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Analyzing Transit Travel Time Performance

HERBERT S. LEVINSON

A detailed analysis of transit speeds, delays, and dwell times based on surveys conducted in a cross section of U.S. cities is summarized. The relationships and parameters provide inputs for planning service changes and assessing their impacts. The surveys and analyses find that car speeds are consistently 1.4 to 1.6 times as fast as bus speeds; time the typical bus speeds about 48 to 75 percent of its moving, 9 to 26 percent at passenger stops, and 12 to 26 percent in traffic delays; and peak-hour bus travel times approximate 4.2 min/mile in suburbs, 6.0 in the city, and 11.50 in the central business district. Bus dwell times (including door opening and closing) approximate 5 sec plus 2.75 times the number of passengers; during peak hours local buses stop at 68 to 78 percent of the designated stops. Bus travel times and speeds were derived as a function of stop frequency, stop duration, and bus acceleration and deceleration times observed in the field. Reducing bus stops from eight to six per mile and dwell times from 20 to 15 sec would reduce travel times from 6 to 4.3 min/mile, a time saving greater than that which could be achieved by eliminating traffic congestion. Transit performance should be improved by keeping the number of stopping places to a minimum. Fare-collection policies and door configurations and widths are important in reducing dwell time, especially along high-density routes. Such time savings will likely exceed those achieved from providing bus priority measures or improving traffic flow.

Transit travel times and operating speeds influence service attractiveness, costs, and efficiency. They also provide important descriptions of system performance for use in the transportation planning process. Yet, despite their importance, relatively few studies have been made to quantify these factors as they relate to ridership density, traffic conditions, and land use.

A detailed analysis of transit speeds, delays, and dwell times based on surveys conducted in a cross section of U.S. cities in 1980 (1) is summarized. The study was initially designed to verify and update INET reports on transit speed and roadway type (2). In a broader sense, however, it provides parameters for use in planning service changes and estimating their impacts.

The study included the following steps:

1. Available literature on transit-delay characteristics over the last several decades was assembled and analyzed;
2. Field studies were conducted of bus (and rail) performance in Boston, Chicago, New Haven, and San Francisco in 1979 and 1980;
3. Transit acceleration and deceleration characteristics were simulated and compared with actual times observed in the field; and
4. Results were integrated to produce a consistent and realistic picture of transit performance in U.S. cities.

Research findings address the following areas:

1. A comparison of line-haul bus and car travel times,
2. Bus speeds and delay,
3. Passenger service times at bus stops,
4. Bus (and train) dwell times (per stop) and stop frequencies (stops per mile),
5. Bus acceleration and deceleration, and
6. Transit speeds as a function of stop frequencies and dwell times.

The components of transit travel time that have been quantified are shown in Figure 1.

BUS AND CAR SPEEDS

Ratios of car to bus speed in Chicago's Loop, midtown Manhattan, Dallas, New Haven, and San Jose are shown in Table 1 (3-6). Car speeds are consistently 1.4 to 1.6 times faster than bus speeds. These ratios appear independent of year of study or type of city.

TRANSIT SPEED AND DELAY

Peak-hour transit speed and delay data for eight cities are summarized in Tables 2 and 3 (7-10). Minutes per mile (delay rate) has been used as the basic parameter, since it enables times to be added as needed. Means, standard deviations, and percentage distributions are given for time spent moving, at passenger stops, and in traffic delays. (The

Figure 1. Transit time components.

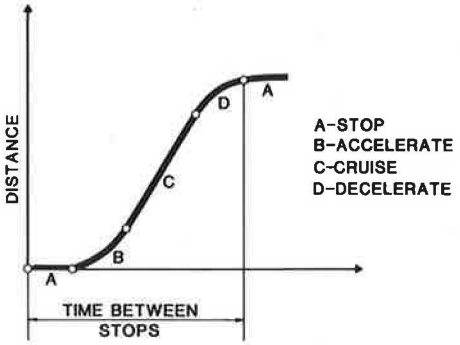


Table 1. Comparative bus and car speeds for selected urban areas.

		Relation of Car to Bus Speed (min/mile)					
		Morning Peak		Midday		Evening Peak	
City and Year	No. of Routes	Ratio	SD	Ratio	SD	Ratio	SD
Chicago (Loop), 1950	NA	–	–	1.39[a]	–	1.38	–
Dallas, 1972	14	1.61	0.28	–	–	1.65	0.16
New Haven, 1975	15	–	–	1.54	0.22	–	–
Midtown Manhattan, 1968	16	1.59	0.35	1.63	0.43	1.48	0.30
San Jose, 1968	NA	1.42	–	1.48	–	1.37	–

Notes: NA = not available.
Some data are from the Bureau of Traffic Operations, New York City Department of Transportation.

[a] 8:00 a.m. to 6:00 p.m.

Table 2. Travel time and delay for typical transit routes.

				Proportion of Journey Time (%) Spent for			
Mode	City and Year	No. of Routes or Streets	Avg. Travel Time (min/mile)	Traffic Delays	Passenger Stops	Moving	Remarks
Bus	Oakland, Alameda-Contra	4	4.95	19.4	26.7	53.9	Suburban
	Costa County, CA; 1979	1	3.18	18.6	23.6	57.9	Intercity
	Minneapolis, MN; 1977	3[a]	11.34	25.8	24.0	50.2	CBD
	Philadelphia, PA; 1977	2[a]	11.41	26.5	25.8	47.7	CBD
	Santa Clara, CA; 1969	3	4.38	16.2	9.1	74.7	Suburban
	St. Louis, MO; 1957-1958	20	5.47	12.1	17.9	70.0	City lines
	New Haven, CT; 1979-1980	2	6.14	19.0	18.4	62.6	Urban-suburban
Streetcar	Beacon St., Boston, MA; 1968	1	6.06	14.8	22.9	62.3	In center reservation
	St. Louis, MO; 1957-1958	4	6.60	12.7	17.7	69.6	City lines

Note: Some data are from field surveys in conjunction with the Regional Planning Agency of South Central Connecticut.

[a] Streets.

Table 3. Transit travel times for typical routes.

			Travel Time (min/mile)								
		No. of Routes or Streets	Avg or Total		Traffic Delays		Passenger Stops		Moving		
Mode	City and Year		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Remarks
Bus	Oakland, Alameda-Contra	4	4.95	0.37	0.96	0.19	1.32	0.26	2.67	0.16	Suburban
	Costa County, CA; 1979	1	3.18	0.25	0.59	0.11	0.75	0.07	1.84	0.26	Intercity
	Minneapolis, MN; 1977	3	11.34	1.96	2.93	1.46	2.72	1.23	5.69	1.19	CBD
	New Haven, CT; 1979-1980	1	5.88	0.51	0.99	0.14	1.15	0.22	3.74	0.31	Urban
		1	6.40	0.86	1.35	0.38	1.10	0.37	3.95	0.73	Urban
	Philadelphia, PA; 1977	2	11.41	0.88	3.03	0.50	2.94	0.64	5.44	0.36	CBD
	Santa Clara, CA; 1969	3	4.38	0.20	0.71	0.08	0.40	0.06	3.27	0.10	Suburban (low density)
	St. Louis, MO; 1957-1958	20	5.47	0.48	0.66	0.29	0.98	0.21	3.83	0.37	City lines
Streetcar	Beacon St., Boston, MA; 1968	1	6.07	0.83	0.90	0.24	1.39	0.46	3.78	0.22	In center reservation
	St. Louis, MO; 1957-1958	4	6.60	1.09	0.84	0.46	1.17	0.24	4.59	0.38	City lines

Note: Some data are from field surveys in conjunction with the Regional Planning Agency of South Central Connecticut.

