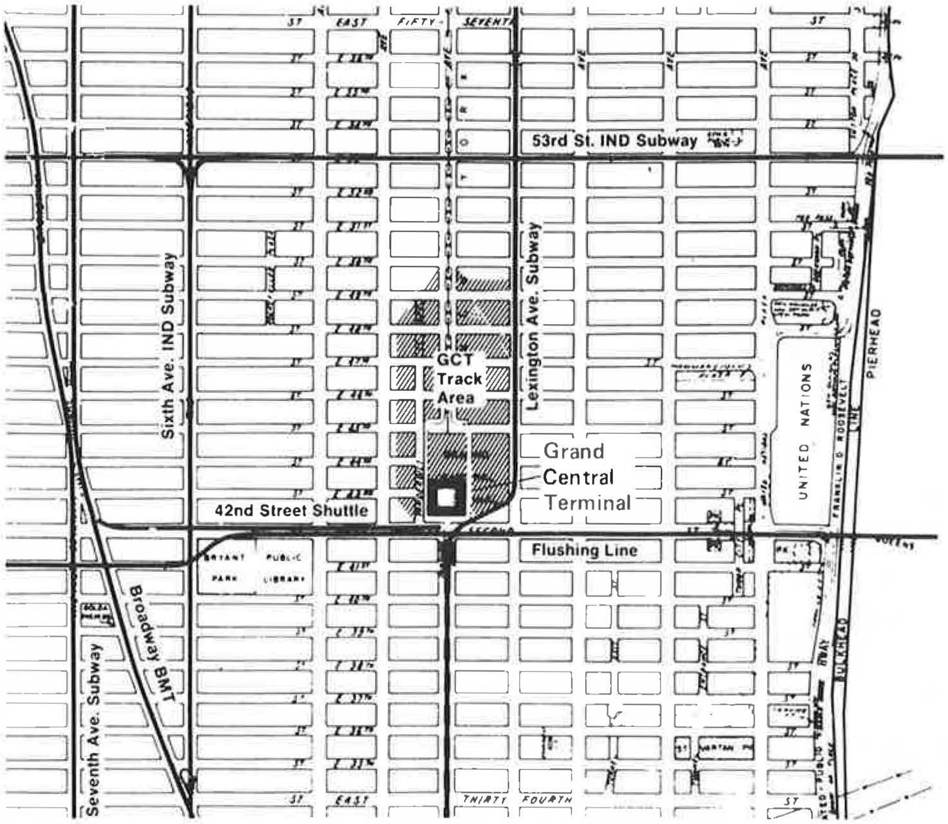


FIGURE 1 Grand Central Terminal and environs.

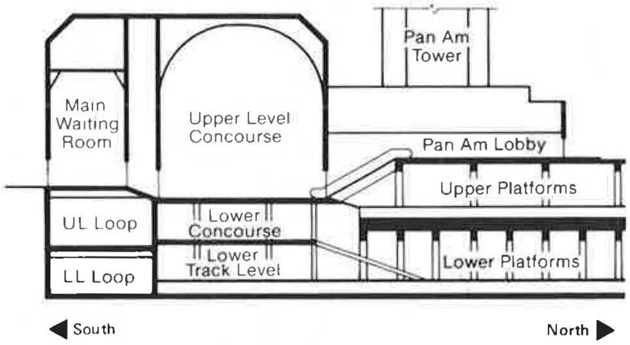


FIGURE 2 Section of Grand Central Terminal. All passengers presently must walk south to the concourses.

tween the upper and lower train levels--one under 45th Street and a second one under 47th Street. The 45th Street cross passageway will serve the lower level platforms by new stairs. The 47th Street cross passageway will serve the upper level platforms. The cross passageways range in width from 25 to 33 ft whereas each of the north-south spines is approximately 25 ft wide. There are eight proposed surface connections for north end access--four along 45th Street and four along 47th Street. In addition, two additional surface connections are possible as parts of proposed development projects.

The North End Access Improvements were originally proposed and recommended in 1975 when the New York Metropolitan Transportation Authority issued the Grand Central Terminal Improvements Technical Study (2). In that study, the need, feasibility, and desirability of the improvements were established. For a variety of reasons--primarily the lack of funding--the North End Access Improvements were not advanced beyond the 1975 feasibility study. In 1984 Metro-North contracted with Parsons Brinckerhoff Quade & Douglas, Inc., to prepare the necessary planning, architectural, and engineering analyses and documents to implement the proposed North End Access Improvements.

The work program for the North End Access Improvements project was undertaken in two phases. The first phase reexamined the 1975 concept in terms of need, effectiveness, costs and benefits, and implementability. These analyses provided Metro-North the information and materials it needed to gain approval and funding for the improvements. In the second phase, the architectural and engineering documents needed to implement the project are being prepared.

As part of the work program, a means of examining peak passenger loads in the proposed pedestrian facilities was needed. Because the proposed facilities are to be built within the confines of existing structures while maintaining peak-period train capacity, the sizes and configurations of new elements, and therefore their capacities, are physically constrained. Therefore, the key to the design process was to determine the performance and adequacy of the various elements of the North End Access Improvements--corridors, vertical circulation, and waiting areas--given their physical and operational constraints. The expected peak volumes within portions of proposed facilities were to be compared to the available capacities at a design standard level of service.

No existing pedestrian flow simulation computer program was found to fulfill the requirements of the study scope and design process, particularly one that would meet the project's tight budget and schedule. Therefore, the study team decided to develop a passenger flow simulation model geared specifically to the needs of this study, based on readily available personal computer hardware and

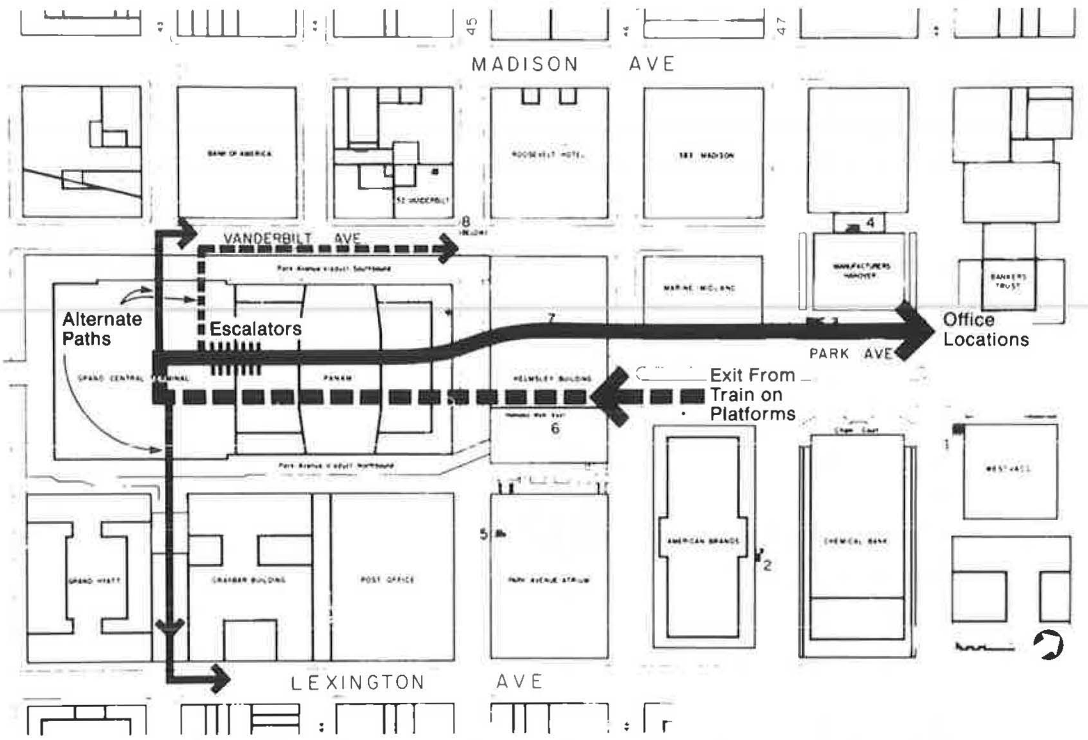


FIGURE 3 Path of typical Metro-North commuter from midpoint of platform to northward destination.

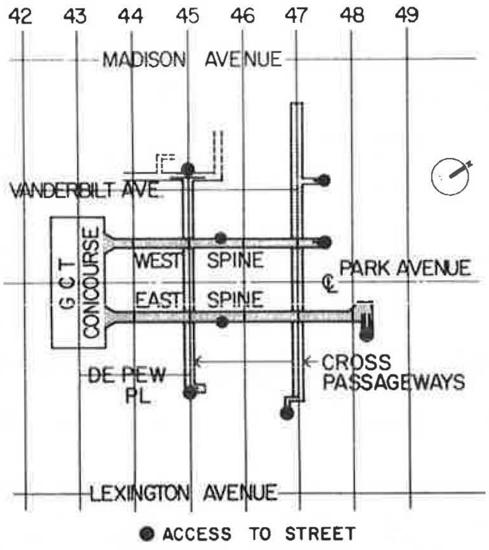


FIGURE 4 North End Access concept.

software. The program operates on an IBM PC using the LOTUS 1-2-3 spreadsheet program. This program is a simplified model that traces its origin to the UMTA Transit Station Simulation (USS) model (3).

MODEL DESCRIPTION

The basic components of the pedestrian flow simulation model are network definition, trip generation, trip distribution, trip assignment, assessment of congestion levels, and sensitivity analysis (see Figure 5). Each component is discussed in the paragraphs that follow.

Network Definition

The first step in the process is to define a pedestrian network in terms of links, nodes, sources, and sinks, as shown in Figure 6. Each link represents a portion of a pedestrian path such as a corridor or stair. The proposed Grand Central Terminal Improvement network is modeled by 44 links. Each node represents either a point of intersection between links or a "source" or "sink." A source node defines a place where people enter the network system; a sink node is where they leave the system. The network has 12 source nodes and 13 sink nodes.

In the model, the primary sources of pedestrians are the train platforms where Metro-North riders leave their trains and begin walking toward their destinations. Grand Central Terminal actually contains 13 lower level platforms and 15 upper level platforms, but for modeling purposes, groups of adjacent platforms were aggregated, forming five source nodes on each level. Two additional sources represent entrances where pedestrians enter the system from the street or adjacent subway stations by way of the main concourse of the terminal.

There are 13 sinks or exits by which pedestrians can leave the North End Access pedestrian system. Ten of the exits are new ones created by the project (including the two potential connections with new development projects), and three represent existing exits through the main concourse itself.

Trip Generation

The number of pedestrians arriving at each source was estimated from train arrival schedules and passenger loadings for a typical Metro-North weekday. Using Lotus 1-2-3 as a database manager, train movements for an entire day were entered onto a spreadsheet. The database contains for each train information about train arrival time, platform and track

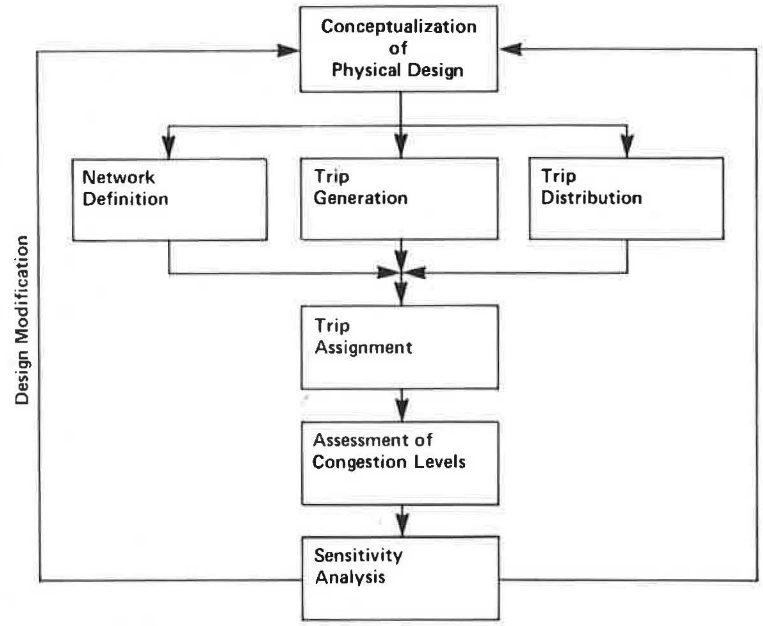


FIGURE 5 Pedestrian flow simulation methodology.

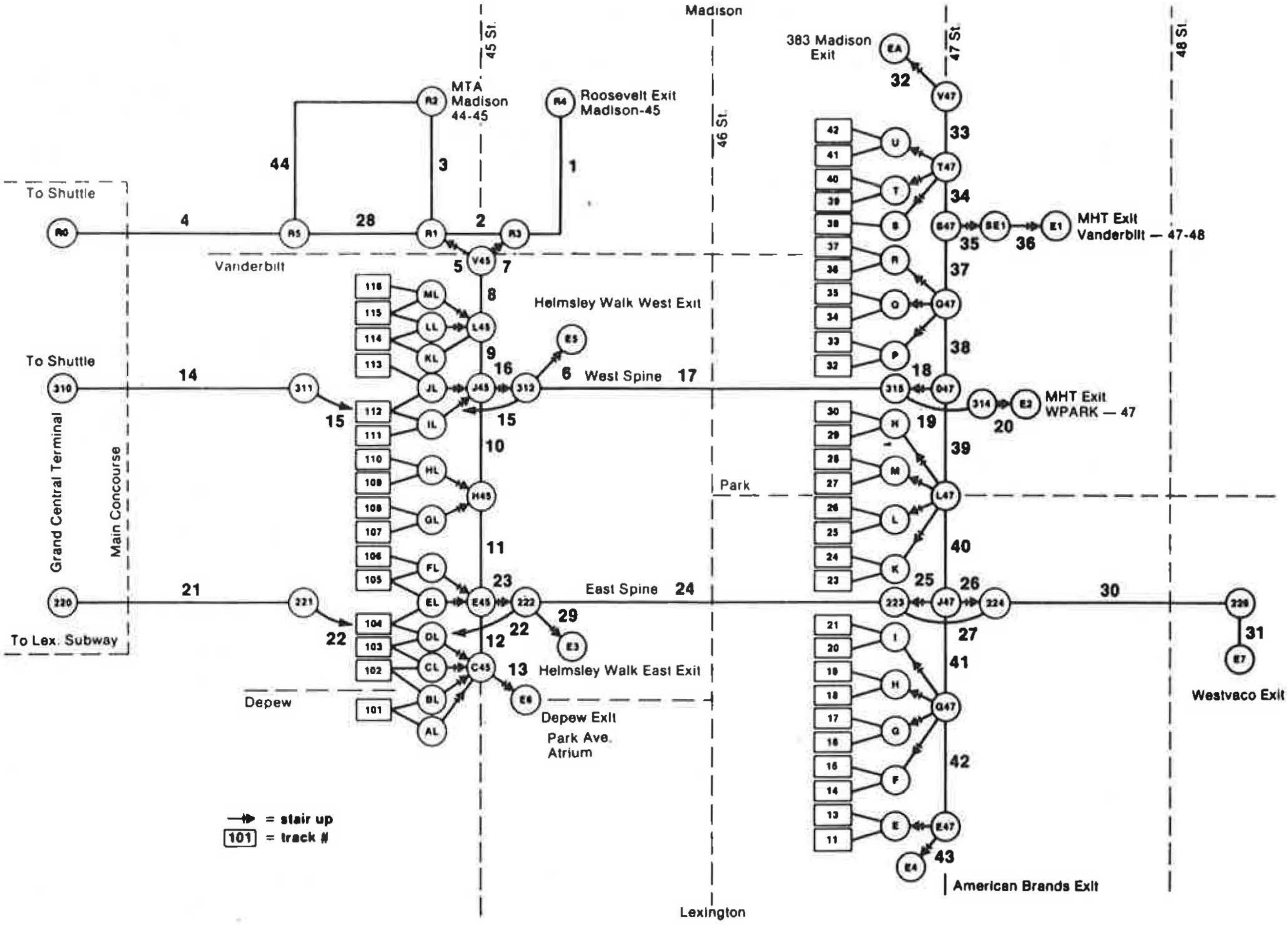


FIGURE 6 Schematic Plan of North End Access flow network shows upper and lower level tracks (sources), passageways (links), transfer points (nodes), and exits (sinks).

location, the number of cars, the typical number of passengers, and the branch of the rail network where the train picked up passengers.

The database of arriving trains was sorted by time of arrival and track location. For each 15-min period of the day the number of arriving passengers was aggregated in order to find the peak 15-min and 1-hr periods in the morning and afternoon. Once the peak time periods were chosen, the passenger arrivals were aggregated by platform groupings making up each source in the network. Trip generation for future years was accomplished by applying various demographic growth rates representing growth in rail ridership and in Manhattan employment.

In addition to peak direction Metro-North commuters, three other groups of potential users of the proposed system were included in the simulation model:

- "Reverse" direction Metro-North commuters.
- Non-Metro-North users walking in a north-to-south direction.
- Non-Metro-North users walking in a south-to-north direction.

Trip Distribution

For the purposes of the pedestrian flow simulation model, Manhattan was divided into 24 geographic zones surrounding Grand Central Terminal. The arriving train passengers were distributed to these destination zones according to a passenger origin-destination survey completed for this project.

The distribution of passengers walking to each zone was calculated by multiplying the number of arriving passengers headed for each zone by the percentage of passengers walking to that zone. The percentage walking was also determined from the ridership survey. Trip distribution for future years was determined by applying employment growth factors that were specific to each geographic zone of Manhattan.

Once the passengers were distributed into the geographic zones, they were distributed to North End Access exits. Passengers headed for each zone were assigned the exit offering the most direct walking path to that zone. Statistical analysis of the Metro-North ridership origin-destination survey shows that on the current Grand Central Terminal pedestrian facilities, virtually all morning peak riders use the exit that provides the shortest path to their ultimate destination. Currently, these commuters walk through the exit best oriented toward their destinations. It was assumed, then, that given new North End Access facilities, riders would choose the new exit that is along the shortest path.

Trip Assignment

The trip assignment was undertaken in two steps--the determination of a probable path for each source-to-exit pair, and the assignment of a number of pedestrians to the probable paths. For each source-to-exit pair, a shortest path through the network passageways was assigned, based on survey results that showed that commuters overwhelmingly choose the most direct path to their destinations. The path assignments were completed manually by inspecting the network, and they took into account distance and ease of passage. Many paths require walking up or down stairs to get to another level. When there was a choice between two paths of roughly equal distance, but one path required traversing more flights of stairs, the path with fewer level changes was chosen. In no case did the chosen path involve more than two level changes. The path was coded into the simulation program as a probability that trips between a source and exit would use a particular link.

A table of probable paths was coded for each of the 13 exits. In order to simplify the coding process and to visualize the paths more clearly, one network diagram was drawn for each exit. Each diagram highlighted all the links that a pedestrian would walk through to reach that exit from each of the 12 sources (train platforms). In cases where two or more paths were equally desirable, the pedestrians were assigned proportionally to those paths.

The pedestrian assignment model was completed using the Lotus 1-2-3 spreadsheet. The entire network was represented on the spreadsheet in tabular form with 44 rows representing links and 12 columns representing sources. One such table, or base assignment matrix, was set up for each of the 13 exits (see Figure 7).

The network tables were used to represent the probable pedestrian paths to each exit. Using the probable path diagrams created above as a guide, the tables were filled in with ones and zeros; a 1.0 in a spreadsheet cell represents a link traveled on the probable path for the source-exit pair, and a zero represents an untraveled link. In cases in which there were two equally likely paths, a factor of 0.5 was used for each of the two links involved.

The second step of the trip assignment is to assign a number of pedestrians to the probable paths. Pedestrians are assigned to the links by multiplying the base assignment matrices by two factors--the number of pedestrians coming from each source, and the percentage of all pedestrians headed for each exit. This matrix multiplication process results in one table for each of the 13 exits. Each exit table contains link volumes headed toward that exit, with 44 rows of links and 12 columns of sources. These 13 tables were summed together cell by cell, according to the rules of matrix addition, which resulted in one table of link volumes for all exits. The resulting link volumes for the various morning and afternoon period simulation scenarios were plotted on diagrams of the proposed facilities. An example is shown in Figure 8.

Assessment of Congestion Levels

The pedestrian assignment model simulated pedestrian flow volumes on each link. The volumes were for 15-min and 1-hr intervals, depending on whether 15-min or 1-hr source volumes were used in the assignment process. Pedestrian level of service (LOS) guidelines were used to determine the carrying capacity of each link at LOS C (4). The ratio of volume-to-capacity (V/C) on each link is used as a measure of congestion. The V/C ratios are calculated by the model for both 15-min and 1 hr intervals. The resulting V/C levels were then used to determine the ability of particular North End Access facilities to handle the expected peak pedestrian volumes at LOS C. A V/C of 1.0 indicates that during the period simulated, the links operated at full capacity at level of service C-D. A ratio greater than 1.0 means that the level of service degrades below the design standard, possibly resulting in some delays or queuing, which may be acceptable if they are of short duration. A V/C of less than 1.0 means that the facility is functioning at a level of service better than C-D and has capacity available for additional flow volume.