Table 4. Estimated peak-hour transit travel times by component.

	Travel Time (min/mile)[a]		
Component	CBD	City	Suburbs
Traffic delay	3.00 ± 1.00	0.90 ± 0.30	0.70 ± 0.10
Passenger stops	3.00 ± 1.00	1.20 ± 0.30	0.50 ± 0.10
Moving	5.50 ± 1.00	3.90 ± 0.30	3.00 ± 0.12
Total	11.50 ± 3.00	6.00 ± 0.90	4.20 ± 0.30

Note: Data are from Tables 2 and 3.

[a] Plus-or-minus values represent one standard deviation.

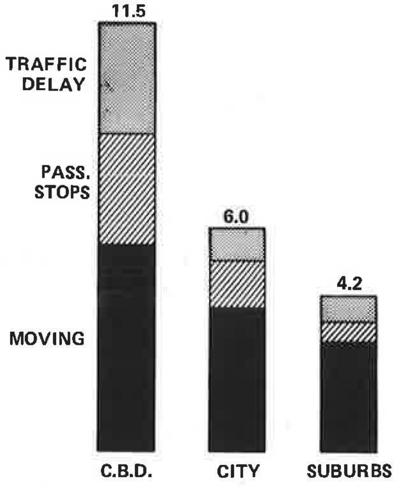
standard deviations reflect the variations among average times reported for various bus or streetcar routes in each community.)

Reported ranges for U.S. cities in the time spent enroute are moving, 48 to 75 percent; at passenger stops, 9 to 26 percent; and in traffic delays, 12 to 26 percent.

Transit travel times vary by type and location of route. Generalized peak-hour travel times for the central business district (CBD), central city, and suburban bus lines by time component are shown in Table 4 and Figure 2 in minutes per mile. The following characteristics may be noted:

1. Peak-hour bus travel times approximate 4.20 min/mile in suburban areas, 6.00 min/mile in the central city, and 11.50 min/mile in the CBD.
2. The time in motion approximates 3.00 min/mile in the suburbs, 3.90 min/mile in the central city, and 5.50 min/mile in the CBD. It appears to vary inversely with the frequency of stops.
3. Passenger stops account for 0.50 min/mile in the suburbs, 1.20 min/mile in the city, and 3.00 min/mile in the CBD.
4. Traffic delay amounts to 0.70 min/mile in the suburbs, 0.90 min/mile in the city, and 3.00 min/mile in the CBD.

Figure 2. Peak-hour bus travel times.



In the central city, passenger stop delay exceeds traffic delays, whereas they are about equal in the CBD. Therefore, ways to reduce passenger delays on a citywide basis may prove more beneficial than efforts focused only on alleviating traffic congestion at key locations.

BUS-STOP FREQUENCIES AND PASSENGER SERVICE TIMES

Information on passenger stops and dwell times was obtained from specially conducted field surveys in Boston, Chicago, New Haven, and San Francisco. The results of these studies are summarized in Table 5 in which the following information is given on a route-by-route basis:

1. Route location and distance;
2. Range and mean of actual stops made per mile;
3. Range and mean for maximum dwell times reported;
4. Range and mean for the average dwell times reported; and
5. Representative formulas for estimating passenger dwell times, including time spent opening and closing doors.

The formulas take the following form:

$$T = an + b$$

where n is the number of interchanging passengers per bus and T is the total stopped time per bus in seconds. Representative values of the coefficients a and b are as follows:

Location	Activity	a	b
Boston	Mainly discharging	1.2-1.7	4.0
Boston	Paying when outbound	2.0	4.3
New Haven	Boarding and alighting	2.6-3.0	3.9-5.6

The formula $T = 2.75n + 5$ sec provides a reasonable estimate of the dwell times in any community.

The variations in dwell time along specific routes reflect the location of stop, surrounding land uses, and the number of interchanging bus lines. Although stops generally average less than 20 sec, buses spent 30 to 60 sec at major transfer points, terminals, or rail-bus interchange locations. Examples of dwell times at major bus stops are shown in Table 6.

In estimating bus performance, it is necessary to

Table 5. Summary of observed bus-stop frequencies and passenger dwell times.

City	Bus Route	Distance (miles)	Time of Day	Direction	Stops per Mile		Dwell Time per Stop (sec)				Representative Formula	Remarks
							Maximum		Average			
					Range[a]	Mean[b]	Range[a]	Mean	Range[a]	Mean		
Boston	1	4.0	p.m.	Both	5.0-5.5	5	29-35	32	10.4-13.2	11.8	1.7n + 4.0	Urban route, mainly discharging passengers
	1	4.0	Midday	Both	3.3-3.5	3	37-61	49	14.4-17.3	15.7	2.5n + 5.0	Urban route, high density
	71	3.3	a.m.	SB	6.7	7	37	37	11.6[c]	11.6[c]	2.6n + 2.1	White-collar passengers Urban-suburban route
	71	3.3	Midday	Both	2.7-4.5	3	12-29	20	8.6-13.0	10.9	3.1n + 5.1	Suburban-urban route
	77	5.3	p.m.	NB	4.7	5	38	38	13.1	13.1	2.0n + 4.3	Pay when entering inbound, when leaving outbound; suburban limited stops
	77	5.3	Midday	Both	1.3-1.5	1	21-28	25	7.0-8.5[c]	7.8[c]	1.2n + 4.0	Mainly alighting passengers; suburban limited stops
	240A	8.8	Midday	Both	1.1-1.5	1	34-54	41	9.8-18.2[c]	13.6[c]	3.7n + 5.7[c]	Suburban line
Chicago	11	6.2	a.m.	SB	5.2	5	40	40	13.2	13.2	NA	Urban line
	11	1.2	a.m.	SB	6.7	7	40	40	17.7	17.7		Urban line, heavy section
	22	1.7	Midday	SB	6.5	6	27	27	14.1	14.1	NA	Central section, high-density line
New Haven				SB			21-40[d]	28[d]	8.5-14.3[d]	10.5[d]		
	B-1	4.1	p.m.	Southern leg	3.2-4.7	4	40-51	39			3.2n + 3.9	Urban route
	B-1	8.2	p.m.	SB through center	5.1-7.2	6	35-53[d]	44[d]	11.0-15.7[d]	14.5[d]	2.7n + 5.6	Urban route
	D1-2	6.6	p.m.	NB (northern leg)	4.1-5.6	5	26-39[d]	30[d]	10.1-13.5[d]	11.6[d]	2.5n + 5.1	Urban-suburban route
	D1-2	10.4	p.m.	SB through center	3.7-5.0	4	25-53[d]	34[d]	11.3-13.1[d]	11.9[d]	3.0n + 5.1	Urban-suburban route
	J1,2,3	4.8	p.m.	SB (southern leg)	5.2-6.3	6	30-45[d]	38[d]	9.5-11.5[d]	10.8[d]	2.8n + 4.4	Urban-suburban route
	J1,2,3	8.5	p.m.	NB through center	2.9-5.5	4	22-32[d]	30[d]	8.7-11.9[d]	10.7[d]	2.6n + 4.6	Urban-suburban route
	Q	3.0	a.m.	EB	5.3-6.0	6	9-20[d]	16[d]	4.5-8.2[d]	6.5[d]	NA	Urban route
San Francisco	Stockton	NA	a.m.	To center		6	30	30	21	21.0	NA	Urban route
Boston	Green Line	2.3	a.m.	Inbound	6.2	6	NA	33	NA	18.0	NA	Light-rail line, urban route
	Green Line	2.3	p.m.	Outbound	6.6	7	NA	37	NA	17.5	NA	Light-rail line, urban route

[a] Ranges are for averages for runs along each route.

[b] Mean stops per mile rounded to nearest integer.

[c] Excludes terminal stops.

[d] Excludes main CBD stops.

Table 6. Typical dwell times at major bus stops, 1979-1980.

Type of Stop	City	Route	Location	Time of Day	Observed Dwell Time (sec) Mean	SD
End of bus line at rail transit station	Boston	1, Massachusetts Avenue	Harvard Square, Red Line	p.m., midday	33	18
			Dudley Square, Orange Line	p.m., midday	38	13
		71, Watertown	Brattle Station, Red Line	a.m.	37	NA
		240, Randolph	Ashmont, Red Line	a.m.	55	NA
Transfer point at rail transit station	Boston	1, Massachusetts Avenue	Auditorium, Green Line	p.m.	36	8
		1, Massachusetts Avenue	Central Square, Red Line	p.m.	24	6
		77, Arlington Ltd.	Harvard Square, Red Line	a.m., midday	25	NA
	Chicago	11, Lincoln	Western, Ravenswood	a.m.	23	NA
		11, Lincoln	Fullerton, North, South	a.m.	23	NA
Major transfer point to another bus line	Chicago	11, Lincoln	Foster	a.m.	40	NA
	New Haven	Congress, Savin Rock	West Haven Center	p.m.	29	9
Major non-CBD stop, movie, town hall, hospital, school, etc.	Boston	71, Watertown	Watertown Square	a.m., midday	26	4
	Boston	77, Arlington Ltd.	Three major stops	p.m.	34	6
	New Haven	Congress	Yale, New Haven Hospital	p.m.	40	18

Notes: NA = not available.
Data are from field studies.

Table 7. Designated versus actual bus stops, 1979-1980.

City	Route	Time of Day	No. of Runs	Direction	Stops per Mile Scheduled	Actual	Actual to Scheduled (%)
Boston	1, Massachusetts Avenue	p.m.	2	NB	6.5	5.2	80.0
	71, Watertown-Brattle	a.m.	2	EB	7.6	6.7	88.0
	240, Randolph-Ashmont	a.m.	2	NB	1.7	1.5	83.3
	1, Massachusetts Avenue	Midday	4	NB, SB	6.5	3.4	52.3
	71, Watertown-Brattle	Midday	4	EB, WB	7.6	3.1	40.8
	77, Arlington Heights Ltd.	Midday	4	NB, SB	4.7	1.4	29.8
	240, Randolph-Ashmont	Midday	2	NB, SB	1.7	1.3	76.7
Chicago	11, Lincoln	a.m.	1	SB	7.7	5.2	67.5
	11, Lincoln, heavy 1.2 miles	a.m.	1	SB	8.3	6.7	80.7
	22, Clark	Midday	1	SB	11.2	6.5	58.0
New Haven	Q, Edgewood	a.m.	3	EB	6.6	5.7	85.8

Note: Data are from field studies.

know how often a bus stops as well as how long. Table 7 compares the number of scheduled stopping places with the bus stops actually made during peak and off-peak conditions. During peak hours local buses stopped at 68 to 78 percent of the designated stopping places. During off-peak periods, the ratio of actual to scheduled stops was as low as 30 percent. These figures suggest that transit systems could reduce the number of designated stops without adversely affecting ridership.

ACCELERATION AND DECELERATION TIME

Bus acceleration and deceleration time was computed by two separate methods, and the results were then compared. Actual times observed in field studies were summarized. Times were computed based on assumed cruise speeds and rates of acceleration and deceleration set forth in the first edition of the Transportation and Traffic Engineering Handbook (11). In effect, speed profiles were developed for various stop spacings.

Table 8 (7,12) gives detailed data on bus acceleration and deceleration based on various field studies. Total acceleration and deceleration time per stop ranged from 11 to 23 sec, depending on stop frequencies. Analysis of these data showed that the total acceleration plus deceleration time per stop followed this formula:

$$T = 23.4 - 1.53X \qquad R = -0.78$$

where X is the number of stops made per mile and T is the total acceleration and deceleration time per stop.

Acceleration and deceleration time based on this formula is compared below with that obtained based on theoretical calculations: The theoretical calculations assumed that a bus accelerates at its normal or maximum rate to reach the maximum possible cruise speed and subsequently decelerates at the maximum comfortable rate to a full stop (1):

No. of Stops per Mile	Acceleration and Deceleration Time (sec) Field Survey	Theoretical Calculation
1	21.9	44-62
2	20.3	44
3	18.8	37
4	17.3	30
5	15.8	24
6	14.2	24
7	12.7	18
8	11.2	13-18

The acceleration and deceleration time observed in the field was consistently less than that derived from the vehicle performance calculations, especially as the spacing between stops increases. For example, at six stops per mile, the field surveys found a 14-sec acceleration and deceleration time, whereas a bus

Table 8. Observed bus acceleration and deceleration times per stop.

City	Route	Avg Stops per Mile (X)	Acceleration and Deceleration Time per Stop (T) (sec)		Remarks
			Mean	SD	
Boston	1	3	14.8	3.8	Urban, high-density line
	71	3	20.2	4.3	Suburban line
	77	1	22.3	5.7	Suburban, limited stops
	240A	1	22.5	5.0	Suburban
Oakland	51	NA	17.3	3.0	Suburban
New Haven	Q	6	10.8	1.8	Urban
Chicago	11	5	18.0	2.7	Urban
	22	6	16.8	5.9	Urban, high density
Hong Kong	Small single-deck bus	–	14.5	4.4	
	Large single-deck bus	–	16.7	4.4	

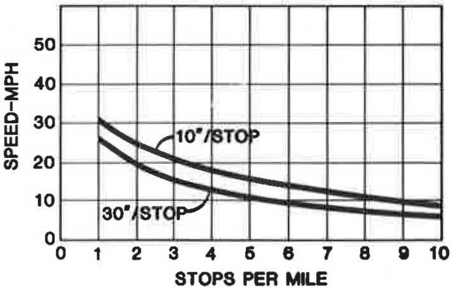
Note: Data are from field studies.

Table 9. Bus travel times and speeds as function of stop spacing.

	Dwell Time per Stop							
	10 sec		15 sec		20 sec		30 sec	
Stops per Mile	Minutes per Mile	Miles per Hour	Minutes per Mile	Miles per Hour	Minutes per Mile	Miles per Hour	Minutes per Mile	Miles per Hour
1	1.97	30.5	2.05	29.3	2.13	28.2	2.30	26.1
2	2.40	25.0	2.56	23.4	2.73	22.0	3.07	19.5
3	2.85	21.0	3.10	19.4	3.35	17.9	3.85	15.6
4	3.27	18.3	3.60	16.6	3.93	15.3	4.60	13.0
5	3.75	16.0	4.17	14.4	4.58	13.1	5.42	11.1
6	4.30	14.0	4.80	12.5	5.30	11.3	6.30	9.5
7	4.67	12.8	5.25	11.4	5.83	10.3	7.00	8.6
8	5.33	11.3	6.00	10.0	6.67	9.0	8.00	7.5
9	6.00	10.0	6.75	8.9	7.50	8.0	9.00	6.7
10	7.00	8.6	7.83	7.7	8.67	6.9	10.33	5.8
12	8.17	7.3	9.23	6.5	9.33	6.4	11.33	5.3

Note: Based on an acceleration and decleration rate of 3 mph/sec and acceleration-deceleration times observed in field.