Figure 9 shows an example of the simulation program summary table output that provides information on each link: (a) facility type and characteristics, (b) capacity, (c) flow volumes, and (d) V/C.

Matrix describing paths through links from a given origin (source) to a given destination (exit).
1 signifies that the link is on the Origin - Destination pair

EXIT NODE #EA (383 Madison)

Source ID

Source Number (Platform letter, Platform group, and Source number)

Link ID #	Location	Nodes A to B	E E47 1	FGHI G47 2	KLMN L47 3	PQR Q47 4	STU T47 5	ABCDE C45 6	EF E45 7	GH H45 8	IJ J45 9	JKL L45 10	Lex Sbwy 220 11	Shuttle Subway 310 12	
1	Roos Pas	R4 -R3													1
2	Roos Pas	R3 -R1													2
3	Roos Pas	R1 -R2													3
4	Roos Pas	R0 -R5													4
5	Stair to Pas	R1-V45													5
6	Helmsley Wlk.W	E5 -312													6
7	45 Xpass	R3-V45													7
8	45 Xpass	V45-L45													8
9	45 Xpass	L45-J45										1			9
10	45 Xpass	J45-H45						0.5	0.5	1					10
11	45 Xpass	H45-E45						0.5	0.5						11
12	45 Xpass	E45-C45						1							12
13	Depew Str	C45-E6													13
14	Spine 31 GCT	310-311												1	14
15	Spine 31	311-312												1	15
16	SpineStr-45Xp	J45-312						0.5	0.5	1	1	1			16
17	Spine 31	312-313						0.5	0.5	1	1	1		1	17
18	SpineStr-47Xp	313-047						0.5	0.5	1	1	1		1	18
19	Spine 31	313-314													19
20	MfrHan Str-Park	314-E2													20
21	Spine 22 GCT	220-221											1		21
22	Spine 22	221-222											1		22
23	Str to 45Xpas	E45-222						0.5	0.5						23
24	Spine 22	222-223						0.5	0.5				1		24
25	Str to 47Xpas	223-J47						0.5	0.5				1		25
26	Str to 47Xpas	J47-224													26
27	Spine 22	223-224													27
28	Roos Pas	R1-R5													28
29	Helmsley Wlk.E	222-E3													29
30	Spine 22	224-226													30
31	Westvaco Stair	226-E7													31
32	383 Madison	EA -V47	1	1	1	1	1	1	1	1	1	1	1	1	32
33	47 XPassage	V47-T47	1	1	1	1	1	1	1	1	1	1	1	1	33
34	47 XPassage	T47-S47	1	1	1	1		1	1	1	1	1	1	1	34
35	MfrHan Pass	S47-SE1													35
36	MfrHan-Vand Str	SE1-E1													36
37	47 XPassage	S47-Q47	1	1	1	1		1	1	1	1	1	1	1	37
38	47 XPassage	Q47-047	1	1	1			1	1	1	1	1	1	1	38
39	47 XPassage	047-L47	1	1	1			0.5	0.5				1		39
40	47 XPassage	L47-J47	1	1				0.5	0.5				1		40
41	47 XPassage	J47-G47	1	1											41
42	47 XPassage	G47-E47	1												42
43	AmerBrand Stair	E47-E4													43
44	Roos Pas	R5-R2													44

FIGURE 7 Base assignment matrix.

Sensitivity Analysis

The simulation model was used repeatedly for sensitivity analyses. "What if" testing was performed to examine the effects on V/C ratios of eliminating or adding links, sources, and exits. This was done by changing the factors in particular rows and columns of the spreadsheet. For instance, if a link was to be removed from the network, the network diagram was inspected to determine if any probable paths would change as a result of the elimination. The base assignment matrices of probabilities (ones and zeros) were then modified to reflect the new probable paths. The rest of the analysis process was then repeated. It was also easy to examine the effects of building narrower passageways or of increasing demographic growth factors by changing the appropriate cell values.

ROLE IN DESIGN PROCESS

The simulation model results were used to evaluate the adequacy of the proposed facility to handle the anticipated flow volumes at several stages of the design process. In the planning concept stage, the overall system was tested and found to work well. Several components were found to require additional capacity. Among these components were certain vertical circulation areas where the available corridor width is divided between stairs and/or escalators and corridor space. During the definitive design phase, the widths of several stairs and corridors within the total width available were adjusted to balance the relative capacities with the flow volumes. Escalators were added or removed. As detail design and engineering of the North End Access Improvements proceeded, several modifications were

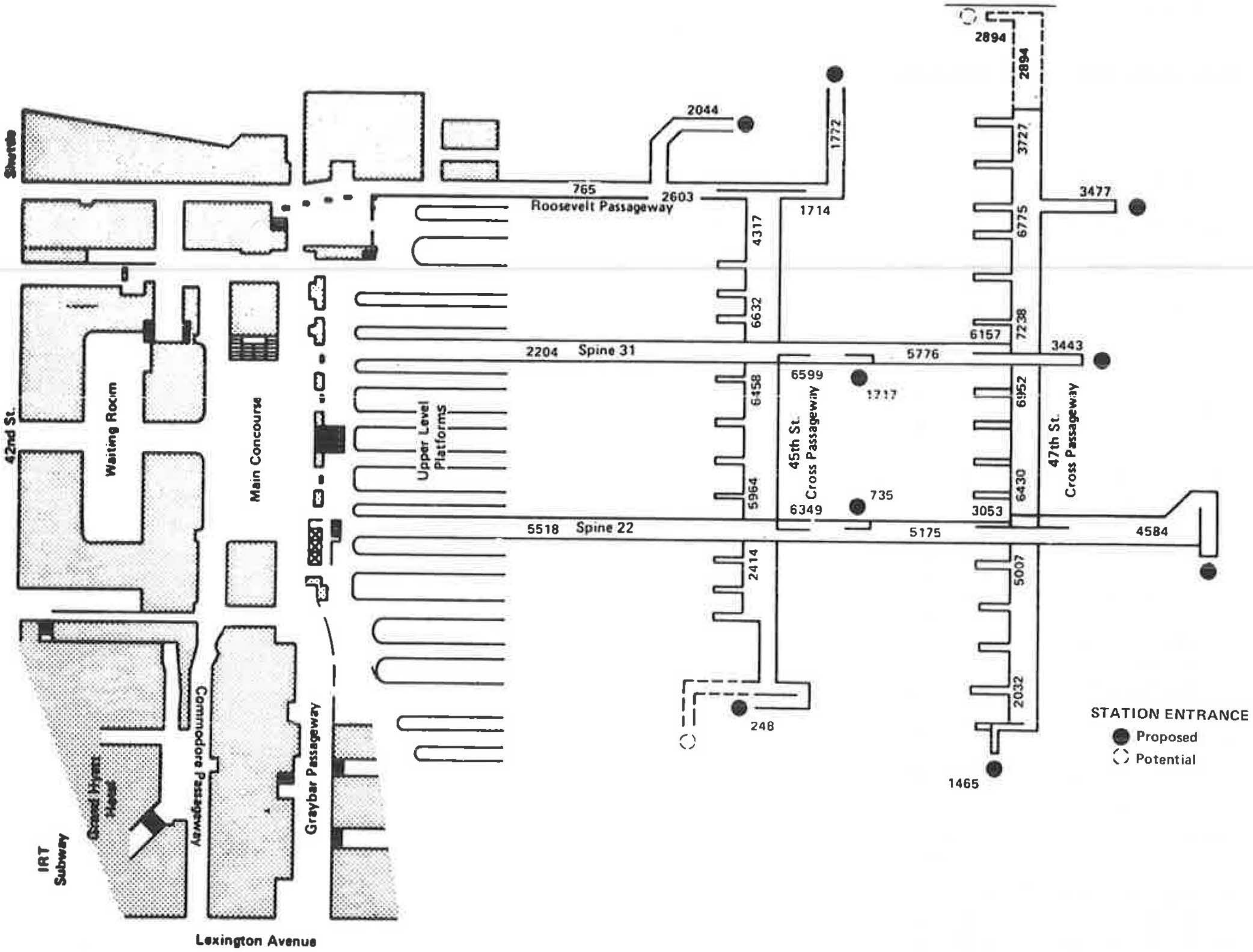


FIGURE 8 Pedestrian flow volumes through North End Access passageways and exits in the year 2000, 8:00 to 9:00 a.m.

required by structural or operational constraints, and the changes were tested using the simulation model.

Phasing plans were developed in the event that the total capital funds required to build the entire project suddenly do not become available. More than a dozen different options were simulated to test their ability to handle the anticipated pedestrian volumes in future years. Several options proved to be unworkable based on the results of the passenger flow program and were eliminated from consideration.

CONCLUSION

The approach to analyzing pedestrian flows for Grand Central Terminal North End Access was to take a rather sophisticated pedestrian flow model framework and simplify it. The simplified model provided a means for evaluating and comparing many alternatives within a tight budget and schedule that precluded the use of a more detailed simulation model approach. As such, the microcomputer model was shown to be quite flexible and applicable to a variety of pedestrian planning and design problems. It is easy to use and is relatively portable because of its reliance on Lotus 1-2-3 or similar common spreadsheet packages.

In the design process, therefore, the model was used as an evaluation tool, functioning in a "what if..." mode. Analysts could vary the input train schedule and aggregate passenger volumes, the network (by inserting and removing links and exits), and the capacities of network elements.

In the Grand Central project, the new access passageways had to be shoehorned into a very tight existing infrastructure between beams and columns carrying streets above while maintaining clearance for trains below. Consequently, the ability to evaluate the impact of dimensional changes on the capacity of the pedestrian system was of prime importance. The flexibility and ease of use of the program allowed it to be used as schemes were being developed and as design constraints were being discovered. For example, 12 variations of construction phasing were analyzed. The model thus became a key element in the design process.

The simplified approach of this model has several disadvantages when compared to a more sophisticated model, such as the UMTA Transit Station Simulation (USS) program. First, the stochastic element of the real-time simulation is not available. The simplified model is purely deterministic, allowing no random flow variations that would be expected in real life. Second, the paths are determined manually. Although the manual path assignment process probably requires less time for a simple network than coding for use by a computer algorithm, it would be cumbersome for a large network. Nevertheless, in spite of these shortcomings, the PC-based flow simulation

Link ID #	Location	Loc Node A-B	Total Vol 1 Hour Peak	Nominal Width (feet)	Effective Width (feet)	Length (feet)	Facility Type	Total Vol 15 Min. Peak	Capacity 15 Min.	Vol/Cap	
1	Roos Pas	R4 -R3	1777	10	8		S	553	1200	0.46	1
2	Roos Pas	R3 -R1	62	7	5		C	13	1125	0.01	2
3	Roos Pas	R1 -R2	1022	12	10		S	318	1500	0.21	3
4	Roos Pas	R0 -R5	765	13	11		C	222	2475	0.09	4
5	Stair to Pas	R1-V45	2603	6	5		S	816	750	1.09	5
6	Helmsley Wlk.W	E5 -312	1717	1/6	1/5		E/S	540	2250	0.24	6
7	45 Xpass	R3-V45	1714	4	1		E	540	1500	0.36	7
8	45 Xpass	V45-L45	4317	34	30	90	C	1356	6750	0.20	8
9	45 Xpass	L45-J45	6632	34	30	60	C	1980	6750	0.29	9
10	45 Xpass	J45-H45	6458	34	30	95	C	1568	6750	0.23	10
11	45 Xpass	H45-E45	5964	34	30	95	C	1484	6750	0.22	11
12	45 Xpass	E45-C45	2414	34	30	70	C	233	6750	0.03	12
13	Depew Str	C45-E6	748	8	7		S	233	1050	0.22	13
14	Spine 31 GCT	310-311	2204	27'6"	20	430	C	698	4500	0.16	14
15	Spine 31	311-312	2410	13	8	95	C	793	1800	0.44	15
16	SpineStr-45Xp	J45-312	6599	1/6	1/5		S	1966	2250	0.87	16
17	Spine 31	312-313	5776	27'6"	20	360	C	1717	4500	0.38	17
18	SpineStr-47Xp	313-047	6157	10	9		S	2026	1350	1.50	18
19	Spine 31	313-314	3443	10'6"	9		C	1077	2025	0.53	19
20	MfrHan Str-Park	314-E2	3443	1/6	1/5		E/S	1077	2250	0.48	20
21	Spine 22 GCT	220-221	5518	28	19	430	C	1312	4275	0.31	21
22	Spine 22	221-222	5518	10	6	95	C	1312	1350	0.97	22
23	Str to 45Xpas	E45-222	6349	1/6	1/5		S	1592	2250	0.71	23
24	Spine 22	222-223	5175	28	19	350	C	1222	4275	0.29	24
25	Str to 47Xpas	223-J47	3053	11	10		S	739	1500	0.49	25
26	Str to 47Xpas	J47-224	2463	11	10		S	941	1500	0.63	26
27	Spine 22	223-224	2121	10	9		C	483	2025	0.24	27
28	Roos Pas	R1-R5	1715	9	7		C	526	1575	0.33	28
29	Helmsley Wlk.E	222-E3	735	6	5		S	231	750	0.31	29
30	Spine 22	224-226	4584	15'6"	14		C	1425	3150	0.45	30
31	Westvaoo Stair	226-E7	4584	1/1/6	1/1/5		E/E/S	1425	3750	0.38	31
32	383 Madison	EA -V47	2894	1/8	1/7		E/S	896	2250	0.40	32
33	47 XPassage	V47-T47	2894	28'8"	25	45	C	896	5625	0.16	33
34	47 XPassage	T47-S47	3727	28'8"	25	60	C	1438	5625	0.26	34
35	MfrHan Pass	S47-SE1	3447	11'8"	10		S	1066	1500	0.71	35
36	MfrHan-Vand Str	SE1-E1	3447	1/5'8"	1/5		E/S	1066	2250	0.47	36
37	47 XPassage	S47-Q47	6775	28'8"	25	70	C	2244	5625	0.40	37
38	47 XPassage	Q47-047	7238	28'8"	25	70	C	2425	5625	0.43	38
39	47 XPassage	047-L47	6952	28'8"	25	95	C	2332	5625	0.41	39
40	47 XPassage	L47-J47	6430	28'8"	24	95	C	2075	5400	0.38	40
41	47 XPassage	J47-G47	5007	28'8"	25	100	C	1555	5625	0.28	41
42	47 XPassage	G47-E47	2032	28'8"	25	65	C	454	5625	0.08	42
43	AmerBrand Stair	E47-E4	1465	5'4"	5		S	454	750	0.61	43
44	Roos Pas	R5-R2	1022	9	7		R	318	1215	0.26	44

FIGURE 9 Spreadsheet showing pedestrian flow volumes through North End Access passageways and exits in the year 2000, 8:00 to 9:00 a.m.

model produced good results in a short time and fulfilled the needs of the designers.

On balance, the model documented here provided many of the advantages of more sophisticated pedestrian simulation models while offering added flexibility of analysis, simplicity of spreadsheet programming, and quick response associated with personal computing. It is expected that the software and methodology described here will be refined and used on further projects.

REFERENCES

1. Parsons Brinckerhoff Quade & Douglas, Inc. Grand Central Terminal North End Access Improvements Concept Report. Metro North Commuter Railroad Company, New York, 1985.
2. Harry Weese and Associates. Grand Central Terminal Improvements Technical Study. Metropolitan Transportation Authority, New York, 1975.
3. J. Lutin and G. Benz. USS Reference Manual. UMTA, U.S. Department of Transportation, 1978.
4. J. Fruin. Pedestrian Planning and Design. Metropolitan Association of Urban Designers and Environmental Planners, New York, 1971.

Application of the Time-Space Concept to a Transportation Terminal Waiting and Circulation Area

GREGORY P. BENZ

ABSTRACT

Demonstrated in this paper is the application of the time-space concept to the analysis of pedestrian activities in the waiting and circulation area of a transportation terminal. It is intended to show how this approach can address situations and problems not adequately handled by the use of other methods. The time-space concept is described first. It is a new procedure for analyzing pedestrian activities (especially those associated with transportation facilities and dense urban centers) in which the following factors are taken into account: (a) the total amount of space required for the various activities of people within an area, (b) the amount of time they require that space, (c) the amount of available space, and (d) the amount of time that space is available. Following the discussion of the time-space concept, a case study is presented to demonstrate some of its capabilities and features. The problem is analyzed first by using the traditional flow rate approach and second by using the new time-space method. Finally, the two analyses are compared and the situations in which the new approach would be advantageous are pointed out.

The time-space concept is a new approach to analyzing and evaluating facilities for handling pedestrian activities, especially those associated with transportation terminals, transit stations, and dense urban centers. The time-space concept, first introduced as a method for examining sidewalk corners and crosswalks (1-2), can be applied to any facility where pedestrian activities--walking, waiting or queuing, and processing--occur. This approach can address many situations and problems that cannot be adequately addressed using other methods.

Basically, the time-space concept considers the total amount of space required by the people involved in various activities within an area, and the amount of time that they require that space. At the same time, it considers the amount of space available for these activities and the amount of time that the space is available.

Demonstrated in this paper is the application of the time-space concept to the analysis of pedestrian activities within a proposed facility for a transportation terminal. The time-space concept is described first. Then, a case study is presented that demonstrates some of the capabilities and features of the time-space concept. The same problem is analyzed using the more traditional flow rate technique and the two approaches are compared.

PEDESTRIAN PLANNING AND DESIGN FUNDAMENTALS

Most of the material presented here is based on three sources (2-4). It is readily recognized that people

---

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

require certain and varying amounts of space for different activities and that the amount of space available affects a person's performance and comfort level. A person waiting on a platform requires a minimum of 7 ft^2 of space, but prefers and needs approximately 10 to 13 ft^2 to remain comfortable for any length of time. About 25 ft^2 of space per person is the threshold of "free flow," where someone can walk as fast as desired with reduced chances of interference from or conflict with other pedestrians. As the area per person decreases, the chance of conflicts with other pedestrians increases and the speed at which the person can walk is reduced. When the area per person decreases to 7 ft^2, walk speeds are typically reduced to 140 to 150 ft/min, about one-half the free-flow norm.

This relationship between walk speed and space per person has been demonstrated by Fruin (3) and others (4) who established the relationships of area per person to walking speed and flow volume (passengers per minute per foot width). (See Figures 1 and 2.) Level-of-service standards were defined, ranging

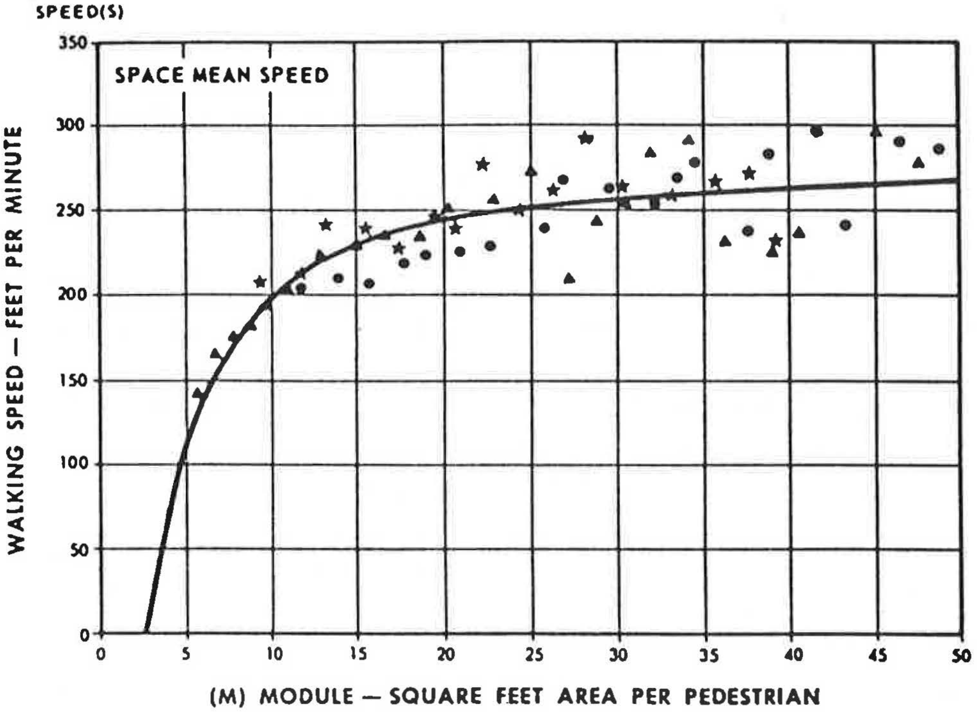


FIGURE 1 Relationship between pedestrian speed and space.