Figure 3. Bus speed versus stops.



reaching its maximum possible cruise speed would spend 24 sec accelerating and decelerating.

Several factors underlie these differences:

1. Buses usually do not reach their maximum attainable cruise speeds between stops when operating on city streets because of posted speed limits, intersection interference, traffic signal controls, or street congestion. A bus making one stop per mile on a suburban street may never exceed 30 to 35 mph even though theoretically it would reach 50 to 60 mph.
2. Acceleration sometimes takes place through a series of steps in which the bus operates at several cruise speeds. Only the first step was considered as acceleration in the field.

Bus travel times and speeds as a function of stop spacing, dwell times, and observed acceleration and deceleration patterns are shown in Figure 3 and Table 9. Bus speeds as a function of stop spacing are similar to those reported in previous studies (13). These exhibits provide a practical guide for estimating bus travel times for various operating conditions and for assessing the changes in travel times resulting from reducing the frequency and duration of stops.

For example, at eight stops per mile and 20 sec/stop, bus travel time is 6 min. If the stops are reduced to six per mile and the dwell time to 10 sec/stop, bus travel time would be 4.30 min. This time saving exceeds the minute per mile buses normally lose due to traffic delay.

APPLICATIONS

General guidelines for peak-hour bus dwell times and stop frequencies as a function of location and route type are summarized below. These data provided inputs for Table 9 in estimating overall bus performance.

Passenger stops made per mile, passenger dwell time per stop, and acceleration and deceleration time per stop are given as a function of general location:

1. The number of passenger stops per mile actually made decreases with decreasing population density; suggested values are 8, CBD; 6, city; 4, inner suburbs; and 2, outer rural areas.
2. Passenger dwell times (seconds per stop) range from 30 (average) to 60 (major) sec in the CBD; they

average 15 sec in the city and 10 sec/stop in suburban areas.

3. Acceleration and deceleration time loss per stop average 11-13 sec in the CBD, 14-15 sec in the city, and 17-25 sec in suburban areas.

The type of route and type of stop vary among urban areas; they reflect ridership densities (reported by the transit agency), route configuration, and land use patterns.

Type of Route

Suggested guidelines for bus dwell times by type of route are given next (these exclude the CBD). A heavy urban route, for example, would have stops averaging 20 sec as compared with 16 sec for a medium route and 12 sec for a light route. For suburban and rural areas, heavy routes would have stops averaging 16 sec; medium routes, 12 sec; and light routes, 8 sec.

CBD Stops

Guidelines for peak-hour dwell times at CBD bus stops are shown below (based on 1979 New Haven data):

	Peak-Hour Dwell Time (sec)		
Type of Stop	Maximum	Avg. Mean	SD
Business	120	50	35
Other	60	20	15
Outlying	20	10	7

Bus dwell times will average 50-60 sec at the busiest stops, 20-30 sec at most stops, and 10 sec at lightly used stops on the CBD fringe. The maximum dwell times will be twice these values.

Major Bus Stops

Suggested guidelines for dwell times at major bus stops during evening peak hours include 40 sec for the end of the bus line at rail transit, 30-35 sec at the transfer point to rail transit or at a major bus stop, and 30-35 sec at other major stops.

Stops per Mile

Guidelines for the number of bus stops per mile actually made by type of route and area are given below:

Type of	Bus Stops per Mile		
Route	Urban	Suburban	Rural
Heavy	7	5	3
Medium	6	4	2
Light	5	3	2

Buses operating on a heavy urban route would make seven stops per mile as compared with six for a medium urban route and five for a light one.

IMPLICATIONS

The preceding parameters and relationships can be used directly in developing and assessing operating and service changes. They also provide inputs to long-range planning procedures. Field studies should be conducted to obtain city-specific parameters if greater precision is needed.

Several service planning and policy implications are apparent. Transit performance should be improved by keeping the number of stopping places to a minimum. Fare-collection policies and door configurations and widths are especially important in reducing dwell times along high-density routes. Many European transit systems have adopted such actions, but implementation in the United States generally has been limited even though the U.S. transit industry has recognized the need for fewer stopping places for 75 years.

It is desirable to eliminate traffic-induced congestion by improving general traffic flow or by providing bus priority lanes or streets or, in selected situations, bus signal preemption. These actions will improve bus performance in congested areas. Nevertheless, these gains often may be less than those resulting from reducing passenger service delays over the entire system. Herein lies an important challenge to transit operators.

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Modeling Bus Delays due to Passenger Boardings and Alightings

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Two causes of bus delay are examined: the delay from the stopping and starting at passenger stops and the dwell time as the passengers board and alight from the bus. Evaluation of data on the number of passengers boarding and alighting at stops along a route showed that the negative binomial is a good descriptor of this distribution. Additional data were used to determine dwell time per passenger as a function of the passenger boardings and alightings. By using these intermediate results, a procedure was developed to determine the resulting bus delay and its effect on operating speed, ridership, and ultimately on route performance. This methodology was then tested with data from Milwaukee, Wisconsin.

A significant deterrent to the use of public transportation is the excessive travel time, including both out-of-vehicle and in-vehicle times. The out-of-vehicle or excess travel time includes walking to the bus stop, waiting for the bus, transferring, and walking to the destination. The in-vehicle travel time in bus transportation is also usually longer than that in automobile transportation. The two main elements contributing to this difference are circuitous routing and stopping for passengers and starting again. In the past, not much attention was given to explicitly evaluating the impact on system operation of time spent by the bus in stopping for passengers. By using a performance evaluation model (1,2), we will examine the function for determining how many stops the bus will make along a route, the dwell time required at each stop, and the resulting effect on system operation.

DESCRIPTION OF PERFORMANCE EVALUATION MODEL

The performance evaluation model is used to evaluate changes in operational performance due to a short-range change in service expressed in terms of travel-time changes. After the travel-time changes expected from a service change have been estimated, the ridership change is estimated according to the values of the demand elasticities input into the model, as follows:

$$Q_1 = Q_0[1 + \alpha(\mathrm{DIVTT}) + \beta(\mathrm{DOVTT})]\ r \qquad (1)$$

where

Q_1 = new service demand in passengers per hour over the length of the route,
Q_0 = old service demand in passengers per hour over the length of the route,
α = demand elasticity with respect to in-vehicle travel time,
DIVTT = percentage of change in in-vehicle travel time,
β = demand elasticity with respect to out-of-vehicle travel time,
DOVTT = percentage of change in out-of-vehicle travel time, and
r = ratio of new to old person-trip ends served by the route.

The in-vehicle travel time is a function of the average travel distance and the overall operating speed of the bus after corrections for passenger stops have been made. The bus running speed without stops for passengers is an input into the model. For each passenger stop, a time penalty of delta (δ) is made, averaging 10 to 20 sec. A dwell time of epsilon (ϵ), averaging 3 to 5 sec, is added for each passenger boarding and alighting.