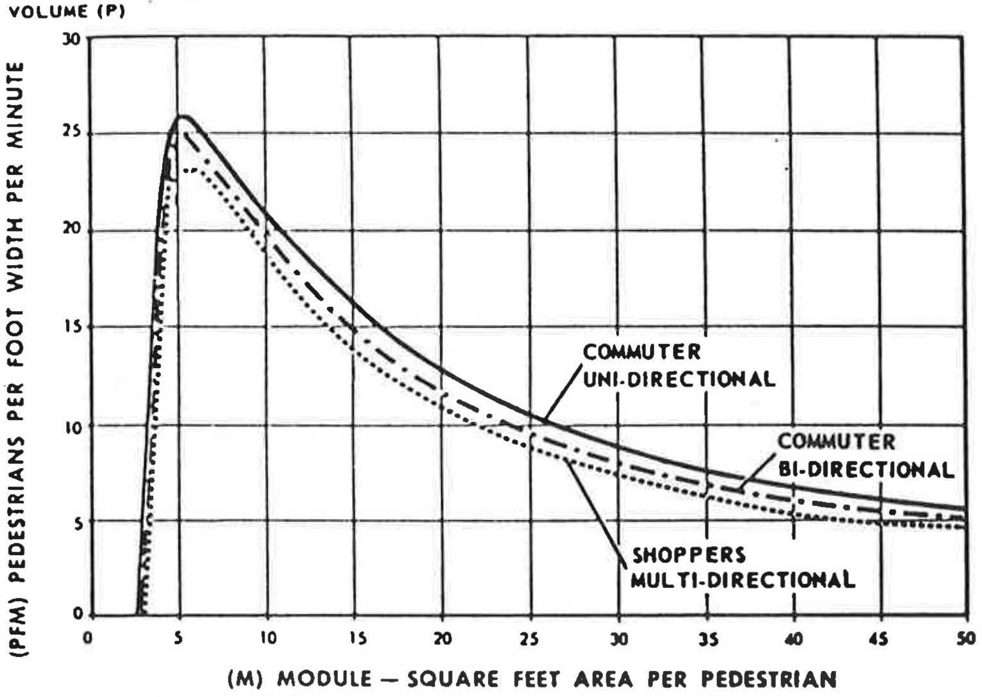


FIGURE 2 Relationship between pedestrian flow and space.

TABLE 1 Pedestrian Level of Service on Walkways: Average Flow Conditions *(5)*

Level of Service	Space[a] (sq ft/pedestrian)	Average Unit Width Flow Rate[a,b] (pedestrian/min/ft)	Average Speed[c] (ft/min)	Volume/Capacity Ratio[d]
A	Over 40	Under 6	Over 250	Under 0.24
B	24-40	10-6	240-250	0.24-0.40
C	16-24	14-10	224-240	0.40-0.56
D	11-16	18-14	198-224	0.56-0.72
E	6-11	25-18	150-198	0.72-1.00
F	Under 6	0-25	0-150	Variable

[a] These space per person and flow rates from Transportation Research Circular 212 vary slightly from those originally presented by Fruin *(2)*. Fruin's standards were developed for commuter facilities, while those above were developed for sidewalks, corners and crosswalks; however, both are similar in concept.

[b] Flow ratesare relative to effective walkway widths.

[c] Speeds are computed from equation: Speed = Flow x Space.

[d] Assumed Capacity = 24 pedestrian/min/ft.

from A (best) to F (worst), on the basis of these relationships and on the relative probability of conflicts among pedestrians, comfort levels, and the ability of a person to walk at a desired speed along his path of choice. Each level of service is defined as a range of space per person values and flow rates (pedestrians per minute per foot width, or PMF), as shown in Table 1.

Fruin developed similar level-of-service standards for stairways and for queuing (waiting) areas (3). The queuing standards (Table 2) provide a range of areas per person and average interpersonal spacing (distance between people). The space that people require depends somewhat on the type of queue--ordered or linear and random or batch type--and the duration of time the person is in the queue. For instance, people crowding onto an elevator will tolerate close contact with strangers and accept 2 to 3 ft^2 of space per person (which is level of service E) because the expected duration of the condition is relatively short. However, on train platforms and similar waiting areas where passengers wait for a relatively long time, as much as 10 to 15 min, people will require 10 to 13 ft^2 of space per person.

These level-of-service standards, primarily based on the space needs of people involved in various activities, are widely used today for planning and design of facilities for pedestrians. Most often, however, these norms are applied to either average or peak volumes of people who will use the space over a given time period. The duration of the peak load condition or the amount of time that people will require the space is usually not considered. This disregard of the duration factor can lead to overdesign of the facility which, in the case of underground or elevated facilities, can waste capital funds.

In addition, the walking standards are generally valid only for linear flow, such as along a corridor. In areas with multidirectional flow or those with other activities occurring at the same time, such as a waiting area or the intersection of several corridors, the flow rate method of analysis is not valid.

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. Time-space is the product of an area (or space) and a time period (1). For instance, a pedestrian walking through a waiting room may require up to 24 ft^2 for movement, but will occupy that space for only a relatively short period of time, such as 10 sec. This would be 240 ft^2-sec or 4 ft^2-min. A pedestrian who is 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 who are involved in each. The amounts of time-space required for each activity are summed and compared to the time-space available or proposed within the facility.

TABLE 2 Pedestrian Level of Service on Stairways *(3)*

Level of Service	Space (sq ft/pedestrian)	Average Unit Width Flow Rate[a] (pedestrian/min/ft)	Description
A	20 or more	5 or less	Sufficient area is provided to freely select stair locomotion speed, to bypass slow pedestrians, and to easily permit reverse flows.
B	15-20	5-7	Virtually all persons may freely select stair locomotion speeds, but some difficulties would be experienced passing slower pedestrians; reverse flows present no serious conflict.
C	10-15	7-10	Stair locomotion speed would be restricted slightly due to inability to pass slower pedestrians; no serious conflicts with reverse flows.
D	7-10	10-13	Stair locomotion speeds would be restricted for the majority of persons due to the inability to pass slower pedestrians; reverse flows would encounter some conflicts.
E	4-7	13-17	Normal stair locomotion speeds reduced because of minimum tread length space and inability to bypass others; intermittent stoppages may occur; reverse flows experience serious conflicts.
F	4 or less	Variable to 17	Representative of complete breakdown in traffic flow with many stoppages.

[a] Flow rates are relative to effective walkway width.

Mathematically, the time-space concept can be described as

$$T\text{-}S_{req} = \sum P_i M_i T_i$$

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 compared to the time-space available ($T\text{-}S_{avail}$) to compare 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

$$T\text{-}S_{avail} = A_{avail} \times T_{avail}$$

Application of the Time-Space Concept

When the time-space concept is applied to solving a problem, any of the factors or elements defining the activities or spaces involved can be considered the unknown variable that is to be determined from the other known variables. For example, the time-space approach can first determine the amount of time-space required by waiting or queuing pedestrians. When this time-space for queuing activities is subtracted from the total time-space available, the remaining time-space available can be used for circulation (walking). The total time required by the walking pedestrian can be determined by estimating the average walk time per person through the space (which is a function of walk speed and distance) and multiplying it by the number of people walking through the space. Dividing the total time-space available for circulation by the total required walk time produces an area (square feet) per person that can then be compared to the pedestrian level of service criteria. This procedure, used in the study that follows, can be expressed as follows:

$$\text{Total } T\text{-}S_{avail} - \text{Queue } T\text{-}S_{req} = \text{Circ } T\text{-}S_{avail}$$

where

$T\text{-}S_{avail}$ = time space available,
Queue $T\text{-}S_{req}$ = queuing time-space required, and
Circ $T\text{-}S_{avail}$ = circulation time-space available.

and

$$\text{Circ } T\text{-}S_{avail} = \text{Circ S Per Person}_{avail} / \text{Circ } T_{req}$$

where

Circ $T\text{-}S_{avail}$ = circulation time-space available,
Circ T_{req} = circulation time required, and
Circ S Per Person_{avail} = circulation space per person available.

The case study that follows serves as an illustration of an application of the time-space concept to the analysis of spaces that handle high levels of pedestrian flow and a large number of waiting pedestrians. The case study is a rather simple application of time-space, but a variation is introduced later to demonstrate some of the other analytical capabilities of the time-space concept.

CASE STUDY DESCRIPTION

The case study involves a new passenger facility, referred to as a cross passageway, that will provide access to and from the ends of platforms of a busy commuter rail terminal that currently has access at one end only. The cross passageway is essentially a wide corridor that will run perpendicular to and above the platforms, with stairs connecting the cross passageway to each platform. The cross passageway is connected to the surface at several points. (See Figure 3.)

The cross passageway is to serve as a corridor for circulating passengers as well as a queuing area for passengers waiting for the opening of gates that provide access to the platforms from which their trains will depart. Passengers will assemble in the portions of the passageway adjacent to the gates. Surveys showed that passengers departing on trains typically start to gather in front of a gate about 23 min before the train's scheduled departure time and assemble at the following rates:

Time Before Departure (Minutes) 20 15 10 5 1

Departing Passengers (Percent Gathered) 9 26 53 86 100 (gates closed)

The maximum accumulation of passengers outside the gate to the train platform occurs just before the opening of the gate--typically 10 min before train departure when 53 percent of the passengers leaving on the train are present. The accumulation of waiting passengers, if large enough, can easily affect the cross passageway width available to handle longitudinal flow. The problem here is to examine whether the corridor can meet the space requirements of both queuing passengers and circulating passengers, at the design standard level of service, within a portion of the cross passageway adjacent to a departure gate. The analysis period is the 1 min before the opening of the gate when the maximum accumulation of waiting passengers will occur.

In this case study the 140-ft long portion of the cross passageway to be examined has an effective width of 25 ft (i.e., the width actually available for passenger activities: the wall-to-wall dimension minus the width occupied by obstructions and columns and the boundary or "cushion" maintained by pedestrians along walls). During the 1 min before the opening of the departure gate, 194 people will be waiting in the cross passageway. The flow rate of people walking along the corridor during this time will be 167 people per min.

With a design criterion of level of service C, the space per waiting person is 10 ft^2. This classification reflects the unordered (random) nature of the queue in this space, the need for some circulation and movement within the queue, and the comfort level expected by commuter rail passengers.

FLOW-RATE ANALYSIS APPROACH

This problem can be analyzed using the traditional flow-rate analysis method. This approach estimates the maximum number of people in the queue and the total amount of space they require. The 194 people waiting require 1,940 ft^2 (at 10 ft^2 per person). The shape of the queue has to be estimated in order to determine the portion of the 25-ft wide cross passageway the queue will occupy. In this case study, the waiting passengers, occupying 1,940 ft^2 and assumed to be evenly distributed along the 140-ft linear dimension of the space, are expected to require 14 ft at the widest point of the queue. This

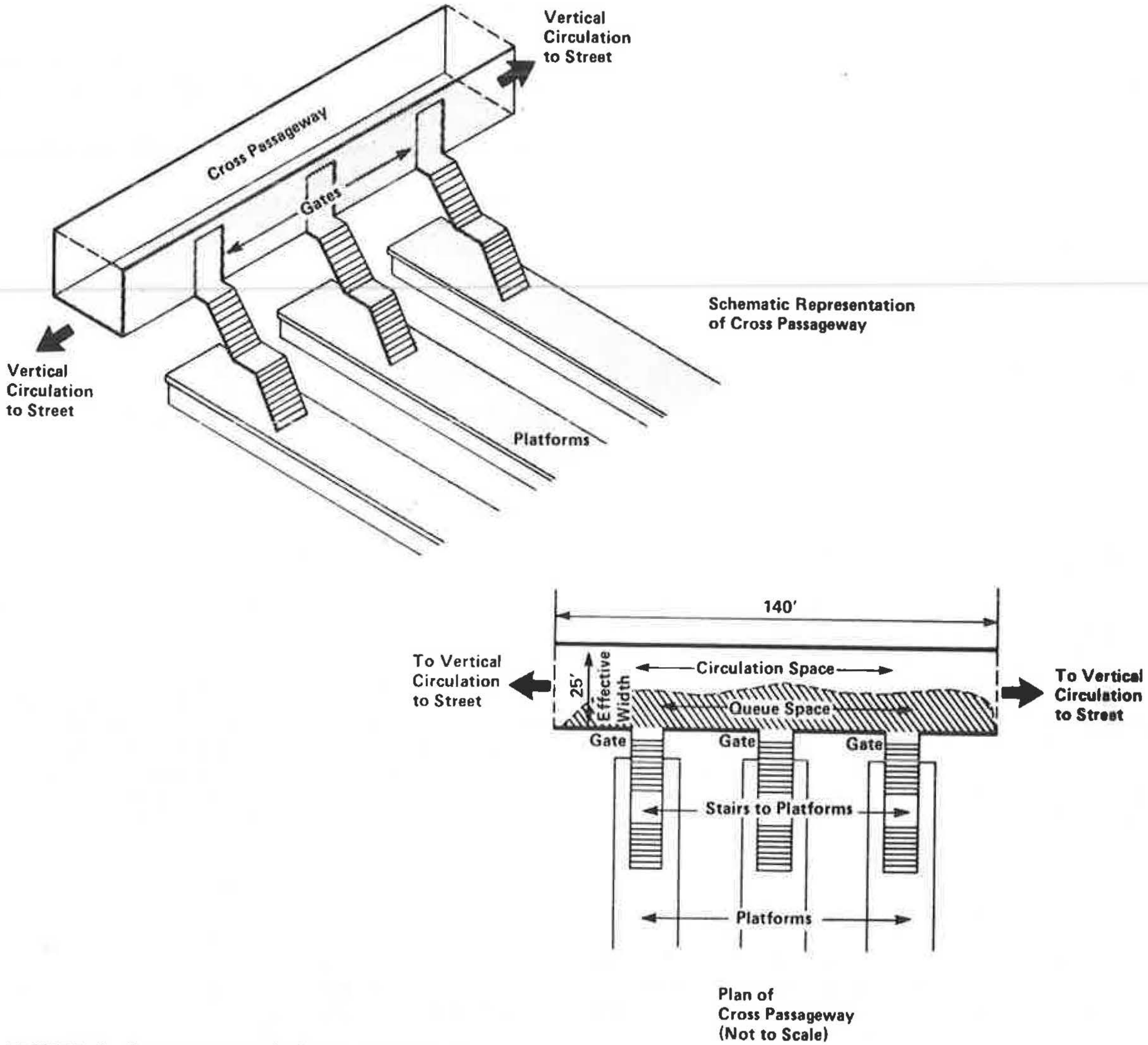


FIGURE 3 Commuter terminal cross passageway.

leaves 11 ft available for the flow of the 167 circulating passengers who would walk through the cross passageway during the 1 min peak queue period. The flow rate per minute per foot width of corridor available is 15.2. This rate equates to level of service C/D, using the flow-rate level-of-service standards, which means that the condition is at the 15 pedestrians per min per ft width (PMF) boundary between levels of service C and D.

TIME-SPACE APPROACH TO PROBLEM

The time-space approach to this problem is first to determine the amount of time-space available in this portion of the cross passageway. The time-space required by the waiting passengers is then deducted from the total time-space available. The remaining time-space is available for the circulating (walking) passengers. The total walk time spent in the area by the circulating passengers is determined, which, when divided into the time-space available for circulating passengers, gives the area per person for circulating passengers. This figure can then be equated to pedestrian level-of-service standards.

The cross passageway (140 ft long and 25 ft wide) has an area of 3,500 ft^2. Within the 1-min analysis period, the time-space available for all pedestrian activities in the cross passageway is 3,500 ft^2-min (3,500 ft^2 x 1 min), that is, 3,500 ft^2 are available for pedestrian activities for 1 min.

The 194 people waiting during the maximum 1-min peak period before the opening of the gate will require 10 ft^2 per person (which is equivalent to level of service C). This equals 1,940 ft^2-min required by the waiting passengers (194 people x 10 ft^2/person x 1 min). Subtracting this from the total time-space available in this cross passageway segment, leaves 1,560 ft^2-min available for circulating passengers (3,500 ft^2-min - 1,940 ft^2-min).

The 167 persons who will walk through the cross passageway during the 1-min period will require 0.62 min to traverse the space at a walk speed of 225 ft/min. Flow-rate analysis showed the flow rate in the corridor to be 15 pedestrians per min per ft width. Referring to Figures 1 and 2, this equates to a walk speed of 225 ft^2/min. The total walk time required by the 167 pedestrians is 104 person-minutes (167 people x 0.62 min).

The time-space available for these circulating pedestrians is 1,560 ft^2-min. The area per pedestrian is found by dividing the time-space available for circulation (1,560 ft^2-min) by the total time required by the circulating passengers (104 person-minutes). The result is 15.0 ft^2 per person. This area per person is then compared to the pedestrian level of service standards, which, for this example, is the border of level of service C and D. This is considered an acceptable level of service for the maximum peak condition.

The calculation steps are summarized as follows:

1. Total space available: Length x Width = 140 ft x 25 ft x 3,500 ft^2.
2. Total time-space available: Space available x Time period = 3,500 ft^2 x 1 min = 3,500 ft^2-min.
3. Total queuing time-space: Number of people in queue x Time in queue x Queue area per person = 194 people x 1 min x 10 ft^2/person = 1,940 ft^2-min.
4. Time-space available for circulation: Total time-space available - Total queue time-space = 3,500 ft^2-min - 1,940 ft^2-min = 1,560 ft^2-min.
5. Walk time per person: Walk distance ÷ Walk speed = 140 ft ÷ 225 ft/min = 0.62 min/person.
6. Total walk time: Number of people x Walk time per person = 167 people x 0.62 min/person = 104 min.
7. Area per person for walking: Total time-space available for circulation ÷ Total walk time = 1,560 ft^2-min ÷ 104 min = 15.0 ft^2/person, 150 ft^2/person → Level of Service C/D.

Refinement Step

An important feature of the time-space method is that it can be used to evaluate the impact of activities that cannot be quantified by other methods, as illustrated in the following example.

A significant number of passengers will need to stop momentarily or slow down to read the information screen to determine the platforms from which their trains will depart. This activity will consume a certain amount of time-space and the impact of this pausing on the cross passageway can be analyzed within the context of the initial case study.

Of the 167 persons who will walk through the cross passageway, an estimated 60 percent will stop or slow down to read the information screen. Each person will take an average of 3 sec to read the screen and will occupy about 5 ft^2 during that activity. Therefore, the time-space required for this activity is 25 ft^2-min (167 persons x 60 percent x 3 sec/person x 5 ft^2/person - 60 sec/min). This amount can be added to the time-space required by the pedestrians in the passageway segment. Of the 3,500 ft^2-min available in the cross passageway, the waiting pedestrians will require 1,940 ft^2-min while the time-space requirement of those stopping or slowing to read the information screens is 25 ft^2-min. The remaining time-space available for the circulating passengers is 1,535 ft^2-min. The total walk time is 104 person-minutes. Dividing this remaining time-space available by the walk time required results in an area per person of 14.8 ft^2 for walking that equates to a level of service C/D.

The refinement described earlier had only a marginal effect on the results. It demonstrates, however, the capability of the time-space concept to examine problems at different levels of detail and treat each of the activities in the space discretely. Different groups of people within the total population of users can be treated separately. For instance, the walk time-space requirements for people encumbered with luggage, or small children, or characteristics of the user population can be included in the time-space analysis.

COMPARISON OF ANALYTICAL TECHNIQUES

When the cross passageway segment was analyzed using both the time-space technique and the more conventional flow-rate method, the different approaches produced similar results. The time-space technique result was 15 ft^2 per person, which is on the boundary between levels of service C and D. The flow-rate method result was 15.2 PMF which, in a strict sense, is level of service D. Because the boundary between levels of service C and D is 15 PMF, this level of service is very close to level of service C.

Although both methods produce similar results, the advantage of the time-space technique is that it analyzes the entire space, not just the narrowest point of one dimension of the space. Furthermore, as observed here and as will be observed in the subsequent application studies, the time-space technique can account for pedestrian activities and behavior such as stopping to read the information screen, which is not readily addressed by available methods.

Although the flow-rate technique, as applied here, has the advantage of considering the amount of cross passageway width consumed by the waiting passengers and the amount of width available for circulation, the time-space technique can be applied in such a way as to take this factor into account. (In this example, the constricted corridor width affected the longitudinal walk speed, which was reflected in the walk time-space requirement.) Where such issues are of major concern, both techniques should be applied.

In a recently completed master thesis study at Carleton University, Grigoriadou (6) applied the time-space concept to a train platform and found that this concept can replicate observed and measured pedestrian level-of-service conditions. In addition, ongoing research by the author reveals that the time-space concept can model spaces (station mezzanines) in which a variety of activities take place, including multidirectional passenger flow. The time-space requirement for each walking, queuing, and processing activity is calculated separately, summed, and compared to the time-space available. Another study involved dividing a platform into several time-space zones, calculating the walking and waiting time-space requirement for each zone, and comparing the result to the time-space available in that zone. In this way, conditions in a specific part of the platform can be analyzed, instead of being treated in the aggregate, as traditionally done.

CONCLUSION

The time-space concept offers a means of analyzing pedestrian activity spaces that could not be adequately analyzed using other methods. Time-space, a new way of thinking about these facilities and how they are used, introduces the time dimension into the analysis by including the amount of time a space is required. The time-space approach is a new tool for planners and designers who must size and evaluate these spaces. Not necessarily a replacement for the existing techniques in all situations, the time-space approach is a superior method for many types of spaces that could not be analyzed before.

REFERENCES

1. J. Fruin and G. Benz. Pedestrian Time-Space Concept for Analyzing Corners and Crosswalks. In Transportation Research Record 959, TRB, National Research Council, Washington, D.C., 1984, pp. 18-24.
2. Proposed Chapters for 1985 Highway Capacity Manual--Addendum 1 to TRB Circular 281. In Transportation Research Circular 284. TRB, National Research Council, Washington, D.C., Oct. 1984.

3. J. Fruin. Pedestrian Planning and Design. Metropolitan Association of Urban Designers and Environmental Planners, New York, 1971.
4. B. Pushkarev and J. Zupan. Urban Spaces for Pedestrians. MIT Press, Cambridge, Mass., 1975.
5. Interim Materials on Highway Capacity. In Transportation Research Circular 212. TRB, National Research Council, Washington, D.C., Jan. 1980.
6. M. Grigoriadou. Analysis of Pedestrian Activity on Metro Station Platforms Using the Time-Space Technique. M.S. thesis, Carleton University, Ottawa, Ontario, Canada, 1985.

BART Patron Egress/Ingress Study: Use of Stairs and Escalators Between Platform and Concourse Levels

MATT du PLESSIS

ABSTRACT

The shorter headways planned for 1989-1990 and the increased patronage projected over the next 5 years caused concern about the capacities of the Bay Area Rapid Transit (BART) stations to handle exiting patron loads. A basic objective at BART has been that patrons from one train should be off the platform before the next train coming from the same direction arrives; that is, within the existing headway. To analyze the patron egress/ingress capacities of BART's stations, five parameters were considered: (a) the planned headways between trains, (b) the projected patronage at each station, (c) the availability of escalators, (d) the processing rates for the stairs and escalators, and (e) the number of patrons that can be expected to use the stairs. On the basis of these five parameters, a basic criterion was developed: The projected 95th percentile of peak patron loads during the exit rush 2 hours should be able to use the stairs and escalators to exit the platform within 2.25 min, even if one escalator is unavailable. Each station was analyzed under four conditions. The analysis revealed that nine stations would have problems in the 2.25-min time frame when one escalator is unavailable. Each of the nine stations was evaluated in detail, and preliminary recommendations were made for the number of escalators or stairs to add to the stations. To facilitate a decision on constructing an escalator or stairwell at each station, cost estimates should be obtained and considered in light of the indicated severity of potential egress/ingress problems.

The Bay Area Rapid Transit District (BART) will be experiencing significant changes by 1990. The new C-cars will be added to the fleet of revenue vehicles, and the Daly City extension track will have been constructed. At the same time, BART staff are planning to reduce headways between trains to 2.25 min in 1989, and patronage is projected to increase by 40 to 45 percent in the next 5 years. A critical issue for BART is the egress/ingress capacity of the stations under these conditions. Is there enough escalator and stairway capacity to handle projected volumes of patrons?

The manager of station operations asked management services to conduct an analysis of the egress/ingress capacity of the stations to determine (a) which stations, if any, would not be able to handle the projected patronage increases within the shorter headways; and (b) the estimated number of escalators or stairways needed to handle the increased load.

The issue of additional faregates and other automatic fare collection (AFC) equipment was not considered a part of this study, but will be addressed by the AFC Study Committee.

Described in this paper is the analysis of the station egress/ingress capacities between the platform and concourse level only. The concourse-to-street-level capacities are not expected to be as critical as the platform-to-concourse capacities and were analyzed in a separate study.

The analysis described in this paper will demonstrate the method used to evaluate station egress/ingress capacities. The analysis was based on current patronage projections for 1989-1990. Based on this analysis, those stations that may have egress/ingress problems will be identified, and the number of escalators or stairwells recommended for adequate capacities under adverse conditions will be presented. The actual locations and cost estimates for installing escalators and stairs will be determined separately by design engineering staff.

To evaluate whether the escalator and stairway

ETM Consulting, P.O. Box 29906, Oakland, Calif. 94604.

capacity between the platform and concourse levels is adequate, five parameters must be considered:

1. Planned headways between trains,
2. Projected patronage at each station,
3. Availability of escalators,
4. Processing rates for the stairs and escalators, and
5. Number of patrons that can be expected to use the stairs.

PLANNED HEADWAYS

The BART District is planning to reduce the minimum scheduled headway between trains incrementally over the next 5 years. In early 1986 the minimum headway will be reduced from 3.75 min to 3.5 min. Further reductions will be made in each successive year until the headway is 2.25 min in 1989, if the necessary projects are completed on time. These minimum scheduled headways apply primarily to the downtown Oakland (K line) and San Francisco (M line) service. The headways on the suburban lines (R, C, and A lines) will be 4.5 min.

A basic objective is to have patrons off the platform before the next train arrives. Therefore, the time frames used to calculate each station's capacity were 2.25 min for the minimum headways for all lines and 2.25 or 4.5 min for the average headways, depending on the line. The consideration of the longer time frames provides a basis for determining the magnitude of the egress/ingress problem. However, the 2.25-min time period represents the desirable criterion for adequacy of capacity under minimum headways and for avoiding patron inconvenience in other cases. Also, the desire for equity on all lines favors using the 2.25-min criterion for the entire system.

PROJECTED PATRONAGE

The average weekday patronage for fiscal year 1988-1989 is projected to be 285,200, almost 40 percent greater than in 1983-1984. For individual stations the growth in exit-rush patronage during the commute periods varies from 3 to 25 percent. Twenty-four of BART's 34 stations have projected increases of less than 10 percent.

One important aspect of patron flow is that it fluctuates. High peaks are often followed by a low number of disembarking patrons. This fluctuation raises the issue of whether to design the system to handle the large peaks or to allow the patrons from the next train to encounter queues. For this analysis, the possibility of slight train delays causing a series of crowded trains led to a design criterion of having enough capacity to handle the 95th percentile of peak patron loads during the exit rush 2 hours. Thus, when the worst case occurs, patrons from the following train may encounter queues, but 95 percent of the time exiting patrons will have cleared the platform before the following train's arrival.

To determine the 95th percentile of peak patron loads in 1989-1990, current data were obtained for patrons alighting from trains and multiplied by the growth factors for each station--except for the downtown San Francisco stations. The heavily loaded trains from the East Bay are already at full capacity and have experienced little growth in recent years. However, the number of alighting patrons from West Bay trains was multipled by the station growth factors. The projected patronage figures are given in Table 1 for three of BART's five lines.

TABLE 1 Projected 95th Percentile of Peak Patron Loads During Exit Rush Two Hours in 1989-1990 by Station and Centroid

Station/Centroid		Projected Peak Patron Loads
C LINE		
Rockridge		140
Orinda		150
Lafayette		180
Walnut Creek		230
Pleasant Hill		320
Concord		500
K LINE		
12th Street	- N	40
	- C	100
	- S	30
19th Street	- N	170
	- C	90
	- S	40
MacArthur		160
M LINE		
Oakland West		90
Embarcadero	- E	340
	- W	440
Montgomery	- E	320
	- W	610
Powell	- E	60
	- W	220
Civic Center	- E	130
	- W	170
16th/Mission		90
24th/Mission		160
Glen Park		220
Balboa Park		200
Daly City		510

AVAILABILITY OF ESCALATORS

Of BART's 133 escalators, 81 of them connect the platform to the concourse level. The escalators can be out of service for one of three reasons: (a) preventive maintenance, (b) a malfunction, or (c) a major overhaul. Preventive maintenance is usually completed during the off-peak hours and therefore does not represent a major concern for this analysis. As for escalator overhauls, more than 80 escalators will be rehabilitated in the system during the next 3 years. The rehabilitation process should be completed before 1989, however.

The average availability of escalators at 6:00 a.m. on weekdays was as follows:

July	98.6 percent
August	95.6 percent
September	97.1 percent

According to Reliability Engineering staff, each escalator is available more than 95 percent of the time at 6:00 a.m. An analysis of the trouble incidents between July 1 and October 28 showed that the average amount of time an escalator is down is 5 hr and 15 min. The range was from 1/2 hr to 37 hr. Inoperative escalators are required by BART's safety department to be blocked off so that patrons cannot use them.

The important consideration is that an escalator that goes out of service during the commute period could lead to a major problem when headways are 2.25 min. Also, the stations that are more than two stories underground should have one escalator operating in the up direction at all times. This means that during one of the commute periods (evening, generally), one escalator will be unavailable to transport patrons down to the platform. Therefore, the condition of one escalator being unavailable is included as part of the analysis to ensure adequate capacity under adverse conditions and/or to allow for one escalator operating in the reverse direction.

PROCESSING RATES--STAIRS AND ESCALATORS

The processing rates for stairs and escalators depend on the direction patrons are going on the stairs (up or down) or on the speed at which the escalator is operating, the width of the stairs or escalators, and the existence of a queue. The rate for going up a set of stairs is less than the rate for going down and, naturally, the faster an escalator is operating, the more patrons it will transport--up to a safe maximum.

The width of the stairs or escalators determines the number of lanes of pedestrian traffic that can be accommodated. The standard design width for stairs is 30 in. between handrails for one person and 52 in. for two persons. The stairs in the BART stations have two basic widths: approximately 4 ft or approximately 6 ft. In either case the stairs were found to accommodate two lanes of traffic. The 6-ft wide stairs provide additional space between two patrons using the stairs side by side, but not enough space to provide a third lane. The absence of a handrail also deters the development of a third lane. Therefore, all platform stairs except those at the North Berkeley station are assumed to have two lanes for pedestrian traffic. The stairs at the North Berkeley station are only 3 1/2 ft wide and are presumed to accommodate only one lane each. The number of stairwell lanes per station-centroid and the flow rates per station-centroid are given in Table 2 for three lines.

The flow rates given in Table 2 were based on National Fire Protection Association Code 130 (1) and confirmed by field observations. The flow rates

TABLE 2 Number of Stairwell Lanes Per Station-Centroid and Associated Flow Rates

Station/Centroid	Number of Stairwell Lanes	Exit Flow Rates (Patrons/Minute)	Entering Flow Rates (Patrons/Minute)
C LINE			
Rockridge	6	240	210
Orinda	4	160	140
Lafayette	4	160	140
Walnut Creek	2	80	70
Pleasant Hill	2	80	70
Concord	2	80	70
K LINE			
12th Street - N	2	70	80
- C	2	70	80
- S	2	70	80
19th Street - N	2	70	80
- C	2	70	80
- S	2	70	80
MacArthur	4	160	140
M LINE			
Oakland West	2	80	70
Embarcadero - E	4	140	160
- W	4	140	160
Montgomery - E	2	70	80
- W	6	210	240
Powell - E	2	70	80
- W	6	210	240
Civic Center - E	2	70	80
- W	2	70	80
16th/Mission	4	140	160
24th/Mission	4	140	160
Glen Park	2	70	80
Balboa Park	4	140	160
Daly City	2	80	70

per lane are 35 patrons/min for ascent and 40 patrons/min for descent. Thus, a two-lane stairway in an elevated station would process 80 exiting patrons/min, whereas in an underground station it would only handle 70 exiting patrons/min. A critical supposition in these processing rates for stairs is that all patrons are going in one direction; that is, no reverse pedestrian flow exists. Patrons attempting to use the stairs in the opposite direction will reduce the flow rates. If the reverse traffic is frequent enough, the number of available lanes must be reduced by one. Generally, the reverse flow in BART stations is not heavy enough to cause problems during the commute periods. However, to provide a simplified and consistent calculation of a station's processing capacity, the lower patron flow rates for going up a stairwell were used for calculating the stairs' capacity.

In the case of the escalators, the two operating speeds used in the BART District lead to two processing rates for each of the different width escalators. A nominal 48-in. escalator operating at a speed of 90 ft/min (fpm) has a capacity of 85 to 100 patrons/min when a queue exists. At a speed of 120 ft/min the capacity with a queue is 100 to 135 patrons/min. A nominal 30-in. escalator has flow rates of 60 to 75 patrons/min for the 90 ft/min speed and 75 to 100 for the 120 ft/min speed. For design purposes, the lower value of a range should be used; that is, 85 patrons/min and 100 patrons/min for the 48-in. escalator. These flow rates have been found to be reasonable based on field observations. It should also be noted that patrons walking on moving escalators do not add to the capacity of the escalators. Because all platform escalators have a 48-in. width and operate at 120 ft/min, their processing rate is therefore 100 patrons/min.

PATRON USE OF STAIRS

Several factors affect patrons' decisions to use the stairs instead of the escalators. Normally, a small percentage of patrons will always use the stairs no matter what the situation is. These patrons consider the use of stairs a form of physical exercise to help keep themselves in shape. Many patrons, however, will only use the stairs if one or more of the following conditions exist:

- Stairs are closer than an escalator and are going down,
- A large queue has formed at the escalator,
- Stairs are not too long or steep,
- Stairs are not too crowded, and
- Escalator is out of service and an alternative escalator is too far away.

Even in stations that have additional centroids, patrons tend not to use the other end of the station if their usual escalator is out of service. These patrons will wait for long periods to use the secondary escalator at their end of the station.

BART stations can be grouped into three basic categories: (a) elevated stations, (b) underground stations in which the platform is less than 24 ft below the concourse, and (c) underground stations in which the platform is more than 24 ft below the concourse.

For each of these three types of stations, patron behavior and service criterion will differ. The 24-ft criterion is based on American Public Transit Association (APTA) design guidelines for escalators in rapid transit facilities: backup "up" escalators should be considered where vertical rise exceeds 24 ft.

Elevated stations cause the least concern for patrons exiting from the platform. Observations in the field found that 40 to 60 percent of patrons will use the conveyance that is closest, either the stairs or the escalator. Therefore, stairs in elevated stations are presumed to be used to full capacity. Fortunately, 20 of BART's 34 stations are of the elevated type.

Seven of the underground stations have platforms that are less than 24 ft below the concourse level. In these stations patrons tend to use the escalators more than the stairs, but are not resistant to climbing the stairs, especially if an escalator is out of service or is operating in the opposite direction. Therefore, as with the elevated stations, stairs in underground stations with platforms less than 24 ft below the concourse are presumed to be used to full capacity.

The seven underground stations that have platforms of more than 24 ft below the concourse are all located in downtown Oakland and San Francisco and are the ones that require close scrutiny. Although most patrons may be willing to climb stairs that are one or two stories, they are hesitant to climb stairs that are more than two stories. The general pattern at the downtown stations for the majority of disembarking patrons is to use the escalator until an extremely large queue develops. Then patrons divert to the stairs until a queue develops for the stairs. The queue for the stairs is never as large as the queue for the escalator and dissipates long before the escalator queue does. So the stairs at the downtown stations are never used to the degree the escalators are. Therefore, a reduced use of the stairs' capacity was employed in the analysis of the downtown stations.

After sampling at the Embarcadero and Montgomery stations during the morning commute period it was found that the average percentage of patrons using the stairs was almost 9 percent, with all the escalators working. When one of two escalators in proximity was out of service, the average percentage during the morning commute period increased to slightly more than 20 percent, although there were specific instances in which 25 to 28 percent of the patrons used the stairs. To achieve these kinds of usage rates, the stairs were presumed to be used at 25 percent of capacity when all escalators are operating and 50 percent of capacity when one escalator is out of service. This could also be interpreted to mean that stairs are used to full capacity for 25 or 50 percent of the time that patrons are moving from the platform to the concourse level, as was observed during the survey of stations. For the stations or centroids with one stairwell and two escalators, this equates to 8 percent of the patrons using the stairs when both escalators are operating and 26 percent of the patrons using the stairs when only one escalator is operating. For centroids with more than one stairwell, the percentages are higher.

The condition of stairs being used at full capacity when one escalator is out of service will also be included in the analysis to show the maximum capacities of the downtown stations. However, the only circumstance for which patrons could be expected to fully use the stairs would be for evacuation purposes.

ANALYSIS

On the basis of the foregoing discussion, the analysis of potential egress/ingress problems will incorporate the following suppositions:

- A 2.25-mi design egress time should be used as a desirable objective for station capacity between trains and to avoid patron inconvenience.
- The projected 95th percentile of peak patron loads should be processed by a station's escalators or stairs, or both.
- To ensure adequate capacity under adverse conditions or to allow for one escalator operating in the reverse direction, one escalator should be presumed unavailable.
- To provide a simplified method for estimating a station's processing capacity, the lower patron flow rates for stairs should be used and a processing rate of 100 patrons/min should be used for escalators.
- Stairs in elevated stations and underground stations with platforms less than 24 ft below the concourse will be fully utilized; stairwells in other underground stations will experience reduced usages of only 25 percent when all escalators are operating and 50 percent when one escalator is out of service.

With all available escalators presumed to be operating in the same direction, an indication of stations that may have egress/ingress problems from the platform to the concourse level can be obtained by analyzing the capacity of the stairways and escalators under four conditions:

1. Maximum 2.25-min capacity. The optimum capacity with all escalators working and with normal patron use of stairs.
2. Desirable criterion. The 2.25-min capacity with one escalator unavailable and with normal patron use of stairs.
3. Basic criterion. The capacity under planned headway times with one escalator unavailable and with normal patron use of stairs.
4. Maximum design/capacity. The capacity under planned headway times with one escalator unavailable and with patrons assumed to use stairs to maximum capacity.

The capacities for the four conditions are listed in Table 3 for three of BART's five lines. Those capacities that are less than the projected 95th percentile of peak patron loads during exit rush 2 hours in 1989-1990 (see Table 1) are enclosed in

TABLE 3 Patron Flow Capacities by Station-Centroid

	(1)	(2)	(3)	(4)
	All Working	One Escalator Unavailable		
	2.25 Minute Capacity		Planned Headway Capacity	
Station/Centroid	Normal Patron Use of Stairs			Full Use
C LINE				
Rockridge	700	470		
Orinda	540	315		
Lafayette	540	315		
Walnut Creek	380	$\boxed{160}$	315	315
Pleasant Hill	380	$\boxed{160}$	$\boxed{315}$	$\boxed{315}$
Concord	610	$\boxed{380}$	765	765
K LINE				
12th Street – N	490	300		
– C	490	300		
– S	490	300		
19th Street – N	490	300		
– C	490	300		
– S	490	300		
MacArthur	765	540		
M LINE				
Oakland West	380	160		
Embarcadero – E	530	380		
– W	530	$\boxed{380}$	$\boxed{380}$	540
Montgomery – E	490	$\boxed{300}$	$\boxed{300}$	380
– W	790	690		
Powell – E	490	300		
– W	790	690		
Civic Center – E	490	300		
– W	490	300		
16th/Mission	540	315		
24th/Mission	540	315		
Glen Park	490	300		
Balboa Park	540	315		
Daly City (Ptfm. 3)	$\boxed{380}$	$\boxed{160}$	$\boxed{160}$	$\boxed{160}$

☐ = Capacities that are less than the projected peak patron loads.

boxes. Nine stations throughout the whole BART system, six of which are given in Table 3, are indicated to have problems in the 2.25-min time frame when one escalator is unavailable. The problems range from occasional inconveniences to frequent bottlenecks. Each of the nine stations was evaluated in detail in the actual report. For this paper, only three of the stations are discussed in detail.

EMBARCADERO STATION

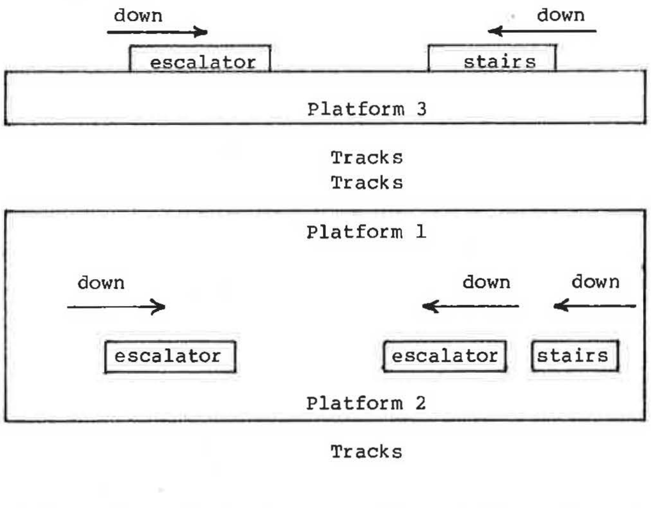
The Embarcadero underground station is one of the two busiest BART stations. The station's two centroids are mirror images, each having two escalators and two stairwells. During the morning commute, all the escalators are operated in the up direction to the concourse level.

The difficulty is that if one of the escalators goes out of service, queues could last longer than 2.25 min at the west centroid. Admittedly, increased use of the stairs by patrons could obviate the need for an additional escalator as shown by the lack of a box around the capacity in the last column of Table 3. Patron use would have to increase to almost one-half, however, when one escalator is out of service. As previously indicated, patrons are hesitant to climb the long stairs at the downtown stations, and only about one-fourth of the patrons can be expected to use the stairs. Furthermore, Embarcadero station experiences patron peaks of 1,000 or more. In those situations, and with one escalator unavailable, 60 percent of the patrons at the west centroid would have to use the stairs to avoid delays.

Patron's resistance to climbing the long stairs and the large peaks experienced by this station make it critical to have adequate capacities even when one escalator is out of service or unavailable. Therefore, a third escalator should be added to the west centroid. This backup escalator would again serve as a reverse flow escalator when all escalators are working.