To determine the number of passenger stops, the assumption is made that the passenger demand is uniformly distributed along the route. Consequently, the number of passengers boarding and alighting at each stop would follow a Poisson distribution. The probability of a stop with z passengers boarding and alighting is given as

$$p(z) = \exp(-m)m^z/z! \qquad (2)$$

where m is the average number of passengers per stop.

The probability that a stop will actually be made is 1 minus the probability of a zero-passenger stop, as follows:

$$1 - p(0) = 1 - \exp(-m) \qquad (3)$$

The total time spent by the bus in the starting and stopping maneuver in seconds per mile is given as

$$D_1 = \delta Y[1 - p(0)] \qquad (4)$$

where Y is stops per mile and D_1 is the starting and stopping time per mile.

The dwell time while passengers are boarding and alighting in seconds per mile is given as

$$D_2 = 2Q_1\epsilon \mathrm{HDWY}/L \qquad (5)$$

where D_2 is the dwell time per mile and L is the route length in miles.

The operating speed is given as the reciprocal of the total travel time per mile:

$$S = 1/[1/\mathrm{RSPD} + (D_1 + D_2)/3{,}600] \qquad (6)$$

where S is the operating speed in miles per hour and RSPD is the running speed in miles per hour without passenger delays.

The in-vehicle travel time is then determined to be as follows:

$$\mathrm{IVTT} = M/S \qquad (7)$$

where M is the average passenger-trip length.

During the development of the initial version of the performance evaluation model, two assumptions were made: (a) the passenger boardings and alightings along a route follow a Poisson distribution, and (b) the dwell time per passenger is independent of the number of passengers boarding and alighting at each stop. Field data were used to analyze the validity of these assumptions. A discussion of this analysis is presented below.

PASSENGER BOARDING AND ALIGHTING DISTRIBUTION ALONG BUS ROUTE

Two routes in Milwaukee, Wisconsin, were studied to check the validity of the Poisson assumption. Route 27 is a heavily traveled crosstown route traversing primarily high-density residential and commercial areas. Because Milwaukee's streets are in a grid pattern, a large amount of transferring takes place between Route 27 and the downtown-oriented routes with which it intersects. Headways range from 8 min during the peak hours to 17 min late at night. Route 28 is also a crosstown route, but it is located in a primarily suburban area and is lightly used. Neighboring land use is primarily strip commercial, light industrial, and medium-density residential. The bus enters a regional shopping center at the middle of the route. Headways are 30 to 36 min on weekdays. No weekend or evening service is offered.

Data for each route were available from an on-board sample. The passenger boardings and alightings were recorded at each stop once for each scheduled run of the bus. Data from three round trips were selected for each route. One trip occurred during the morning peak hour, one was at midday, and the third was during the evening peak. Northbound and southbound data were analyzed independently for each route.

Table 1 gives the recorded data for each one-way run of the bus for Route 27, and Table 2 gives the same for Route 28. The average number of passengers at a stop, sample variance, chi-square, and test values for the two sets of data are given in Table 3.

By using the original assumptions of the model, the passenger distributions were determined from a Poisson distribution. The Poisson distribution uses

Table 1. Passenger distribution along Route 27.

No. of Boardings and Alightings per Stop	Observed Data (no. of stops)	Poisson Prediction	No. of Boardings and Alightings per Stop	Observed Data (no. of stops)	Poisson Prediction
Northbound, Morning Peak			Southbound, Morning Peak		
0	41	7.9	0	26	0.5
1	18	20.8	1	7	2.7
2	15	27.4	2	6	6.7
3	11	24.1	3	11	11.3
4	6	15.9	4	6	14.1
5	4	8.3	5	3	14.2
6	2	3.7	6	3	11.9
7	5	1.4	7	3	8.5
8	2	0.5	8	1	5.4
9	1	–	9	1	3.0
11	2	–	10	2	1.5
16	1	–	11	1	0.7
18	1	–	13	3	–
37	1	–	15	1	–
			21	1	–
			22	2	–
			23	1	–
			24	1	–
			31	1	–
			32	1	–
Northbound, Midday			Southbound, Midday		
0	39	4.8	0	44	5.7
1	12	14.3	1	10	16.8
2	11	21.3	2	14	24.7
3	12	21.1	3	13	24.2
4	1	15.6	4	4	17.7
5	3	9.3	5	6	10.4
6	2	4.6	6	2	5.1
7	2	1.9	7	1	2.1
8	0	0.7	8	3	0.8
9	4	–	9	3	–
10	1	–	10	1	–
12	1	–	11	1	–
13	2	–	12	4	–
15	1	–	16	1	–
17	1	–	39	1	–
20	1	–			
28	1	–			
Northbound, Evening Peak			Southbound, Evening Peak		
0	30	3.3	0	19	1.9
1	15	10.9	1	15	7.0
2	10	18.1	2	11	13.2
3	9	20.1	3	10	16.6
4	6	16.6	4	4	15.7
5	5	11.0	5	5	11.9
6	4	6.1	6	5	7.5
7	2	2.9	7	4	4.0
8	1	1.2	11	1	–
10	2	–	12	2	–
12	1	–	13	1	–
13	1	–	16	1	–
14	1	–	23	1	–
15	1	–	25	1	–
21	1	–	28	1	–
22	1	–			
28	1	–			

Table 2. Passenger distribution along Route 28.

No. of Boardings and Alightings per Stop	Observed Data (no. of stops)	Poisson Prediction	No. of Boardings and Alightings per Stop	Observed Data (no. of stops)	Poisson Prediction
Northbound, Morning Peak			Southbound, Morning Peak		
0	49	44.2	0	48	37.9
1	11	18.4	1	15	23.3
2	5	3.8	2	3	7.1
3	2	0.6	3	1	1.7
			5	2	–
			9	1	–
Northbound, Midday			Southbound, Midday		
0	54	49.7	0	54	39.5
1	9	14.8	1	6	22.6
2	2	2.2	2	4	6.4
3	1	0.2	3	3	1.4
4	1	–	4	1	–
			5	1	–
			8	1	–
Northbound, Evening Peak			Southbound, Evening Peak		
0	44	41.0	0	54	40.1
1	17	20.2	1	8	22.3
2	3	5.0	2	2	6.2
3	2	0.9	3	2	1.3
4	1	–	4	1	–
			5	2	–
			7	1	–

Table 3. Summary of statistics from Tables 1 and 2.

Data Set	Mean No. of Passengers	Variance	Chi-Square	Test Value
Route 27				
Northbound				
Morning peak	2.636	21.142	221.[a]	18.47 (7 df)
Midday	2.968	23.414	310.[a]	16.81 (6 df)
Evening peak	3.318	25.316	253.[a]	18.47 (7 df)
Southbound				
Morning peak	5.024	51.950	323.[a]	20.09 (8 df)
Midday	2.935	24.040	300.[a]	16.81 (6 df)
Evening peak	3.778	28.770	105.[a]	16.81 (6 df)
Route 28				
Northbound				
Morning peak	0.403	0.569	3.83[b]	9.21 (2 df)
Midday	0.298	0.538	3.64[b]	9.21 (2 df)
Evening peak	0.493	0.698	1.49[b]	9.21 (2 df)
Southbound				
Morning peak	0.614	2.008	6.02[b]	9.21 (2 df)
Midday	0.571	1.873	18.4[a]	9.21 (2 df)
Evening peak	0.557	1.818	16.9[a]	9.21 (2 df)

[a] Significantly different from the Poisson distribution at the 0.01 level.