DALY CITY STATION

The Daly City elevated station is the third busiest in the BART system. It has only one centroid, but it has two platforms with stairs and escalators distributed as shown below:



Currently, all trains use either platforms 1 or 2 at Daly City. Platform 3 is only used if trains are occupying both tracks at platforms 1 and 2 or some other problem exists. The plan for routing trains once the extension track is complete is to unload all patrons at platform 3, go into the extension area, and then return to the station to board patrons on platforms 1 or 2.

To handle the 95th percentile of patronage within the 2.25-min headway and with one escalator unavailable, platform 3 would need three stairways total, two more than it presently has. Extra capacity for the worst case patron loads could be achieved by adding two escalators instead of stairs. Otherwise, it may be necessary to devise an alternative plan for routing trains into the Daly City station when crowds develop on platform 3.

Another possible means of clearing platform 3 is to build a bridge from the platform to the parking structure across the street. This bridge could have faregates for exiting only and no addfares or vendors. Patrons would have to go down to the concourse level to use addfares or vendors. The installation of faregates on the platform level, however, could lead to fare evasion and equipment problems that would require having an agent on the platform. As for platforms 1 and 2, the two escalators and one stairwell would be adequate for the expected patron flow for boarding patrons even if one escalator were out of service.

PLEASANT HILL STATION

The Pleasant Hill station is elevated and is representative of most of the suburban stations in the BART system. It has the fifth largest projected peak patronage. Because of the parking problem at the Concord station, many patrons use the Pleasant Hill station as their embarkation point. This station also experiences peak patron loads that are almost as large as the ones at Concord.

The station has two platforms, each with one escalator and one set of stairs, that lead down to a common set of faregates. As is indicated by the boxed capacity figures in Table 3, patrons at this station would encounter queues if the escalator were unavailable. Even allowing for the greater headway time, the one stairwell at Pleasant Hill will not adequately handle the 95th percentile of peak patron loads, much less the larger peaks that can occur. But as indicated previously, the 2.25-min time frame should be the desirable criterion for evaluating the need for additional stairs or escalators in the case of alighting patrons. For the boarding situation in the morning commute, the longer headway time could be used. However, even with that allowance the Pleasant Hill station will have ingress problems if the one escalator goes out of service. Therefore, the need to install an escalator or stairwell at both platforms at the Pleasant Hill station should be given serious consideration.

Similar to the Concord station, Pleasant Hill is experiencing tremendous office development near the station. The potential increase in reverse patron flow at commute time increases the need for adding escalators or stairwells to both platforms.

CONCLUSIONS

On the basis of projected patronages for 1989-1990, BART will have nine stations that do not meet the following desirable criterion: the 95th percentile of projected peak patron loads should be able to use the stairs and escalators to exit the platform within 2.25 min, even if one escalator is unavailable.

The Daly City station will have the most critical problem because all trains will unload patrons at platform 3 only. Pleasant Hill is expected to have serious problems for both the morning and evening commute periods, should the one escalator at each platform be out of service. The Embarcadero and Montgomery Street stations will have problems because of patron resistance to climbing the long stairs at these stations. The Concord, El Cerrito Del Norte, Walnut Creek, Union City, and Hayward stations could use an additional escalator or stairwell. However, with their current configurations, the longer headway times at these five stations would allow patrons to exit the platform before the next train arrives.

The recommendations for additional escalators or stairwells are as follows:

Station	Escalator or Stairwell Location
Daly City	Two at platform 3
Pleasant Hill	One at each platform
Embarcadero	One at the west centroid
Montgomery	One at the west centroid
Concord	One for its single platform
El Cerrito Del Norte	One at the east platform
Walnut Creek	One at the east platform
Union City	One at the west platform
Hayward	One at the west platform

To facilitate a decision on constructing an escalator or stairwell at each station, cost estimates should be obtained and considered in light of the indicated severity of potential egress/ingress problems.

A Microcomputer-Based Fare Collection Dependability Model

DAVID I. HEIMANN

ABSTRACT

With the increasing sophistication of fare collection structures and consequently of fare collection equipment, equipment reliability and cost are becoming increasingly important issues. Techniques have been developed to analyze the interrelationships among reliability, cost, and the ability of a fare collection system to deliver dependable service to passengers. These techniques, based on mainframe computers and an investigation of the steady-state performance of the system, evaluate the performance of a given system, analyze its sensitivity to changes, determine specifications necessary for a given level of performance, and make trade-offs between system parameters. Microcomputers are becoming progressively more powerful, inexpensive, and readily available. So that the analysis techniques can be used more easily by transit personnel and analysts, a fare collection dependability model has been developed to run in a user-interactive microcomputer environment. The model determines the likelihood of equipment failures affecting system operation during a peak period. If equipment failures cause insufficient capacity to adequately process passenger demand, the fare collection system is defined as "in trouble." The likelihood of trouble is called the "trouble rate," whereas the likelihood of adequate capacity is called "peak period dependability." The technical approach for the performance and cost aspects of the model is discussed, both the probabilistic basis and the computational methodology to minimize execution time. The software to enable the user to interactively operate the model is described, and instructions are provided for its use. A sample fare collection dependability analysis session, consisting of four runs, is also provided.

The collection of transit system fares has been receiving increased attention as fares rise and federal operating subsidies decrease. Transit authorities are becoming more concerned about ways to maximize revenue and minimize costs while providing equitable fare and reliable, convenient service for passengers. Fare collection methods have a significant impact on total transit costs, amount of revenue generated, and passenger service (1,2). Fare collection costs range from 7 to 31 percent of passenger revenue at rail transit systems, and revenues generated from fares can vary from 40 to 90 percent of total transit

---

U.S. Department of Transportation, Transportation Systems Center, Kendall Square, Cambridge, Mass. 02142.

costs (3). Fare collection systems must therefore be selected only after careful examination of their cost, revenue, and service effects.

New fare collection concepts such as automated collection, barrier-free service, or credit-card use offer potential for reducing costs by minimizing the need for personnel to perform cumbersome, repetitive functions. However, the newer and more complex a piece of equipment, the more likely it is to have frequent failures, which can lead to significant passenger delay, lower throughput capacity, and general frustration (4-6). In improving this reliability, it should be known just how much of a reliability increase is required, as the extent of a reliability increase effort makes a significant difference in its cost and likelihood of success.

Because of the significant cost of fare collection equipment, the number and cost of equipment units to acquire for a given station also are quite important. Too many units can increase total system cost considerably, whereas too few will not be able to handle peak-period passenger demand, leading to significant passenger congestion and delay problems. One must be able to assess total system costs, and thus control them by determining and comparing the costs, as well as passenger performance, for various candidate system specifications.

To help carry out the aforementioned processes, the author developed and described an analysis technique and accompanying computer software (7). The analysis technique treats the fare collection system as a queue (or network of queues), the number of servers of which varies as equipment units fail and are then repaired. The computer software is interactive and runs on a mainframe computer in a time-sharing environment. The analysis technique obtains, for a specified fare collection system, average frequency distributions and mean values for passenger congestion and delay, as well as annualized costs. This allows a transit decision maker to evaluate a proposed system, evaluate the effects of possible changes in an existing or proposed system, or to determine the specifications necessary for a certain level of performance or cost.

One of the comments and feedback received on the software was that it should be able to run on microcomputers. Microcomputers have become inexpensive, readily available, and reasonably powerful (many of them reach or exceed the capabilities once represented by the IBM 360). With microcomputer software, more transit systems, individual transit staff members, consultants, analysts, and planners could make use of the fare collection system analysis technique.

An apparent drawback to implementing the software on a microcomputer was that the program took a significant amount of time to run even on a mainframe computer. It appeared that the time and space requirements on a microcomputer would be prohibitive. However, a situation that first arose as a problem became instead a key to formulating a microcomputer model.

The situation is that frequently transit systems do not carry out repairs of failed equipment during the peak period. High equipment reliability or spare equipment capacity is used instead to have available enough functional units for the peak-period passenger demand. Under this approach, measuring average steady-state performance over a long term is not very meaningful, because once the capacity of the system falls below the passenger demand as a result of equipment failures, the system cannot recover for the remainder of the peak period. A meaningful performance measure instead is the likelihood of the system running into trouble in this fashion during the peak period or, conversely, the likelihood of the system not encountering significant passenger delay during the peak period.

As it turns out, this trouble rate, or, conversely, the peak-period dependability, can be calculated using a simple probability algorithm that requires a low mainframe computation time (less than 1 sec). Because of the low time requirement, the algorithm can be reasonably converted to a microcomputer environment.

Described in this report are the preceding algorithm, its implementation on a microcomputer, and its use for fare collection dependability analysis. Like the mainframe-based techniques (7), the microcomputer-based analysis technique is interactive and designed to help transit systems make more effective investment decisions in selecting fare collection methods, systems, and equipment to best fit their needs. It is also designed to help them minimize costs and provide equitable and convenient service to passengers.

TECHNICAL APPROACH

The interactive microcomputer fare collection dependability model evaluates the likelihood that during a specified length of time, such as a peak period, the number of equipment units available for use falls because of failures below the minimum number necessary to handle the passenger demand. If this happens, it is assumed that the fare collection service area will not be able to recover without significant passenger delay and is hence (by definition) in trouble. The likelihood that the area gets in trouble is thus the trouble rate, while the likelihood of the reverse, that the system does not get in trouble, is called the peak-period dependability. A trouble rate of 10 percent, which corresponds to a peak-period dependability of 90 percent, for example, means that on the average trouble will occur in 1 out of every 10 time periods. If the time period is a peak period, with two peak periods a day, 5 days a week, this means that trouble will occur during the peak period on an average of once a week.

The trouble rate and peak-period dependability are thus measures of overall system dependability, that is, the likelihood that a system will deliver its intended level of service to its users. They combine into one-term assurance measures, such as equipment reliability and maintainability, and level-of-service measures such as passenger arrival rate at the station, equipment passenger-processing rate, and number of equipment units. By doing so, they provide a top-level assessment of fare collection system performance to passengers at a station.

As mentioned previously, the model is especially suitable for situations in which no on-line repair is carried out during the time period under consideration or, nearly equivalently, where the on-line repair time (including the time for repair personnel to reach the site) is approximately equal to the time period itself. In either case, the fare collection service area will not be able to recover during the time period under consideration, once its capacity to process passengers becomes, because of failures, insufficient to handle passenger arrivals. Passenger congestion and delay will therefore continue to increase during the entire remainder of the time period, leading to the necessity to open emergency gates or other such remedial actions, passenger aggravation, staff aggravation, and, in short, trouble.

In situations in which fast on-line repair is indeed carried out, the model tends to overestimate the impact of failures because it is then possible to recover from an undercapacity situation. Nonetheless it provides a useful conservative estimate (an upper bound) of failure impact.

•

TECHNICAL APPROACH FOR PERFORMANCE MEASURES

The trouble-rate approach to the dependability analysis of a fare collection system is based on the field of probability theory, in particular the time to absorption of a Markov chain (8). The fare collection system can be described as being in one of a number of states, depending on how many equipment units are available for service relative to the minimum number necessary to adequately serve the passenger demand (see Figure 1). In state 0, not enough equipment units are available for service; thus the passenger demand is greater than system capacity and the system is in trouble. In state 1, enough units are available to handle passenger demand, but a loss of even one unit would cause trouble. In state 2, one unit could be lost from service without causing trouble; in state 3, two units could be lost, and so forth. In the maximal state, NMAX, all units are available for service. NMAX is given by N - INT(ARR/SERV), where N is the number of units in the fare collection system, ARR the passenger demand (arrival rate), SERV the rate at which a unit processes passengers, and INT(X) the largest integer less than or equal to X. Note that INT(ARR/SERV) is one fewer than the minimum number of units necessary for adequate service.

If the state of the fare collection system decreases to the trouble state 0 at any point during the peak period, the system gets into trouble and stays in state 0 for the rest of the period (state 0 is thus an absorbing state). The probability that this occurs is determined as a function of the number of passengers n who have arrived during the peak period. Let $P_0(n)$ denote this probability, with $P_i(n)$ being the probability that the system is in state i after n passengers have arrived, i = 0,1,...,NMAX (these probabilities are called the state probabilities). Let the equipment reliability be MCBF, the maintainability MTTR, and the passenger arrival rate ARR. The probability of a transition from state i to the next lower state i-1 because of a failure is then the failure rate F = 1/MCBF, while the probability of a transition from state i (other than 0) to the next higher state i+1 because of a repair is the repair rate R_i = (NMAX-i)/(MTTR*ARR). Note that $R_{NMAX} = 0$, so that the state of the system cannot go above the maximum state NMAX. The system has no failed units at the start of the peak period (n = 0), so that it is in state NMAX. Therefore, $P_{NMAX}(0) = 1$, with $P_i(0) = 0$ otherwise (for i ≠ NMAX). The state probabilities of the system are then given by the following recursive equations:

$$P_0(n+1) = P_1(n)*F + P_0(n) \qquad (1)$$

$$P_1(n+1) = P_2(n)*F + P_1(n)*[1-(F+R_1)] \qquad (2)$$

$$P_i(n+1) = P_{i+1}(n)*F + P_{i-1}(n)*R_{i-1} + P_i(n)*[1-(F+R_i)] \quad 2 \leq i \leq NMAX \qquad (3)$$

In words, Equation 3 states that the system will be in state i after n+1 passengers have arrived [i.e., $P_i(n+1)$] if it either was in state i+1 after n passengers have arrived [i.e., $P_{i+1}(n)$] and a failure then occurs (F), or it was in state i-1 after n passengers have arrived [$P_{i-1}(n)$] and a repair then occurs (R_{i-1}); or it was in state i after n passengers have arrived [$P_i(n)$] and neither a failure nor a repair then occur [$1-(F+R_i)$]. Similar word descriptions fit Equations 1 and 2. Notice that the multiplier of $P_0(n)$ in Equation 1 is 1. This puts into equation form the absorption property mentioned previously; that is, if the system is in the trouble state 0 after n passengers have arrived, it will remain in that state after n+1 passengers have arrived, and it therefore will remain so for the rest of the peak period.

Equations 1-3 can be expressed in condensed form as

$$P(n+1) = T*P(n) \qquad (4)$$

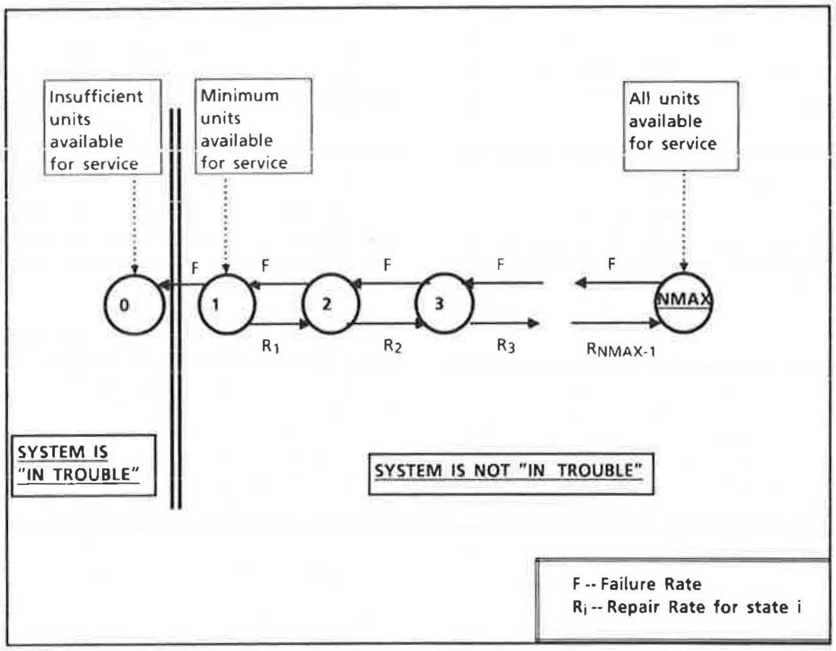


FIGURE 1 Reliability flow graph of fare collection system.

where $P(n)$ is the vector $[P_0(n), P_1(n), \ldots, P_{NMAX}(n)]$ and T is the matrix (T_{ij}), where

$T_{00} = 1$

$T_{i,i-1} = F, \; i>0$

$T_{i,i+1} = R_i, \; i>0$

$T_{i,i} = 1-(F+R_i), \; i>0$

T_{ij} represents the probability that if the fare collection system is in state i after the arrival of any particular passenger, it will be in state j after the arrival of the next passenger. Because these probabilities describe the transition of the system from one passenger to the next, T is called the transition matrix.

The trouble rate of the fare collection system is given by $P_0(n)$, that is, the probability that the fare collection system is in state 0 and so in trouble after n passengers have arrived. The peak-period dependability is given by $1-P_0(n)$.

Computing the Performance Measures

The preceding approach for peak-period performance yields dependability as a function of the number of passengers processed. Because the peak-period length is based on elapsed time, the performance needs to be similarly expressed as a function of time. Let time be denoted by t, with t expressed in increments of 10 min up to a maximum peak period length of 120 min (the discussion can be easily generalized to increments of length dt up to a maximum peak-period length of $T_{max} = Mdt$). Let $Q_i(t)$ be the probability that the fare collection system is in state i at time t, so that $Q_0(t)$ is the time-based trouble rate (the probability that the system gets into trouble during a peak period of length t). Let $Q(t)$ be the vector $[Q_0(t), Q_1(t), \ldots, Q_{NMAX}(t)]$. Then recursive equations for $Q(t)$ can be established in a manner similar to those for $P(n)$ (Equations 1-4) as

$$Q(t+10) = T^{PASS} * Q(t) \qquad (5)$$

$$Q(0) = P(0) \qquad (6)$$

where PASS is the number of passengers arriving in 10 min. PASS at first glance would appear to be ARR/6 (where ARR is the hourly passenger arrival rate). However, ARR/6 is not necessarily an integer. To determine the proper integer values of PASS over the various 10-min intervals in Equation 5, the following algorithm was used:

1. Let NUM = INT(ARR/6) and ID = MOD(ARR,6), where MOD(n,m) is the integer remainder when n is divided by m. Let t = 0, ID1 = ID, INDEX = 1, and $Q(0) = P(0)$.
2. If INDEX = 1, compute $Q(t+10) = T^{NUM} * Q(t)$. Otherwise, compute $Q(t+10) = T^{NUM+1} * Q(t)$.
3. Add 10 to t. If $t \geq 120$, then go to Step 5. Otherwise, continue to Step 4.
4. Add ID to ID1. If $ID1 \geq 6$, then subtract 6 from ID1 and set INDEX = 2. Otherwise, set INDEX = 1. Go to Step 2.
5. The trouble rate for time t (i.e., the probability that the fare collection system will run into trouble sometime during a peak period of time t) is given by $Q_0(t)$.

To compute the matrices T^{NUM} and T^{NUM+1} used in Step 2 is not a routine task. Because the hourly passenger arrival rate ARR can be in the thousands, the value NUM≈ARR/6 can be quite large. To calculate these matrices, the following acceleration algorithm (which requires no more than $2\log_2 NUM + 1$ matrix multiplications, as against the NUM matrix multiplications required by the direct approach is used):

1. Let k = 0, $T_0 = T$, and U = I (where I is the identity matrix, i.e., $A*I = I*A = A$ for any properly sized matrix A).
2. Convert the integer NUM into its binary representation $(b_K b_{K-1} \ldots b_0)$, where $b_j = 0$ or 1. Note that $NUM = b_0+2b_1+4b_2+ \ldots +2^K b_K$.
3. If $b_k = 1$, multiply U by T_k.
4. If k = K, then go to Step 5. Otherwise, compute $T_{k+1} = T_k * T_k$ (note that $T_k = T^{2k}$), add 1 to k and go to Step 3.
5. The matrix T^{NUM} is given by U, and T^{NUM+1} is given by U*T.

TECHNICAL APPROACH FOR COST MEASURES

In addition to assessing the performance of a fare collection system, the analysis software also examines system costs. The costs are computed on an annual basis and include equipment acquisition, spares provision, equipment operation, scheduled maintenance, and corrective maintenance and repairs. The costs are computed by the following formulas [a detailed description of the cost formulas is given by this author (7)].

1. Annualized capital cost

$$ACAP = ACQ * \{r/[1-(1+r)^{-t}]\} * (n)$$

where

ACQ = acquisition cost,
r = discount rate,
t = useful life, and
n = number of equipment units at the service area.

2. Annualized spares cost

$$SPRS = s * (ACAP)$$

where s is spares ratio.

3. Operating cost

$$OPER = n * (UOPR)$$

where UOPR is annual operating cost per unit.

4. Cost of scheduled maintenance

$$SCHD = h * n * w$$

where h is annual hours of scheduled maintenance per unit, and w is hourly pay rate for repair personnel.

5. Cost of corrective maintenance and repair

$$CORR = (VOL) * (1/MCBF) * (MTTR) * (w)$$

where

VOL = annual passenger volume at service area,
MCBF = reliability (mean cycles between failures), and
MTTR = maintainability (mean time to repair).