[b] Evidence is not present that the distribution is not Poisson.

a single parameter (m), which is equal to both the mean and the variance of the distribution. The resulting distributions for separate data sets are shown in Tables 1 and 2. A chi-square (χ^2) goodness-of-fit test was performed for each distribution (Table 3). A significance level of 1 percent was used. This means that if the hypothesis that the passenger distribution is Poisson is rejected, there is a 1 percent chance that the data may in fact be Poisson distributed. The observed χ^2-value along with the test value are shown for each data set in Table 3. It can be noted that because of the low demand for Route 28, very few heavily used stops were recorded. In the northbound direction, no stop was observed with more than four passengers boarding and alighting. The same results were obtained for the southbound morning-peak data. It can therefore be concluded that the Poisson distribution cannot be rejected only in a situation where the passenger boardings and alightings are relatively low. Route 27 has a higher demand and the distribution of passenger boardings and alightings was found to be more significantly different from the Poisson distribution than that observed in the case of the southbound midday and afternoon peak-hour data for Route 28.

A review of the Route 27 data in terms of the Poisson distribution, as shown in Table 1, reveals two major discrepancies. First, many more stops at which no boardings or alightings occurred were observed in the field than the Poisson distribution predicts. The result of using the Poisson distribution in this situation would be a much lower level of service because the model would simulate that the bus stopped far too many times.

The Poisson distribution also projects too few stops serving a large number of passengers. For example, the northbound data for Route 27 during the morning peak included six stops involving more than eight passengers, whereas the Poisson distribution indicated none. Although this is only 5.4 percent of the total stops, 102 boardings and alightings or 35.2 percent of the total is involved.

It therefore appears that the Poisson distribution is not a good descriptor of the distribution of passengers along a route. An improved procedure is necessary to estimate the number of stops with a given number of passengers. This was accomplished as discussed in the following section.

DEVELOPMENT OF IMPROVED PROCEDURE

A comparison of the variances with the corresponding means, as given in Table 3, revealed that the variance is higher in all cases presented here. The Poisson distribution did not fit these data because it requires a variance equal to the mean. Note that these two parameters are most nearly equal for the data from northbound Route 28, where passenger boardings and alightings are low and the assumption of a Poisson distribution could not be rejected.

Consequently, the applicability of the negative binomial distribution was explored. The negative binomial distribution is characterized as having a variance higher than the mean. Three parameters of the distribution are defined as follows:

$$p = m/s^2 \tag{8a}$$

$$q = 1 - p \tag{8b}$$

$$k = pm/q = m^2/(s^2 - m) \tag{8c}$$

where

m = sample mean,
S^2 = sample variance, and
p,q,k = parameters of negative binomial distribution.

The probability of a zero occurrence is then given as follows:

$$P(0) = p^k \tag{9}$$

The probability of z is given as follows:

$$P(z) = [(z + k - 1)/z] \times q \times P(z - 1) \tag{10}$$

The negative binomial distribution was found to be an acceptable descriptor of passenger boardings and alightings under all volume conditions observed in the sample.

One advantage of the Poisson distribution is that only one parameter is required (the mean), whereas the negative binomial distribution requires both a mean and a variance. Nevertheless, a careful examination of the sample means and variances in Table 3 indicates that they may be correlated with each other. Consequently, a linear regression analysis was performed to develop the following second-order equation:

$$s^2 = -1.305 + 4.870m + 1.085m^2 \tag{11}$$

R^2 for this equation was the high value of 0.991. This equation was found to be an accurate predictor except in the situation of an extremely small mean. The predicted variance actually equals the mean at a value of 0.31 and drops below the mean at lower values. Because the negative binomial distribution dictates a variance higher than the mean, the equation was modified to assign a variance of 1.1 times the mean at values below 0.32. This modification produced significant results. One must be careful not to use this equation on other data, however, without careful examination of the results from those data.

By using the predicted value of the variance, negative binomial distributions were fitted to the passenger data as shown in Tables 4 and 5. A goodness-of-fit test was performed for each distribution at a level of significance of 1 percent. The chi-square, test values, and predicted and actual variances for Route 27 and Route 28 data are given in Table 6.

DWELL TIME

The assumption that dwell time per passenger is independent of the number of passengers boarding and alighting may be erroneous. For example, Kraft (3) found that this function follows an Erlang distribution. To further examine this distribution, dwell-time data from a survey of one of the more heavily used routes in Lafayette, Indiana, were obtained (4), as shown in Table 7. Data were tabulated during six 30-min runs of the route. There were two runs from each of the morning-peak, off-peak, and evening-peak periods of the day. The dwell time was recorded along with the number of persons boarding and alighting at each stop. It is interesting to note that although the total dwell time increases, the time per passenger decreases as the number of passengers at a stop increases.

For the data in Table 7, the total number of passengers boarding and alighting is 357, total number of stops is 113, overall average dwell time is 9.54 sec, SD is 7.46, and average dwell time per passenger weighted by passenger is 3.02 and that weighted by stop is 4.07.

By using these data, a regression analysis was performed to relate the natural logarithm of the

Table 4. Test of negative binomial model by using predicted variances for Route 27.

No. of Boardings and Alightings per Stop	Observed Data (no. of stops)	Negative Binomial Model Prediction	No. of Boardings and Alightings per Stop	Observed Data (no. of stops)	Negative Binomial Model Prediction
Northbound, Morning Peak			Southbound, Morning Peak		
0	41	47.64	0	26	22.52
1	18	17.36	1	7	11.25
2	15	10.64	2	6	7.87
3	11	7.41	3	11	6.04
4	6	5.46	4	6	4.83
5	4	4.16	5	3	3.96
6	2	3.24	6	3	3.30
7+	13	14.07	7+	19	21.33
Northbound, Midday			Southbound, Midday		
0	39	37.91	0	44	43.85
1	12	14.71	1	10	16.92
2	11	9.25	2	14	10.61
3	12	6.55	3	13	7.51
4	1	4.91	4	4	5.61
5	3	3.79	5	6	4.33
6+	16	16.88	6	2	3.42
			7+	15	15.75
Northbound, Evening Peak			Southbound, Evening Peak		
0	30	34.16	0	19	27.85
1	15	14.04	1	15	12.20
2	10	9.03	2	11	8.07
3	9	6.51	3	10	5.93
4	6	4.95	4	4	4.58
5	5	3.88	5	5	3.64
6	4	3.10	6+	17	18.73
7+	12	15.32			

Table 5. Test of negative binomial model by using predicted variances for Route 28.

No. of Boardings and Alightings per Stop	Observed Data (no. of stops)	Negative Binomial Model Prediction	No. of Boardings and Alightings per Stop	Observed Data (no. of stops)	Negative Binomial Model Prediction
Northbound, Morning Peak			Southbound, Morning Peak		
0	49	50.93	0	48	51.21
1	11	9.93	1	15	9.22
2	5	3.53	2	3	4.09
3+	2	2.61	3+	4	5.48
Northbound, Midday			Southbound, Midday		
0	54	50.41	0	54	51.76
1	9	13.68	1	6	9.23
2+	4	2.91	2	4	4.00
			3+	6	5.01
Northbound, Evening Peak			Southbound, Evening Peak		
0	44	50.41	0	54	51.94
1	17	9.02	1	8	9.24
2	3	3.68	2	2	3.97
3+	3	3.90	3+	6	4.85

Table 6. Summary of statistics from Tables 4 and 5.

Data Set	Chi-Square[a]	Test Value	Variance Predicted	Variance Actual
Route 27				
Northbound				
Morning peak	5.09	18.47 (7 df)	19.069	21.142
Midday	8.56	16.81 (6 df)	22.705	23.414
Evening peak	3.16	18.47 (7 df)	26.803	25.316
Southbound				
Morning peak	5.83	18.47 (7 df)	50.541	51.950
Midday	9.66	18.47 (7 df)	22.334	24.042
Evening peak	8.05	16.81 (6 df)	32.573	28.765
Route 28				
Northbound				
Morning peak	0.94	11.34 (3 df)	0.833	0.569
Midday	2.26	9.21 (2 df)	0.328[b]	0.5378
Evening peak	8.20	11.34 (3 df)	1.356	0.698
Southbound				
Morning peak	4.51	11.34 (3 df)	2.096	2.008
Midday	1.42	11.34 (3 df)	1.831	1.873
Evening peak	1.50	11.34 (3 df)	1.744	1.818

[a] Evidence against the distribution's being negative binomial by using predicted variances is not present.

[b] Mean = 1.1.

Table 7. Lafayette dwell-time survey results.

No. of Passengers Boarding and Alighting	No. of Stops	Avg Dwell Time (sec)	Standard Deviation of Dwell Time (sec)	Avg Dwell Time per Passenger (sec)
1	41	4.83	2.14	4.83
2	29	9.45	8.21	4.73
3	18	10.82	3.68	3.61
4	10	11.53	6.31	2.88
5	2	6.85	1.63	1.37
6	3	12.00	5.19	2.00
7	1	21.00	-	3.00
8	2	30.50	9.19	3.81
9	1	28.00	-	3.11
14	2	24.00	0.00	1.71
15	2	19.00	0.00	1.27
22	1	26.00	-	1.18
24	1	24.00	-	1.00

dwell time per person to the number of boardings and alightings at each stop. The equation was found to be

$$\epsilon = 5.0 - 1.2[\ln(z)] \qquad (12)$$

where ϵ is the dwell time per passenger and z is the number of boardings and alightings at a stop.

This equation was significant at the 99 percent level by using the F-test. Nevertheless, the relatively low value of 0.36 for R^2 indicates that the variation in dwell time depends not only on the number of passengers but also on other factors. For example, a lower value for dwell time would be expected if

1. Many people board and alight from the bus at only a few stops, such as in an express bus service, or
2. Monthly passes or tokens are in effect, reducing the time needed to pay fares.

The average dwell time might increase if

1. Many elderly and handicapped persons are present,
2. A complex fare structure is used,
3. The basic fare requires a large number of coins (e.g., 45 cents requires at least three coins), or
4. Small buses that have only one door are used.

Further analysis of Equation 12 reveals that the maximum dwell time per stop occurs when there are approximately 24 passengers. The value of ϵ is 1.2 sec at this point. It can be expected that the total dwell time will continue to increase as the number of boardings and alightings increases. Consequently, the model assigns the value of 1.2 sec to

ε whenever 24 or more passengers are using a given stop. The final dwell time as a function of the number of passengers at a stop is then given as

$$\mathrm{TIME}(z) = z\,[5.0 - 1.2\ln(z)] \qquad z \leqq 23 \tag{13a}$$

$$\mathrm{TIME}(z) = 1.2z \qquad z \geqq 24 \tag{13b}$$

METHODOLOGY FOR ESTIMATING BUS DELAY

The findings from the passenger distribution and dwell-time analyses were used to develop a procedure that can estimate the bus delay time as a function of the number of passengers along a route as discussed below.

By using the approach of Sinha and Bhandari (1), the average demand at a stop is obtained:

$$m = 2Q_1(\mathrm{HDWY})/(Y \times L) \tag{14}$$

The variance of passenger demand is computed by using Equation 11. The parameters for the negative binomial distribution can then be determined from Equations 8a, 8b, and 8c on the basis of the values for the mean and variance. The number of nonzero stops per mile can be found from Equation 9 as follows:

$$\mathrm{SPM} = Y \times [1 - P(0)] \tag{15}$$

where SPM is the number of nonzero stops per mile.

The delay per mile for the stopping and starting maneuver of a bus is given by

$$D_1 = \delta \times \mathrm{SPM} \tag{16}$$

The dwell time per mile for stops with 23 or less boardings and alightings can be found by combining Equations 10 and 13 as follows:

$$D_2' = Y \sum_{z}^{23} \mathrm{TIME}(z) \times P(z) \tag{17}$$

The dwell time for those stops with 24 or more boardings and alightings is simply set as 1.2 sec times the number of passengers involved, as follows:

$$D_2'' = 1.2Y \times \left\{m - \sum_{z=1}^{23} [P(z) \times z]\right\} \tag{18}$$

The total dwell time per mile is then

$$D_2 = D_2' + D_2'' \tag{19}$$

The total delay in hours per mile caused by the bus's stopping for passengers is then

$$\mathrm{Delay} = (D_1 + D_2)/3{,}600 \tag{20}$$

This value can be directly substituted into Equation 6 to compute the bus operating speed.

ANALYSIS OF RESULTS

The performance evaluation model was appropriately modified to include a negative binomial distribution for passenger distributions at stops as well as the revised procedure to compute vehicle dwell time. The computation of the operating speed was thus also modified by incorporating the logic for bus delay. The model was then applied to analyze the operation of the same routes in Milwaukee where the passenger data had been obtained. Some key input data are shown in Table 8. The average ridership and trip length were obtained from the data supplied by the Milwaukee County Transit System. The route lengths and numbers of posted stops per mile were determined from measuring the route from an automobile. The running speeds were determined by recording times while riding in the bus.

In Table 9 a comparison is shown of the model results with the actual recorded values from the two routes. In general, the results proved to be within about 10 percent. The notable exceptions were the results of the analysis of Route 27 during the morning peak hour. This difference can be accounted for by exceptionally low ridership during the sampling. As a means of examining how the model performs under different inputs, the ridership and the posted stops per mile were tested at the following levels:

1. Ridership: level 1, as observed in the field (Table 8); level 2, 20 percent increase.
2. Stops per mile: level 1, 12.5; level 2, existing as shown in Table 8; level 3, 2.5.

Some of the results of the analysis of the northbound parts of the routes are shown in Table 10. The ridership results were determined from Equation 1 by using elasticity values of -0.35 for in-vehicle travel time (α) and -0.70 for out-of-vehicle travel time (β). The conclusions obtained from the southbound data were the same and therefore are not discussed here.

An evaluation of the Route 27 results reveals that the decrease in posted stops per mile to 2.5 produced about an 11 to 16 percent increase in oper-

Table 8. Input data for application of performance evaluation on Milwaukee routes.