HOW TO USE THE MODEL FOR FARE COLLECTION SYSTEM ANALYSIS

The direct result of the microcomputer-based fare collection dependability model is information on the trouble rate (or, conversely, the peak-period dependability) and the annualized cost of a fare collection area at a particular station, given the system configuration and passenger demand. The information is given in terms of the trouble rate for peak periods of 10, 20, and 30 min, up to a maximum of 120 min. The costs are partitioned into acquisition cost, spares cost, operations cost, scheduled maintenance, and corrective maintenance.

The fare collection model can be used by transit authorities for a number of different purposes, such as

- Determination of required number of fare collection equipment units,
- Reliability and maintainability specifications,
- Impact of changes in passenger use level,
- Effect of maintenance policy changes, and
- Effect of changes in fare collection method.

In fulfilling these purposes, there are four basic kinds of analyses that can be conducted using the model: (a) evaluation, (b) sensitivity analysis, (c) specification determination, and (d) trade-off analysis. These are shown in Figure 2.

Evaluation examines a given fare collection system (sample question: "What is the system trouble rate for equipment with a reliability of 10,000 MCBF?") The required information about the system is collected and entered into the model as input data. The model produces estimates as to how well the system performs (or costs) under the given passenger demand, reliability, maintainability, and number of machine units.

Sensitivity analysis assesses the impact of a change in the fare collection system description (sample question: "What happens to the system trouble rate if the equipment reliability is 20,000 MCBF instead of 10,000?"). It is natural to want to know, after a system has been evaluated, how the results would change if one or more of the input parameters were different from their current values (this would be particularly true if some of the input values were in doubt). To find out, several runs of the model are made with differing values for a given input parameter, and the changes that occur in system performance (or cost) are observed. This is called sensitivity analysis because it measures the sensitivity of system performance to changes in the input values.

Specification determination represents the opposite of evaluation and sensitivity analysis (sample question: "What equipment reliability must be specified in order to achieve a system trouble rate of no more than 3 percent?"). Instead of fixing an input value and determining the resulting performance, one fixes the desired performance and determines from that the value that a key input parameter, such as reliability, must be to meet that performance standard. In this manner, specifications may be determined so that the fare collection system will meet the desired standard.

Trade-off analysis examines the interaction between two input parameters under a fixed level of performance (sample question: "If there are four equipment units instead of three, by how much can the reliability decrease while still maintaining a trouble rate of no more than 3 percent?"). This allows one to determine how to trade off between two input parameters while achieving the same overall result. For example, if equipment reliability declines, by how much would maintainability have to improve to obtain the same overall performance? Trade-off analysis differs from sensitivity analysis in that trade-off analysis examines the interaction between two input parameters, whereas sensitivity analysis examines the interaction between an input and an output parameter.

SOFTWARE DESIGN AND USER'S MANUAL

An important part of any analysis software is its interaction with the user. The user should be able to

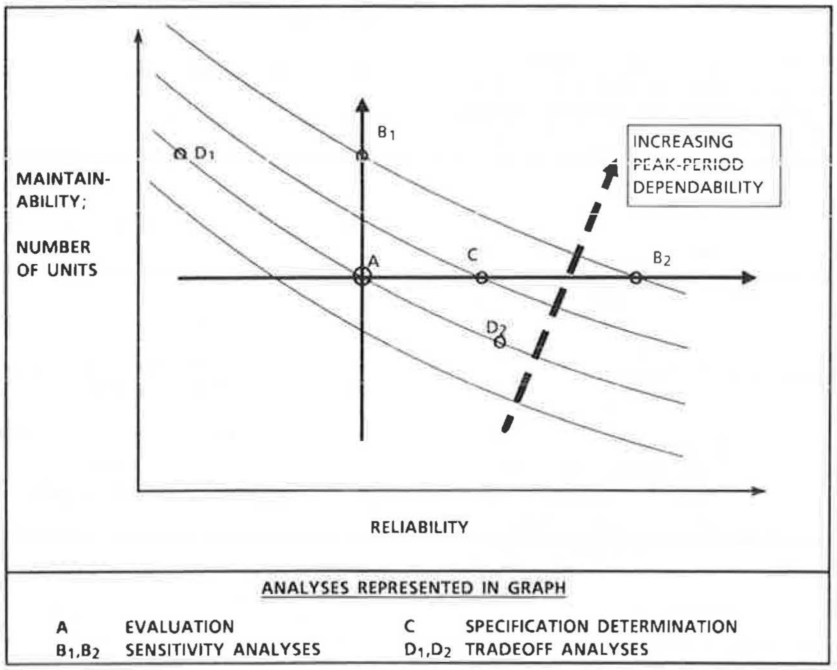


FIGURE 2 Types of dependability analyses.

easily access the program, enter data, make corrections, run analyses, make changes in the data, rerun analyses, and save input and output files. This is especially true with microcomputers, where the user converses directly with the computer instead of submitting runs and waiting for results. The software thus has various routines to communicate with the user and provides the following features:

- The user is guided through the program by prompts, most of which can be answered by "yes" or "no."
- Data can be entered either directly from the terminal or from a stored input file. If entered from the terminal, it can be stored for later use.
- The data to be used for an analysis run can be displayed to the user and, if desired, changes can be made in the data.
- Many runs can be made in the same session. Data for successive runs come either from changes in the previous data or from completely new data (from the terminal or from files).
- The output is compact enough for performance and cost results to fit on the same microcomputer screen.
- In addition to screen display of results, an output file is created for later use.
- Errors in data entry can be corrected, either during the entry of the data item or afterwards.

The full software package, including the analysis algorithm and its user-interface functions, contains six sections as shown in Figure 3:

- Login/Entry
- Terminal Input
- Disk-File Input
- Verification/Change
- Analysis
- Continue/Stop

It is designed to run on any IBM-compatible microcomputer using the MSDOS operating system. Below is a description of each section and its function in more detail, including user prompts and responses.

LOGIN/ENTRY SECTION

When FARE is typed, the operating system starts the program, eventually displaying the message:

```
Accept input from the terminal?
     (Y or N):
```

This asks whether the data for the analysis will be typed in from the terminal or entered from a disk file. A "Y" answer transfers control to the Terminal Input section to accept the data, whereas an "N" response transfers control to the Disk-File Input section to read the file.

TERMINAL-INPUT SECTION

When data are being entered from the terminal, the program will display prompts for each data item required. The prompts consist of a question number, a description of the data item, and the data type [either integer (no fractional values allowed) or real (fractional values accepted)]. There are five performance data, and hence five prompts, as follows:

Prompt	Data	Measurement Units
1	Number of machine units	Number
2	Mean arrival rate	Passengers per hour
3	Mean passenger service rate	Passengers per hour
4	Reliability	Mean cycles between failures
5	Mean repair time	Minutes

To indicate that no repairs are carried out during the peak period, "9999." is entered for the mean repair time.

After accepting the performance-related data, the program then prompts, "Do you wish to include costs in this run?" A "N" answer concludes the input. A "Y" response leads to the following prompts for cost data:

Prompt	Data	Measurement Units
6	Capital cost	Dollar per machine unit
7	Useful life	Years
8	Discount rate	Percent
9	Spares ratio	Percent
10	Operating cost	Dollar per machine unit per year
11	Scheduled maintenance	Hours per machine unit per year
12	Repair wage rate	Dollar per hour
13	Station passenger volume	Passengers per year

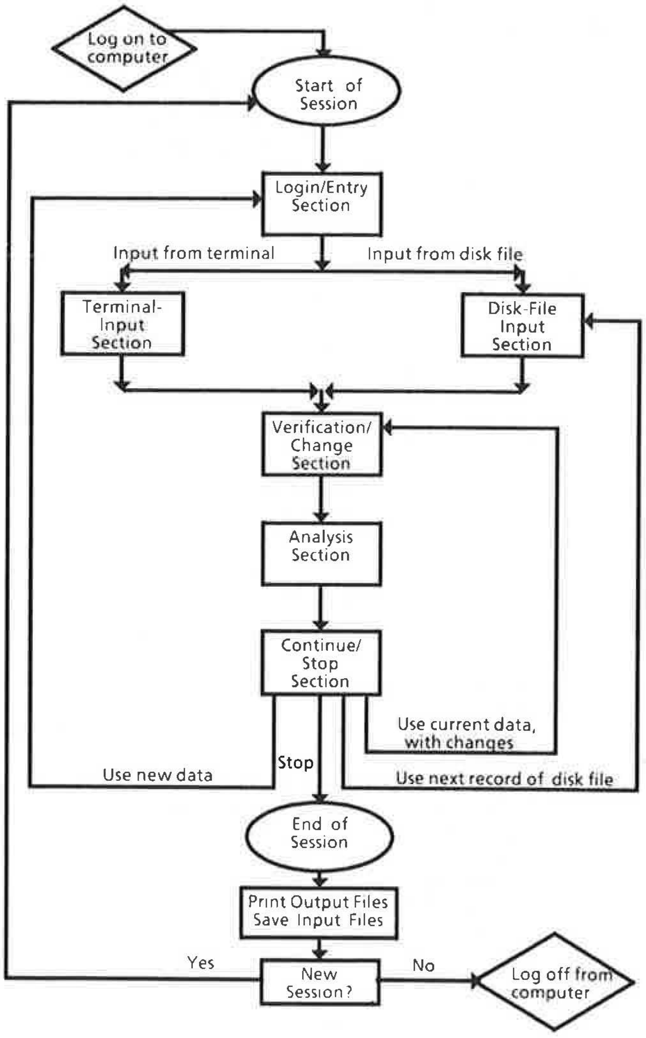


FIGURE 3 Software design—fare collection dependability model.

If costs are included in the analysis, but no repairs are carried out during the peak period, another prompt (Prompt 14) will ask for the mean time (in minutes) to carry out the repair during the off-peak period. This is necessary in order to calculate annual corrective maintenance costs. After accepting the cost data, the program proceeds to the Verification/Change section.

DISK-FILE INPUT SECTION

If the data are to be entered from an existing file, the program requests the name of the file by the message, "Enter input file name (up to 10 characters):" The input file consists of 6 lines if cost data are not included, and 14 or 15 lines if cost data are included. Each line, containing one value as shown below, occurs in the same order as that for the prompts in the Terminal Input section (thus the first line contains the number of equipment units, the second line contains the mean arrival rate, the third line contains the mean service or processing time, etc.). Line 5a contains either the value 0, if costs are not included in the analysis, or 1, if costs are included. Line 14 is necessary only if costs are included and no peak-period repair is carried out, in which case the line contains the off-peak mean repair time; for example:

Line Number	Data Value	Explanation
Performance data		
1	3	Three equipment units
2	2627.	2,627 arrivals per hour
3	1500.	Mean processing rate is 1,500/hr
4	10000.	Reliability is 10,000 MCBF
5	9999.	No peak-period repair
5a	1	Costs are included in the analysis
Cost data		
6	23000.	Capital cost is $23,000 per unit
7	10	Useful life is 10 years
8	10.	10 percent discount rate
9	5.5	5.5 percent spares ratio
10	4100.	Operating cost
11	36.	Scheduled maintenance is 36 hr/year
12	15.66	Repair wage rate is $15.66
13	2300000	Annual station volume is 2,300,000
14	12.	Mean off-peak time to repair is 12 min

VERIFICATION/CHANGE SECTION

This section displays the current data and any desired changes are made before running the model. The prompt message is, "Would you like to see the current input file?" A "Y" answer displays on the screen the data values to be used in the model run. The program then prompts, "Do you wish to make any changes?" A "N" answer transfers control to the Analysis section. A "Y" response, indicating a desire to make data changes, causes the program to request, "Enter the number of the data item you wish to change (Type '99' when you wish to make no further changes)". To select the data value to change, the corresponding prompt number as shown in the Terminal Input section is used (i.e., a "1" changes the number of equipment units, a "2" changes the passenger-arrival rate, a "3" changes the mean processing time, etc.). The program then requests the new data value and replaces the existing value with it. The program continues requesting data items and making changes until the number "99" is given as a data item number, indicating no further changes.

The Verification/Change section is also used to change the inclusion of costs in the analysis. If costs are not included in the analysis, but they should be included, the answer "Y" is given to the make-changes prompt, then "6" is entered as the question number. The program then responds, "Costs are not included in the model. Do you wish to add cost data?" After a "Y" response, the program accepts the new cost data from the terminal in the same manner as it does in the terminal input section.

If costs are included in the analysis, but they should not be, the answer "Y" is given to the make-changes prompt, "6" is entered for the question number, and the acquisition cost is changed to zero. FARE will then ask, "Zero capital cost entered. Do you wish to include costs in this run?" After a "N" response, the program no longer includes costs in the analysis.

ANALYSIS SECTION

This section carries out the actual analysis of the fare collection system, using the data specified in the previous sections. The results, which are also stored in an external file, contain the following:

1. Reiteration of the input data.
2. The trouble rate (i.e., the likelihood of insufficient capacity during the peak period) for peak periods, in increments of 10 min, up to 2 hr in duration.
3. Annualized costs (if the cost option was selected): capital cost, spares cost, operating cost, scheduled maintenance cost, corrective repairs costs, and total cost.

CONTINUE/STOP SECTION

Whether or not further runs are desired is checked in this section. Further runs may be carried out in one of three ways:

1. Use the current input data (with possibly some changes).
2. Use the next record of the input file (if the current data were entered from a disk file).
3. Use completely new data.

The program asks, "Do you wish to make any further runs?" A "N" answer transfers control to the Stop procedure, described in the next paragraph. A "Y" answer leads to the prompt, "Do you wish to use the current data, either as is or with some changes? [answer 'Y' (current data or some changes) or 'N' (use a new data file)]". A "Y" response is used to make another run with exactly the same data as before or with a few changes (alternative 1). In this case, control passes to the Verification/Change section to accept whatever data changes need to be made. If an external input file is being used and the next record of this file is the data for the next run (alternative 2), a "N" response is used, followed by a "Y" response to the next prompt, "Are the new data the next file of (Name) DAT?" Control then passes to the Disk-File-Input section to read the next record of the input file. If completely new data are to be used (alternative 3), a "N" response to the first prompt is returned, and, if an external input file is being used, a "N" response to the second prompt, when it appears, is also returned. Control then passes to the entry procedure of the Log/Entry section (displaying the prompt, "The new data are from the terminal or a new disk file. Accept input from the terminal?") so that the new data may be entered by either the terminal or a new external input file.

Before ending the session, the current input file may be saved as an external disk file. This can save time in future runs if the current input data were entered from the terminal or if significant changes were made from an existing disk file. The program asks, "Do you wish to save the current input file?" A "N" answer ends the session. A "Y" answers leads to the prompt, "Enter the name of file in which to save input (up to 10 characters). (If such a file already exists, the data in it will be overwritten by the current input file.)" "Name of file," at which point the name of the file in which to save the input is entered.

As mentioned previously, the output from all the analysis runs in a given session is stored in an output file. This allows the results to be transmitted to a hardcopy printer and stored for later reference.

SAMPLE ANALYSIS RUNS

To demonstrate how the microcomputer fare collection dependability analysis model operates, a sample interactive computer session is presented. The base-case fare collection system (Run 1) uses performance data from Long Island Railroad plans (Heimann, unpublished analysis) and cost data from "A Reliability-Based Model to Analyze the Performance and Cost of a Transit Fare Collection System" (7). The session contains four analysis runs as follows:

1. The base case, with the data stored in a disk input file. The program displays the input data, then calculates the trouble rates and costs. The trouble rate for a 1-hr peak period turns out to be 2.9 percent, which means that slightly less than 3 out of every 100 peak periods will experience delay problems. At the usual frequency of 10 peak periods per week, this means that a delay problem occurs in this system somewhat less than once every 3 weeks. The cost of the fare collection system, on an annualized basis over the 10-year life of the equipment, is $28,375 per year.
2. A new case, with data entered directly from the terminal. The reliability of the equipment is entered incorrectly at 10,000 MCBF, so the change feature is used to correct it to 1,000. No cost analysis is required. The trouble rate is 9 percent for a 1-hr peak period, which represents a delay in 1 peak period out of 11, or a frequency of slightly less than 1 peak period per week.
3. The reliability in Run 2 is increased to 3,000 MCBF. In addition, a cost analysis is conducted, using figures entered from the terminal. The trouble rate becomes 1.2 percent for a 1-hr peak period (1 peak period in trouble out of 80, or 1 peak period every 8 weeks). The annualized total cost is $30,536.
4. Alternative fare collection equipment is available, performing similarly to the previously considered equipment in terms of passenger processing, reliability, and so forth. The major difference is that the alternative equipment costs more, $30,000 instead of $23,000, but has lower operating costs, $3,000 annually instead of $4,100. This run compares the respective total annualized costs. Because only costs need be recomputed, the performance software is not used in this run. The annualized total cost turns out to be $30,842 per year, about the same as the previous total cost.

The text of the interactive session follows (the responses by the user are underlined). Note that the session has been retyped.

```
FARE

B>DEL OUTPUT.DAT

B>FARET

ACCEPT INPUT FROM TERMINAL?                             RUN 1
   ('Y' OR 'N') :N

ENTER INPUT FILE NAME (UP TO 10 CHARACTERS) :
INPUT.DAT

THE INPUT FILE IS: INPUT.DAT

   WOULD YOU LIKE TO SEE THE CURRENT INPUT FILE?
   ('Y' OR 'N') : Y

 1.  NUMBER OF MACHINES IS            3
 2.  MEAN ARRIVAL RATE IS        2627.0 /HOUR
 3.  MEAN SERVICE RATE IS        1500.0 /HOUR
 4.  MEAN CYCLES BETWEEN FAILURES IS              9999.
 5.  MEAN TIME TO REPAIR IS      (NO ON-LINE REPAIRS)

 6.  CAPITAL COST PER UNIT IS    $  23000.00
 7.  USEFUL LIFE IS              10 YEARS
 8.  DISCOUNT RATE IS            10.00%
 9.  SPARES RATIO IS             5.50%
10.  ANNUAL UNIT OPERATING COST IS    $    4100.0
11.  ANNUAL HOURS OF SCHEDULED MAINTENANCE IS   36.00
12.  REPAIR WAGE RATE IS         $     15.66 /HOUR
13.  ANNUAL STATION PASSENGER VOLUME IS   2700000
14.  MEAN TIME FOR OFF-LINE REPAIR IS       12.00 MIN.

   DO YOU WISH TO MAKE ANY CHANGES ?
   ('Y' OR 'N') : N

ANALYSIS IN PROCESS

FARE COLLECTION PASSENGER-FLOW ANALYSIS
   (TROUBLE-RATE MODEL)

NUMBER OF UNITS =     3
ARRIVAL RATE =      2627. /HR.
SERVICE RATE =      1500. /HR.
MCBF =  9999.
MTTR =  (NO ON-LINE REPAIR)

CAPITAL COST = $ 23000.00
USEFUL LIFE =  10 YEARS
DISCOUNT RATE = 10.0%
SPARES RATIO = 5.5%
OPERATING COST = $    4100.00
ANNUAL SCHEDULED MAINTENANCE HOURS =  36.0
REPAIR WAGE RATE = $ 15.66 /HR
ANNUAL PASSENGER VOLUME =  2700000
OFF-LINE REPAIR TIME =    12.0 MIN.

TROUBLE RATE (PROBABILITY OF INSUFFICIENT CAPACITY)
     DURING PEAK PERIOD (FOR PEAK PERIODS UP TO
                   2 HOURS IN DURATION)

LENGTH OF PERIOD          TROUBLE RATE
0 HR.     10 MIN.           .0%
0 HR.     20 MIN.           .4%
0 HR.     30 MIN.           .8%
0 HR.     40 MIN.          1.4%
0 HR.     50 MIN.          2.1%
1 HR.      0 MIN.          2.9%

LENGTH OF PERIOD          TROUBLE RATE
1 HR.     10 MIN.          3.8%
1 HR.     20 MIN.          4.9%
1 HR.     30 MIN.          6.0%
1 HR.     40 MIN.          7.2%
1 HR.     50 MIN.          8.5%
2 HR.      0 MIN.          9.8%
```

```
--ANNUAL COSTS OF FARE COLLECTION SERVICE AREA--

   ANNUALIZED CAPITAL COST                   $ 11229.43
   ANNUALIZED SPARES COST                    $   617.62
   OPERATING COST                            $ 12300.00
   SCHEDULED MAINTENANCE COST                $  1691.28
   CORRECTIVE REPAIR COST                    $  2537.17

   TOTAL COST                                $ 28375.50

DO YOU WISH TO MAKE ANY FURTHER RUNS?               RUN 2
   (ANSWER 'Y' OR 'N') Y

DO YOU WISH TO USE THE CURRENT DATA, EITHER AS IS OR
WITH SOME CHANGES?
   (ANSWER 'Y' (CURRENT DATA OR SOME CHANGES) OR 'N'
   (USE A NEW DATA FILE)  ) : N

ARE THE NEW DATA THE NEXT RECORD OF: INPUT. DAT?
   (ANSWER 'Y' OR 'N') N

THE NEW DATA ARE FROM THE TERMINAL OR
A NEW DISK FILE.
ACCEPT INPUT FROM TERMINAL?
   ('Y' OR 'N') :Y

1.  ENTER NUMBER OF MACHINES
    (ONE INTEGER VALUE) : 3

2.  ENTER MEAN ARRIVAL RATE PER HOUR-
    (ONE REAL VALUE) : 500

3.  ENTER MEAN SERVICE RATE PER HOUR-
    (ONE REAL VALUE) : 300

4.  ENTER MEAN CYCLES BETWEEN FAILURES-
    (ONE REAL VALUE) : 10000

5.  ENTER MEAN TIME TO REPAIR IN MINUTES-
    (IF NO ON-LINE REPAIR IS DONE, ENTER '9999.')
    (ONE REAL VALUE) : 9999

    DO YOU WISH TO INCLUDE COSTS IN THIS RUN?
    ('Y' OR 'N') : N

    WOULD YOU LIKE TO SEE THE CURRENT INPUT FILE?
    ('Y' OR 'N') : Y

1.  NUMBER OF MACHINES IS          3
2.  MEAN ARRIVAL RATE IS        500.0 /HOUR
3.  MEAN SERVICE RATE IS        300.0 /HOUR
4.  MEAN CYCLES BETWEEN FAILURE IS       10000.
5.  MEAN TIME TO REPAIR IS      (NO ON-LINE REPAIRS)

    DO YOU WISH TO MAKE ANY CHANGES ?
    ('Y' OR 'N') : Y

    ENTER THE NUMBER OF THE DATA ITEM YOU WISH TO
    CHANGE
       (TYPE '99' WHEN YOU WISH TO MAKE NO FURTHER
       CHANGES).

    (ONE INTEGER VALUE) : 4

4.  ENTER MEAN CYCLES BETWEEN FAILURES-
    (ONE REAL VALUE) : 1000

    ENTER THE NUMBER OF THE DATA ITEM YOU WISH TO
    CHANGE
       (TYPE '99' WHEN YOU WISH TO MAKE NO FURTHER
       CHANGES).

    (ONE INTEGER VALUE) : 99

    WOULD YOU LIKE TO SEE THE CURRENT INPUT FILE?
    ('Y' OR 'N') : Y

1.  NUMBER OF MACHINES IS          3
2.  MEAN ARRIVAL RATE IS        500.0 /HOUR
3.  MEAN SERVICE RATE IS        300.0 /HOUR
4.  MEAN CYCLES BETWEEN FAILURES IS       1000.
5.  MEAN TIME TO REPAIR IS     (NO ON-LINE REPAIRS)

    DO YOU WISH TO MAKE ANY CHANGES ?
    ('Y' OR 'N') : N

ANALYSIS IN PROCESS

FARE COLLECTION PASSENGER-FLOW ANALYSIS
   (TROUBLE-RATE MODEL)

NUMBER OF UNITS =      3
ARRIVAL RATE =        500. /HR.
SERVICE RATE =        300. /HR.
MCBF =    1000.
MTTR =    (NO ON-LINE REPAIR)

TROUBLE RATE (PROBABILITY OF INSUFFICIENT CAPACITY)
DURING PEAK PERIOD
     (FOR PEAK PERIODS UP TO 2 HOURS IN DURATION)

LENGTH OF PERIOD              TROUBLE RATE
0 HR.     10 MIN.               .3%
0 HR.     20 MIN.              1.2%
0 HR.     30 MIN.              2.6%
0 HR.     40 MIN.              4.4%
0 HR.     50 MIN.              6.6%
1 HR.      0 MIN.              9.0%


LENGTH OF PERIOD              TROUBLE RATE
1 HR.     10 MIN.             11.6%
1 HR.     20 MIN.             14.4%
1 HR.     30 MIN.             17.3%
1 HR.     40 MIN.             20.3%
1 HR.     50 MIN.             23.3%
2 HR.      0 MIN.             26.4%

DO YOU WISH TO MAKE ANY FURTHER RUNS?
       (ANSWER 'Y' OR 'N') Y

                                                   RUN 3

DO YOU WISH TO USE THE CURRENT DATA, EITHER AS IS OR
WITH SOME CHANGES?
   (ANSWER 'Y' (CURRENT DATA OR SOME CHANGES) OR 'N'
   (USE A NEW DATA FILE) ) : Y

   WOULD YOU LIKE TO SEE THE CURRENT INPUT FILE?
   ('Y' OR 'N') : Y

1.  NUMBER OF MACHINES IS        3
2.  MEAN ARRIVAL RATE IS      500.3 /HOUR
3.  MEAN SERVICE RATE IS      300.0 /HOUR
4.  MEAN CYCLES BETWEEN FAILURES IS   1000.
5.  MEAN TIME TO REPAIR IS  (NO ON-LINE REPAIRS)

    DO YOU WISH TO MAKE ANY CHANGES ?
    ('Y' OR 'N') : Y

ENTER THE NUMBER OF THE DATA ITEM YOU WISH TO CHANGE
    (TYPE '99' WHEN YOU WISH TO MAKE NO FURTHER
    CHANGES).

    (ONE INTEGER VALUE) : 4

4.  ENTER MEAN CYCLES BETWEEN FAILURES-
    (ONE REAL VALUE) : 3000
```

```
ENTER THE NUMBER OF THE DATA ITEM YOU WISH TO CHANGE
    (TYPE '99' WHEN YOU WISH TO MAKE NO FURTHER
    CHANGES).

(ONE INTEGER VALUE) : 6

COSTS ARE PRESENTLY NOT INCLUDED IN THIS MODEL.
DO YOU WISH TO ADD COST DATA?
    ('Y' OR 'N') : Y

6.   ENTER THE CAPITAL COST PER UNIT
     (ONE REAL VALUE) : 23000

7.   ENTER THE USEFUL LIFE OF THE UNIT, IN YEARS
     (ONE INTEGER VALUE) : 10

8.   ENTER THE DISCOUNT RATE, IN PERCENTAGE TERMS
     (ONE REAL VALUE) : 10

9.   ENTER THE SPARES RATIO, IN PERCENTAGE TERMS
     (ONE REAL VALUE) : 5.5

10.  ENTER THE ANNUAL OPERATING COST PER UNIT
     (ONE REAL VALUE) : 4100

11.  ENTER THE ANNUAL SCHEDULED MAINTENANCE HOURS
     PER UNIT
     (ONE REAL VALUE) : 36

12.  ENTER THE REPAIR WAGE RATE, PER HOUR
     (ONE REAL VALUE) : 15.66

13.  ENTER ANNUAL PASSENGER VOLUME AT STATION
     (ONE INTEGER VALUE) : 1500000

14.  ENTER TIME TO DO OFF-PEAK REPAIR, IN MINUTES
     (FOR COST PURPOSES: IF YOU DO NOT WISH TO
     INCLUDE THIS REPAIR IN THE COST FIGURES,
     ENTER '0')
     (ONE REAL VALUE) : 12

WOULD YOU LIKE TO SEE THE CURRENT INPUT FILE?
('Y' OR 'N') : Y

 1.  NUMBER OF MACHINES IS        3
 2.  MEAN ARRIVAL RATE IS     500.0 /HOUR
 3.  MEAN SERVICE RATE IS     300.0 /HOUR
 4.  MEAN CYCLES BETWEEN FAILURES IS     3000.
 5.  MEAN TIME TO REPAIR IS   (NO ON-LINE REPAIRS)

 6.  CAPITAL COST PER UNIT IS   $    23000.00
 7.  USEFUL LIFE IS          10 YEARS
 8.  DISCOUNT RATE IS        10.00%
 9.  SPARES RATIO IS         5.50%
10.  ANNUAL UNIT OPERATING COST IS   $   4100.00
11.  ANNUAL HOURS OF SCHEDULED MAINTENANCE IS   36.00
12.  REPAIR WAGE RATE IS    $   15.66 /HOUR
13.  ANNUAL STATION PASSENGER VOLUME IS    1500000
14.  MEAN TIME FOR OFF-LIFE REPAIR IS       12.00 MIN.

     DO YOU WISH TO MAKE ANY CHANGES ?
     ('Y' OR 'N') : N

SHOULD THE NEW RUN RECOMPUTE COSTS ONLY?
     (ANSWER 'Y' (COSTS ONLY) OR 'N' (PERFORMANCE
     AND COSTS)) :N

ANALYSIS IN PROCESS

FARE COLLECTION PASSENGER-FLOW ANALYSIS
     (TROUBLE-RATE MODEL)


NUMBER OF UNITS =    3
ARRIVAL RATE =     500. /HR.
```

```
SERVICE RATE =     300. /HR.
MCBF =  3000.
MTTR =  (NO ON-LINE REPAIR)

CAPITAL COST = $ 23000.00
USEFUL LIFE =    10 YEARS
DISCOUNT RATE = 10.0%
SPARES RATIO =  5.5%
OPERATING COST = $    4100.00
ANNUAL SCHEDULED MAINTENANCE HOURS =   36.0
REPAIR WAGE RATE = $ 15.66 /HR.
ANNUAL PASSENGER VOLUME =     1500000
OFF-LINE REPAIR TIME =     12.0 MIN.


 TROUBLE RATE (PROBABILITY OF INSUFFICIENT CAPACITY)
                 DURING PEAK PERIOD
    (FOR PEAK PERIODS UP TO 2 HOURS IN DURATION)

LENGTH OF PERIOD               TROUBLE RATE
0 HR.     10 MIN.                .0%
0 HR.     20 MIN.                .1%
0 HR.     30 MIN.                .3%
0 HR.     40 MIN.                .6%
0 HR.     50 MIN.                .9%
1 HR.      0 MIN.               1.2%

LENGTH OF PERIOD               TROUBLE RATE
1 HR.     10 MIN.               1.7%
1 HR.     20 MIN.               2.1%
1 HR.     30 MIN.               2.6%
1 HR.     40 MIN.               3.2%
1 HR.     50 MIN.               3.8%
2 HR.      0 MIN.               4.5%


--ANNUAL COSTS OF FARE COLLECTION SERVICE AREA--

   ANNUALIZED CAPITAL COST              $ 11229.43
   ANNUALIZED SPARES COST               $   617.62
   OPERATING COST                       $ 12300.00
   SCHEDULED MAINTENANCE COST           $  1691.28
   CORRECTIVE REPAIR COST               $  4698.00

   TOTAL COST                           $ 30536.33


DO YOU WISH TO MAKE ANY FURTHER RUNS?              RUN 4
   (ANSWER 'Y' OR 'N') : Y


DO YOU WISH TO USE THE CURRENT DATA, EITHER AS IS OR
WITH SOME CHANGES?
   (ANSWER 'Y' (CURRENT DATA OR SOME CHANGES) OR 'N'
   (USE A NEW DATA FILE) ) : Y


  WOULD YOU LIKE TO SEE THE CURRENT INPUT FILE?
  ('Y' OR 'N') : Y


 1.  NUMBER OF MACHINES IS        3
 2.  MEAN ARRIVAL  RATE IS    500.0 /HOUR
 3.  MEAN SERVICE RATE IS     300.0 /HOUR
 4.  MEAN CYCLES BETWEEN FAILURES IS   3000.
 5.  MEAN TIME TO REPAIR IS     (NO ON-LINE REPAIRS)

 6.  CAPITAL COST PER UNIT IS  $    23000.00
 7.  USEFUL LIFE IS          10 YEARS
 8.  DISCOUNT RATE IS         10.00%
 9.  SPARES RATIO IS          5.50%
10.  ANNUAL UNIT OPERATING COST IS  $    4100.00
11.  ANNUAL HOURS OF SCHEDULED MAINTENANCE IS   36.00
12.  REPAIR WAGE RATE IS  $      15.66 /HOUR
13.  ANNUAL STATION PASSENGER VOLUME IS    1500000
14.  MEAN TIME FOR OFF-LINE REPAIR IS       12.00 MIN.
```

```
     DO YOU WISH TO MAKE ANY CHANGES ?
     ('Y' OR 'N') : Y

ENTER THE NUMBER OF THE DATA ITEM YOU WISH TO CHANGE
     (TYPE '99' WHEN YOU WISH TO MAKE NO FURTHER
     CHANGES).

     (ONE INTEGER VALUE) : 6

6.   ENTER THE CAPITAL COST PER UNIT
       (ONE REAL VALUE) : 30000

ENTER THE NUMBER OF THE DATA ITEM YOU WISH TO CHANGE
     (TYPE '99' WHEN YOU WISH TO MAKE NO FURTHER
     CHANGES).

     (ONE INTEGER VALUE) : 10

10.  ENTER THE ANNUAL OPERATING COST PER UNIT
       (ONE REAL VALUE:) 3000

ENTER THE NUMBER OF THE DATA ITEM YOU WISH TO CHANGE
     (TYPE '99' WHEN YOU WISH TO MAKE NO FURTHER
     CHANGES).

     (ONE INTEGER VALUE) : 99

WOULD YOU LIKE TO SEE THE CURRENT INPUT FILE?
     ('Y' OR 'N') : Y

 1.  NUMBER OF MACHINES IS       3
 2.  MEAN ARRIVAL RATE IS     500.0 /HOUR
 3.  MEAN SERVICE RATE IS     300.0 /HOUR
 4.  MEAN CYCLES BETWEEN FAILURES IS    3000.
 5.  MEAN TIME TO REPAIR IS     (NO ON-LINE REPAIRS)

 6.  CAPITAL COST PER UNIT IS   $    30000.00
 7.  USEFUL LIFE IS           10 YEARS
 8.  DISCOUNT RATE IS          10.00%
 9.  SPARES RATIO IS           5.50%
10.  ANNUAL UNIT OPERATING COST IS   $     3000.00
11.  ANNUAL HOURS OF SCHEDULED MAINTENANCE IS   36.00
12.  REPAIR WAGE RATE IS   $      15.66 /HOUR
13.  ANNUAL STATION PASSENGER VOLUME IS    1500000
14.  MEAN TIME FOR OFF-LINE REPAIR IS        12.00 MIN.

     DO YOU WISH TO MAKE ANY CHANGES ?
     ('Y' OR 'N') : N

SHOULD THE NEW RUN RECOMPUTE COSTS ONLY?
     (ANSWER 'Y' (COSTS ONLY) OR 'N' (PERFORMANCE AND
     COSTS)) :Y


ANALYSIS IN PROCESS

--ANNUAL COSTS OF FARE COLLECTION SERVICE AREA--

     ANNUALIZED CAPITAL COST          $ 14647.09
     ANNUALIZED SPARES COST           $   805.59
     OPERATING COST                   $  9000.00
     SCHEDULED MAINTENANCE COST       $  1691.28
     CORRECTIVE REPAIR COST           $  4698.00

     TOTAL COST                       $  30841.96

DO YOU WISH TO MAKE ANY FURTHER RUNS?
     (ANSWER 'Y' OR 'N') N

DO YOU WISH TO SAVE THE CURRENT INPUT FILE?
     (ANSWER 'Y' OR 'N') Y

ENTER NAME OF FILE IN WHICH TO SAVE INPUT (UP TO 10
CHARACTERS).
     (IF SUCH A FILE ALREADY EXISTS, THE DATA IN IT
     WILL BE REPLACED BY THE CURRENT INPUT FILE.)

NAME OF FILE: DATA.DAT

END OF SESSION.

THE RESULTS OF THIS SESSION ARE CONTAINED IN A FILE
CALLED 'OUTPUT.DAT'. IF YOU WISH TO SAVE THIS FILE,
BE SURE TO RENAME IT BEFORE THE NEXT SESSION.
```

REFERENCES

1. L. Rubenstein, J. Land, G. Deshpande, and B. Harrow. Overview of Rail Transit Fare Collection. JPL Publication 80-89. Jet Propulsion Laboratory, Pasadena, Calif., Aug. 1980.
2. G. Surabian. Automated Magnetic Card Fare Collection Systems: An Overview With Emphasis on the Washington Metro Experience. Urban Transportation Department, Northeastern University, Boston, Mass., May 1980.
3. G. Deshpande, J. Cucchissi, and R. Heft. Rail Transit Fare Collection Study: Policy and Technology Assessment, Vol. 1. UMTA-MA-06-0025-82-4. UMTA, U.S. Department of Transportation, Aug. 1981.
4. J. Heisler and R. Stevens. Assessment of UMTA's Automatic Fare Collection Equipment Performance. UMTA-MA-06-0080-81-1. UMTA, U.S. Department of Transportation, Jan. 1981.
5. J. Morrissey and D. Mesnick. An Assessment of Automatic Fare Collection Equipment at Three European Transit Properties. UMTA-MA-06-0025-82-5. UMTA, U.S. Department of Transportation, Dec. 1982.
6. J. Hitz. Rail Transit System Maintenance Practices for Automatic Fare Collection Equipment. UMTA-MA-06-0153-84-2. Transportation Systems Center, U.S. Department of Transportation, Cambridge, Mass., May 1984.
7. D. Heimann. A Reliability-Based Model to Analyze the Performance and Cost of a Transit Fare Collection System. UMTA-MA-06-0153-85-1. Transportation Systems Center. U.S. Department of Transportation, Cambridge, Mass., June 1985.
8. S. Karlin. A First Course in Stochastic Processes. Academic Press, New York, 1968.

Measuring Station Capacity for Seattle's Bus Tunnel

RAYMOND G. DEARDORF, ROBERT J. BERG, and CHYI KANG LU

ABSTRACT

A discussion of the passenger system capacity of the Downtown Seattle Transit Project is presented in this paper. The purpose of this paper is to analyze the design of the subway stations associated with the Downtown Seattle Transit Project with regard to the levels of service experienced under estimated passenger volumes using the facility. Level of service and capacity methodology for pedestrians are reviewed for individual components of the transit project. Primarily, this analysis is based on observed data and levels of service research conducted by Fruin (1) and Pushkarev and Zupan (2). Estimated station passenger volumes for the years 1990, 2000, and far into the 21st century are analyzed with respect to levels of service. System components examined are the station entrance, mezzanine levels, and station platforms. Presented are examples of Fruin's and Pushkarev's methodology applied to several specific design components of the subway stations.

The Downtown Seattle Transit Project is an innovative response to improving transit service hindered by heavy traffic congestion in downtown Seattle, Washington. Seattle is a city of approximately 0.5 million people and is the employment and population center of the Puget Sound region which has approximately 2.5 million people. During the past decade, significant population and employment growth has occurred in this area. Downtown Seattle has seen a dramatic growth in high-rise office buildings. Office space increased 39 percent between 1975 and 1982. Employment increased 25 percent from 1970 to 1980 and is expected to increase another 25 percent between 1980 and 1990 (3).

Increased transit service provided by Metro (Municipality of Metropolitan Seattle) has accommodated a significant percentage of trips to downtown Seattle. During 1980, 40 percent of peak-hour and 28 percent of daily trips to downtown Seattle were made by transit. The transit mode split to downtown Seattle is expected to grow to 55 percent during peak hour and 40 percent of daily trips by 1990 (3).

To alleviate the present and forecasted traffic congestion and enable buses to move faster (currently, buses average 4 to 5 mph downtown), a subway for buses has been proposed and is in the final design stage. A map of this project is shown in Figure 1.

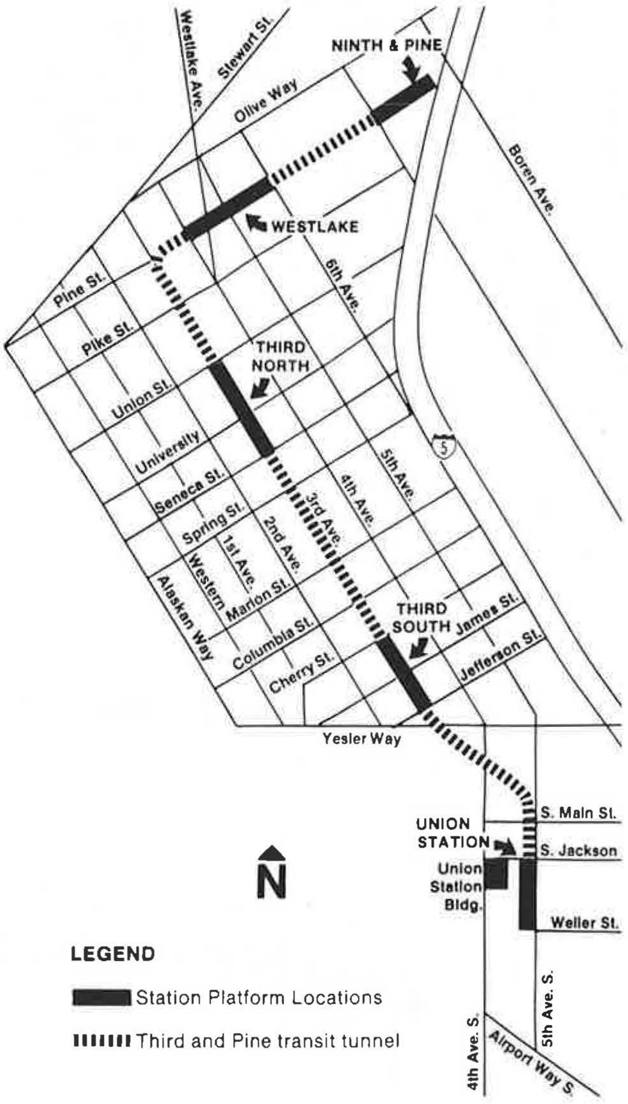


FIGURE 1 Map of project.

SYSTEM DESCRIPTION

The Parsons Brinckerhoff Design Team was selected by Metro for preliminary engineering and final design of Seattle's proposed downtown transit tunnel. Work on the 1.3 mi system began in mid-1984, and preliminary engineering was completed in mid-1985. Construction is planned to start in 1986; the new system will open in 1990.

The proposed tunnel will help facilitate the growing transit demands of the downtown. Currently,

---

R.G. Deardorf and R.J. Berg, Parsons Brinckerhoff Quade & Douglas, Inc., 710 Second Ave., Suite 960, Seattle, Wash. 98104. C.K. Lu, Parsons Brinckerhoff Quade & Douglas, Inc., 1625 Van Ness Ave., 4th Floor, San Francisco, Calif. 94109.

in the peak hours, buses form a wall along Third Avenue, one of the major transit routes through the downtown. The tunnel is expected to remove approximately 300 buses entering the downtown surface street system during the year 2000 peak hours. Both system capacity and vehicle speed will be improved.

The tunnel is being designed for dual propulsion bus technology: a bus intended for electric operation in the tunnel and diesel operation when it leaves the tunnel. Such a bus will operate outside of downtown to suburban destinations. In addition, the tunnel design will permit conversion to light rail transit (LRT) in the future. The design can be expected to accommodate both the dual-propulsion bus and LRT service during a transition period that may involve shared operation for some years.

At this stage, a bored tunnel of twin 18-ft diameter line sections on a north-south alignment is proposed beneath Third Avenue. The tunnel will connect a surface station and south staging area to three underground stations spaced along Third Avenue and Pine Street in an L-shaped corridor. A cut-and-cover tunnel section extending east along Pine Street will connect the underground station under Pine Street at Westlake Avenue to a surface station at the north staging area. Both the north and south staging areas will receive and discharge buses to the freeway system that serves the downtown.

The three intermediate underground stations have been located to intercept existing and projected patronage and to avoid adverse impacts on key activity centers and historic structures in downtown Seattle. The stations are designed with a mezzanine located above low, side-loading platforms. Station entry will be accomplished by locating access within adjacent buildings where possible, avoiding the narrowing of sidewalks. Cut-and-cover construction of the stations will be used to reach levels as deep as 60 ft below Third Avenue in order to maintain tunnel alignment and to avoid major utility dislocation. Figure 2 shows an architect's sketch of the platform area of the Westlake station.

The centerpiece of the system will be the Westlake station, designed to connect, at the mezzanine level, the proposed Westlake Mall development, a relocated Seattle Monorail station, and three major department stores. Located near the Westlake station is Seattle's famous Pike Street Marketplace.

The south staging area will contain a surface station accommodating transferring passengers from surface circulation routes, Seattle Kingdome patrons, and the International and Pioneer Historic District visitors. The staging area will use the abandoned rail yard of historic Union Station, which lies below the grade of the surrounding streets east of the Kingdome.

The north staging area will contain a surface station serving functions similar to that at Union Station. The city of Seattle land use plan anticipates a major office center development in this area. The Seattle Convention Center, which is under construction, will be located nearby as well. The below-grade staging activity will accommodate dual-propulsion buses to be dispatched through the tunnel and will also relieve surface streets that are now used for bus deployment.

Each staging area serves three primary functions. Buses entering the staging area are to be formed into platoons of two to four buses. In addition, the coaches change to or from diesel operation to or from electric trolley bus operation. After the buses have been formed into platoons, they move into a platform station area for passenger loading.

Plans call for the two staging areas to be covered by lids. The intent is to mitigate adverse impacts resulting from the transit staging and conversion from diesel to electric operation. The lid design is expected to be capable of supporting substantial development of the air rights above the staging areas. These and other joint development options are being considered as the engineering proceeds.

PEDESTRIAN LEVELS OF SERVICE

This paper has been prepared to show the application of pedestrian level-of-service guidelines in defining the capability of major components of the Downtown

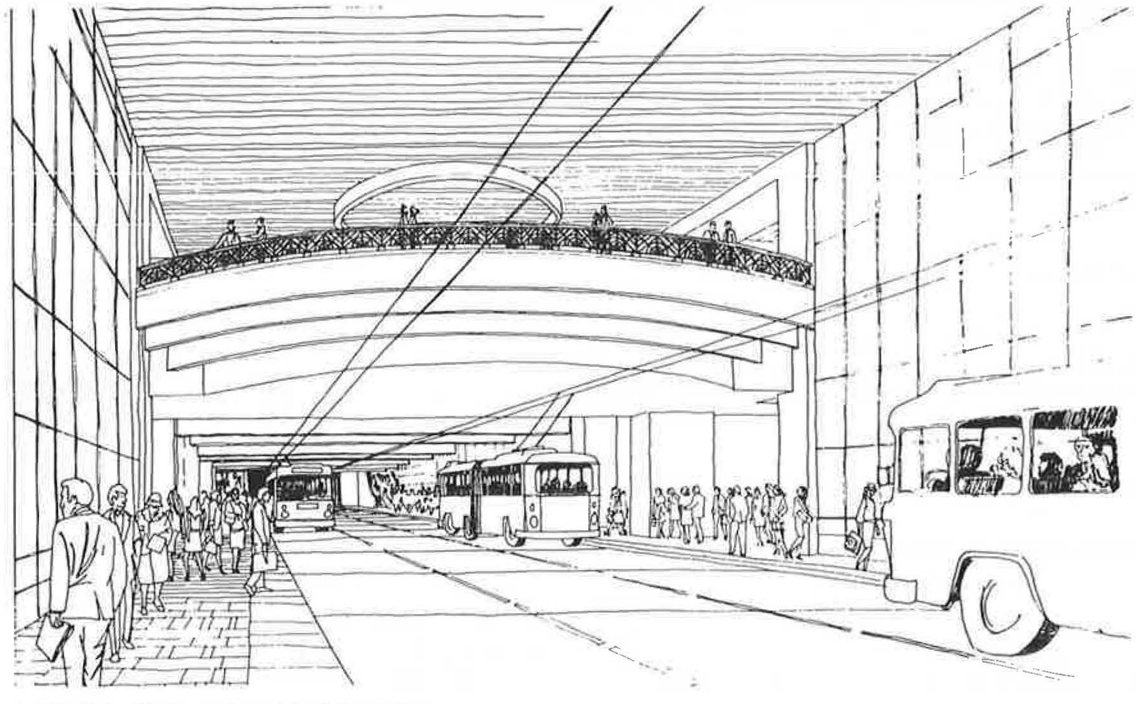


FIGURE 2 Platform view—Westlake station.

Seattle Transit Project to meet the projected levels of patronage for bus operations in 1990, 2000, and at future LRT operations at central business district (CBD) buildout. Major components of the system analyzed include the following:

- Station entrances and exits;
- Station mezzanines (ticketing equipment, areas for queuing and circulation); and
- Station platforms.

The objective of a transportation facility is to accommodate a quantity of demand (pedestrian or vehicular) with an acceptable quality of service. The capacity of various components of the Downtown Seattle Transit Project are measured by either a volume-to-capacity ratio (V/C) or a level of service. Levels of service are a way of assessing the performance of various components of a transportation system under varying conditions of patronage or usage. In general, the six levels of service range in descending order from A to F. Level of service A is associated with a complete lack of congestion and free-flowing operations. Level of service E is the ultimate capacity of a component and is associated with extreme congestion. Level of service F represents forced flow conditions where demand exceeds capacity. Level of service C, typically the level of service designed for, is between A and F and is associated with moderate congestion and is regarded as acceptable to peak periods of service demand.

Volume-to-Capacity Ratio

A volume-to-capacity ratio is the volume of passengers or vehicles experienced at a certain demand level divided by the maximum volume a system component can accommodate. A volume-to-capacity ratio greater than 1.0 means the facility is over capacity; less than 1.0 means either excess design or excess ultimate capacity exists on the facility. This level can vary depending on the denominator; that is, either design capacity or ultimate capacity. In general, here reference to a V/C ratio is meant in terms of design capacity.

The capacities required of a component to meet projected demands were identified for two selected demand levels for bus operations and a future level of rail operations. These are defined as follows:

- Bus tunnel in 1990: 80 buses per hour or 4,800 riders in each direction during the peak hour.
- Bus tunnel in year 2000: 145 buses per hour or 9,000 riders in each direction during the peak hour.
- LRT at buildout: 4-car trains at a 90 sec headway or 25,800 riders in each direction in the peak hour.

STATION ENTRANCES AND EXITS

Different components of the system were investigated for their capacity to accommodate projected pedestrian demand. The first component examined was the entrance and exit capacity of the various stations. Station entrances and exits consist of stairways, or stairways and escalators, for passenger ingress/egress between the street level and the mezzanine level. The capacity of an entrance and exit varies based on the width of stairways (or the total width of stairways and escalators) available for entering and exiting passenger flows and the quality of passenger flow. In analyzing the entrance and exit capacity of the bus tunnel stations, several commonly cited stairway and escalator capacity values were reviewed. These are discussed in the paragraphs that follow.

Stairway Capacity

Stairway capacity was based on studies by Fruin (1) and Pushkarev and Zupan (2). Fruin originally performed a speed-flow analysis of stairways and derived flow-space and speed-space curves based on measurements at the Staten Island Ferry terminal in Manhattan and Shea Stadium in Queens. These yielded a theoretical maximum flow of 18.9 pedestrians/min/ft of width ascending and 20.0 pedestrians/min/ft descending, strictly one-directional flow. Actual observations by Fruin did not exceed 16 or 17 pedestrians/min/ft of stairway width. These observations revealed that movement on stairways begins to approach free flow at 8.7 pedestrians/min/ft of stairway width up and 7.6 pedestrians/min/ft down. Flows as high as 20 pedestrians/min/ft were observed at the PATH World Trade Center station, and this was a surge over a previously empty stairway. Free flow in one direction is usually attained at a flow rate of 5 to 7 persons/min/ft of stairway width (1).

Pushkarev and Zupan (2) made counts at eight subway stairways between the mezzanine and the street in Manhattan. These counts revealed that the maximum upward flow rate was 16.2 persons/min/ft of stairway width. Heavy queuing at the bottom of the stairway was associated with that flow rate. No queuing was observed at flow rates of less than 12 persons/min/ft, if the flow was exclusively in the upward direction and nobody was coming down the stairs in the opposite direction. When an occasional downward movement did occur, that figure dropped to 11 persons/min/ft.

On the basis of their own work and the work of Fruin and others, Pushkarev and Zupan (2) suggest the stairway capacities for three service levels as shown in the following table:

Service Level (quality of flow)	Maximum Flow (persons/min/ft) in Platoons
Impeded	Under 6
Constrained	6-12
Congested	12-17

These flow rates are pedestrians in platoons. The corresponding average flow rate can be much less, depending on passenger arrival and exiting patterns at the station. Stairway flows of less than 6 people/min/ft offer the pedestrian an adequate level of comfort, with some choice of speed, the ability to bypass slower-moving persons, and little conflict with reverse flow. Flows in the 6- to 12-people/min/ft range are constrained. The pedestrian is without the ability to bypass and experiences turbulence and delay due to reverse flow. Under these conditions, walking is shoulder to shoulder, and queuing is possible. A queue is present and congestion exists with flows in excess of 12 people/ft/min.

It is evident that stairways in subway stations or other transit terminals can accommodate up to 20 persons/min/ft of width under congested conditions and with the presence of a long queue. Although flow rates in the congested state have been used in design at several locations, it cannot be considered a standard practice. For the purpose of capacity calculations, a flow rate of 12 persons/min/ft was chosen as a service standard for the Downtown Seattle Transit Project system. At this flow rate, the passenger flow is at the upper end of the constrained level according to Pushkarev and Zupan, which would correspond to the low end of level of service C, defined in this exercise as design capacity (2).

Escalator Capacity

An escalator capacity of 80 persons/min (per 40 in. tread width) at a 90 ft/min speed is cited in the National Fire Protection Association Code 130 standards (4). For 1 ft of tread width, the capacity of a 90 ft/min escalator is about 1.36 times that of a stairway. However, the entire escalator installation is much wider than its moving treads. An escalator with a 40 in. tread width and a nominal dimension of 48 in. at the hip level is about 6 ft wide in terms of total width of escalator and railings. At the no-queuing flow rate of 18 people/ft of tread width, it is really moving people at a rate of 10 people/ft of total width occupied. At a maximum flow rate of 27 people/ft of tread width, it is moving people at a rate of 15 people/ft of total width occupied. Thus, on the basis of total width occupied, the capacity of an escalator is similar to that of a stairway. The capacity of a given band of space to move people is not increased by replacing a stairway with an escalator. An escalator only saves the effort of climbing a grade and does not generally increase capacity without increasing the speed of ascent. For the purpose of this analysis, escalator capacity is defined as 12 persons/min/ft of total width occupied, the same as for a stair at an escalator speed of 90 ft/min (2).

Determining Peak Pedestrian Flow

The peak passenger flow rate was determined by two different methods. In the first method passenger flow rates exiting stations in the a.m. peak hour are examined, because that is anticipated to be the heaviest a.m. peak hour directional flow. The second method involved examining entering passengers during the p.m. peak hour, because that is expected to be the prime direction and heaviest volume during that time period. The higher peak passenger flow rates, either exiting passengers in the a.m. peak hour or entering passengers during the p.m. peak hour are then used to calculate the entrance and exit capacity requirements.

In the first method the passenger flow during the a.m. peak hour was examined when exiting passengers are dominant. Maximum flow occurs in exiting passengers when two bus platoons (one in each direction) arrive at a station at the same time. For year 1990 bus tunnel operations, the maximum exiting passenger volume was based on two 3-bus platoons at 85 passengers per bus. For year 2000 bus tunnel operations, the maximum exiting volume was based on two 4-bus platoons at 85 passengers per bus. For LRT at CBD buildout operations, the maximum exiting volume was based on two 4-car trains at 200 passengers per car. In all cases, all exiting passengers were expected to clear the stairways or escalators within 1 min. At this rate, passengers would be in platoons and no further adjustments are necessary. This method yields the peak flow rates for all CBD riders during the a.m. peak period given in the following table:

	Exiting Flow (passenger/min)	Entering Flow (passenger/min)	Total Peak Flow (passenger/min)
1990 Bus tunnel	510	32	542
2000 Bus tunnel	680	51	731
LRT at CBD buildout	1,600	351	1,951

Entering passenger flows during the p.m. peak hour are examined in the second method. This method involved first converting the estimated p.m. peak hour total station passenger volumes into peak 1-min flows using a 1.3 surge factor for arriving passengers. The peak 1-min flow was further increased by a factor of 1.5 for a platooning effect in passenger flow. The conversion yields the following total peak flow rates for all CBD station users as given in the following table:

	P.M. Peak Hour Total Station Users	Peak Passenger Flow in Platoon (passenger/min)
1990 Bus tunnel	9,622	313
2000 Bus tunnel	17,844	580
LRT at CBD buildout	15,528	1,675

The higher peak passenger flow rates from the two estimates, those from the a.m. peak, were used in calculating the entrance and exit capacity discussed in the example below.

An example of applying this methodology for an actual entrance designed for the Seattle system is presented in Table 1. The performance of the currently designed southwest entrance to the Westlake station is examined under estimated 1990, 2000, and LRT at buildout patronage volumes.

The width in inches required to accommodate the pedestrian volumes at 12 people/min/ft (1 person/min/in.) equals the estimated pedestrian volumes. The width required is then divided by the total width provided by the design (in this case, one escalator occupying 72 in. and one stair occupying 72 in., for a total of 144 in.) to obtain a volume-to-capacity ratio.

For this particular entrance, the volume-to-capacity ratio using 12 pedestrians/min/ft of width as design capacity (low end of level of service C, constrained but with no queuing present) rises from 0.21 in 1990 to 0.29 in the year 2000. Even under LRT at buildout volumes, the volume-to-capacity ratio at 0.72 is still below 1.0.

STATION MEZZANINES

Station mezzanines provide areas for passenger activities between the street level and the platform

TABLE 1 Performance of Southwest Entrance, Westlake Station

	Estimated Peak a.m. Volume (passenger/min)	Width Required (at 12 passenger/min/ft) (in.)	Width Provided by Design (in.)	V/C
1990 Bus tunnel	31	31	144	0.21
2000 Bus tunnel	42	42	144	0.29
LRT at buildout	103	103	144	0.72

level. These activities include ticketing, queuing, and circulation. Often, certain passenger amenities are also provided at the mezzanine level, which would require additional spaces. The capacity of a station mezzanine is determined by the area available for each of these activities to accommodate the peak station passenger volume. Metro's current bus operation does not require fare collection in the CBD, and that activity is not anticipated for bus tunnel operations.

Under normal conditions, the time a passenger takes to complete the various activities at the mezzanine level was estimated to take about 75 sec. This includes 30 sec at ticket vendors and 45 sec for walking between activities and queuing at stairway or escalator approaches. This, of course, assumes that adequate capacity is available at each activity location such that no long queues would occur. Thus, the maximum number of passengers the mezzanine must serve is the projected peak passenger flow rate times 75 sec.

The space required for each activity at the mezzanine level is determined from the estimated number of persons engaged in that activity and the space required by a person to complete the activity at an acceptable level of service. For calculating the volume-to-capacity ratios of station mezzanines under 1990 and 2000 patronage estimates, the area per person required for various mezzanine activities (ticketing, queuing at escalator and stair approaches, walking, etc.) was multipled by the number of persons engaging in that particular activity. This resulted in a total area required for mezzanine activities that was then divided by the mezzanine area provided by the design. In this manner, the maximum volume-to-capacity ratio obtained for any station mezzanine under year 2000 patronage volume was 0.31 for the Third Avenue North station mezzanine, below design capacity. For LRT at buildout volumes, this increased to a V/C ratio of 0.64.

STATION PLATFORMS

Platform space required for passenger queuing was calculated using estimates of p.m. peak-passenger accumulation. A level of service standard of 7 ft²/person was used in the calculation. This standard corresponds to a design level of service on the low end of C, based on the levels of service that Fruin reports in the book Pedestrian Planning and Design and reported in the following table:

Level of Service	Ft²/Person
A	13 or more
B	10-13
C	7-10
D	3-7
E	2-3
F	2 or less

The example from the proposed Seattle system that shows how this methodology was used is the southbound platform of the Third Avenue North station (Table 2). As designed, this platform is 380 ft long and 16.5 ft wide. However, when a 3.5-ft walkway and a 1.5-ft buffer from the edge of the platform is subtracted from the width, the total width available for queuing is 11.5 ft. Multiplying 380 by 11.5 produces 4,370 ft² available for queuing. Peak passenger accumulation estimates for 1990, 2000, and LRT at capacity are then divided by the area available to determine square feet per passenger and level of service.

Although passenger volume for the system as a whole is estimated to be much greater during LRT operations, the peak accumulation on the platforms is estimated to be less than that experienced under year 2000 bus operations. This is because one LRT train should clear the platform of all waiting passengers, while a platoon of buses will not, because of the different route designations (based on a single corridor operation). Therefore, more passengers accumulate under the year 2000 bus tunnel operations.

For this particular platform, this analysis shows that the level of service will be A under 1990 and future LRT passenger accumulations. Even under year 2000 volumes, while at level of service C, the area per passenger is still 2 ft² greater than the minimum design standard providing a comfortable level of service.

SUMMARY

The reason for applying previous research in the pedestrian design field to the design of this particular project was to provide feedback from the preliminary engineering phase into the final design phase. The methodologies presented in this paper for the analysis of platforms, mezzanines, and entrances were applied to all five stations in the system. Ten platforms, five mezzanines, and 12 entrances were analyzed. Examples of each have been presented in this paper. Issues raised by reviewing this analysis of the system as it was defined in preliminary engineering were used as input for change in the final design process.

There is potential for a more refined approach to the analysis for platform capacity. Levels of service for queuing were based on observations at rail platforms. Under bus operations, there exists a potential for a greater amount of movement among the waiting passengers at the platform than observed at rail platforms, on which the level of service used in this analysis is based. Although this is hoped to be minimized by consistent placement of individual bus routes in the bus platoon, it could have the effect of raising the area required per passenger on the platform. Further analysis of this, using the time-space concept, may yield a more refined result to platform capacity (5).

REFERENCES

1. J.J. Fruin. Pedestrian Planning and Design. Metropolitan Association of Urban Planners, New York, 1971.

TABLE 2 Level of Service Third Avenue North Station Southbound Platform

	P.M. Peak Accumulation	Area Available for Queuing, ft²	Square Feet per Person	Level of Service
1990	249	4,370	17.5	A
2000	481	4,370	9.1	C
LRT at buildout	289	4,370	15.1	A

2. B. Pushkarev and J.M. Zupan. Urban Space for Pedestrians. Report of the Regional Planning Association, MIT Press, Cambridge, Mass., 1975.
3. Metro. Draft Environmental Impact Statement. Downtown Seattle Transit Project, Olympia, Wash., March 1984.
4. National Fire Protection Association, Code 130, Quincy, Mass, 1986.
5. G.P. Benz. Application of the Time-Space Concept to a Transportation Terminal Waiting and Circulation Area. Presented at the 65th Annual Meeting of the Transportation Research Board, Washington, D.C., 1986.