Route	Direction	Time Period	Avg Ridership per Hour	Avg Trip Length (miles)	Route Length (miles)	Avg Headway (min)	Posted Stops per Mile	Fare (cents)	Estimated Running Speed (mph)
27	Northbound	Morning peak	603.7	2.20	13.22	11.25	6.9	75	17.5
		Midday	509.8	2.20	12.18	10.59	6.9	75	18.6
		Evening peak	1,067.2	2.20	12.44	8.18	6.9	75	16.1
		Evening	274.0	2.20	12.58	11.66	6.9	75	17.0
		Night	137.3	2.20	9.03	17.60	6.9	75	17.0
27	Southbound	Morning peak	1,176.2	2.20	13.01	7.50	6.9	75	16.9
		Midday	565.3	2.20	12.57	9.47	6.9	75	16.4
		Evening peak	705.3	2.20	13.14	12.85	6.9	75	16.8
		Evening	289.4	2.20	12.97	11.67	6.9	75	17.0
		Night	129.6	2.20	13.08	14.28	6.9	75	17.0
28	Northbound	Morning peak	12.6	2.50	12.1	30.00	5.6	75	22.3
		Midday	10.8	2.50	12.1	36.00	5.6	75	24.0
		Evening peak	28.8	2.50	12.1	30.00	5.6	75	25.1
28	Southbound	Morning peak	28.5	2.50	12.0	30.00	5.6	75	24.3
		Midday	21.0	2.50	12.0	36.00	5.6	75	22.2
		Evening peak	30.2	2.50	12.0	30.00	5.6	75	19.7

Table 9. Comparison of model output with actual recorded values.

			Nonzero Stops per Mile		Total Bus Delay (sec/mile)		Operating Speed (mph)	
Route	Direction	Time Period	Model	Actual	Model	Actual	Model	Actual
27	Northbound	Morning peak	3.8	3.0	82.3	53.5	12.5	13.9
		Midday	3.6	3.3	75.0	71.9	13.4	13.5
		Evening peak	4.3	4.8	99.3	95.0	11.1	11.4
27	Southbound	Morning peak	4.3	3.5	97.3	61.3	11.6	13.1
		Midday	3.5	3.3	73.1	70.4	12.3	12.4
		Evening peak	4.3	4.4	98.3	92.7	11.5	11.7
28	Northbound	Morning peak	0.9	0.9	13.5	13.5	20.5	20.5
		Midday	0.9	0.9	13.8	17.1	22.0	21.5
		Evening peak	1.4	1.3	22.7	22.9	21.7	21.4
28	Southbound	Morning peak	1.3	1.4	22.7	21.4	17.5	21.2
		Midday	1.3	1.2	21.5	20.7	19.6	19.7
		Evening peak	1.3	1.2	22.2	21.4	21.2	17.6

Table 10. Model results on delay from passenger boardings.

Route	Direction	Time Period	Stops per Mile	Ridership Level	Nonzero Stops per Mile	Total Bus Delay per Mile (sec)	User Cost per Passenger ($)	Operating Speed (mph)	Annual Ridership
27	Northbound	Morning peak	2.5	1	1.9	50.1	1.12	14.07	406,439
				2	2.0	55.1	1.13	13.80	490,068
			6.9	1	3.8	82.3	0.99	12.49	461,831
				2	4.1	92.0	1.00	12.09	554,197
			12.5	1	5.2	102.8	0.97	11.66	473,419
				2	5.7	115.9	0.99	11.12	566,399
		Midday	2.5	1	1.8	46.2	1.08	14.99	681,379
				2	1.9	50.9	1.09	14.70	821,636
			6.9	1	3.6	75.0	0.95	13.39	779,994
				2	3.9	84.1	0.96	12.95	935,993
			12.5	1	4.8	93.2	0.92	12.54	801,904
				2	5.3	105.2	0.94	12.03	959,659
		Evening peak	2.5	1	2.0	58.2	1.05	12.78	702,310
				2	2.1	64.0	1.06	12.52	846,560
			6.9	1	4.3	99.3	0.93	11.15	816,408
				2	4.6	110.2	0.94	10.79	979,690
			12.5	1	6.1	126.8	0.92	10.28	841,132
				2	6.7	142.3	0.94	9.84	1,005,822
28	Northbound	Morning peak	2.5	1	0.6	9.8	1.90	21.03	9,057
				2	0.6	10.4	1.84	20.95	10,907
			5.6	1	0.9	13.5	1.69	20.58	9,639
				2	1.1	16.0	1.70	20.29	11,567
			12.5	1	1.0	14.4	1.63	20.47	9,923
				2	1.2	17.2	1.63	20.16	11,902
		Midday	2.5	1	0.6	9.9	1.92	22.52	15,607
				2	0.6	10.5	1.92	22.42	18,799
			5.6	1	0.9	13.8	1.77	21.97	16,524
				2	1.1	16.4	1.77	21.63	19,829
			12.5	1	1.0	14.8	1.71	21.85	16,977
				2	1.2	17.6	1.71	21.48	20,361
		Evening peak	2.5	1	0.8	15.4	1.76	22.67	20,874
				2	0.9	17.3	1.82	22.40	25,029
			5.6	1	1.4	22.7	1.68	21.67	22,032
				2	2.1	31.2	1.63	20.61	22,329
			12.5	1	2.5	36.7	1.64	19.98	26,600
				2	2.8	43.5	1.67	17.13	26,496

ating speed. However, an increase to 12.5 stops per mile caused a somewhat smaller decrease. For Route 28, the effect of a change in posted stops on the operating speed is similar but much less. If the number of stops is reduced to 2.5, the operating speed increases only 2 to 5 percent. On the other hand, if the number of stops is increased to 12.5, the change in operating speed is much less. The implication here is that there is very little demand for posted stops beyond eight per mile along this route with low ridership levels.

For Route 28, the user cost per passenger always decreases with an increased number of stops because of the shorter walking distance, but for Route 27, the user cost per passenger decreases only negligibly with added stops. The reason is that the increase in user cost due to an increase in in-vehicle travel time as the bus makes more stops offsets the associated decreased walking time.

It should be explained that the user costs are larger for Route 28 because of the longer waiting times due to longer headways. In addition, the configuration of Route 28 is such that the walking time to the bus stop is longer.

The ridership decreased by about 5 to 6 percent for Route 27 and by about 11 to 14 percent for Route 28; there was a decrease in posted stops per mile to 2.5. The implication here is that the out-of-vehicle travel time becomes longer with fewer stops, which causes a decrease in ridership. Nevertheless, because of the higher operating speed due to less stops, the in-vehicle travel time decreases, which attracts additional riders. The net result was, however, a reduction in ridership. With an increase to 12.5 posted stops per mile, the ridership increased by much less than the magnitude of the decrease caused by fewer stops per mile. This is a reasonable result because the percentage of change in walking distance is also about one-half of the magnitude, as it was with the decrease in stops per mile.

For both routes, the model indicated that a 20 percent increase in ridership generally caused a decrease in operating speed by about 1 to 4 percent. Also, the number of stops with some passengers boarding or alighting increased by about 5 to 15 percent for a 20 percent increase in ridership. The total delay increased proportionately. For Route 28, the user cost per passenger increased only slightly. Due to the already crowded conditions on Route 27, however, the user costs per passenger were affected to a greater extent. Still, the average increase was only about 1 percent.

CONCLUSIONS

In determining a transportation mode choice, the overall travel time is a very important element. Although the adverse effect of out-of-vehicle travel time is most severe, it is also important to reduce the in-vehicle travel time as much as possible. A major disadvantage of the bus is that it has to stop continually to allow passengers to board and alight. Not much attention has been given to determining explicitly the impact that this stopping has on the overall operating speed of the route.

By using data from Milwaukee, Wisconsin, the distribution of passengers boarding and alighting at stops along a route was analyzed. It was found that a Poisson distribution could be used only on routes with low ridership. Nevertheless, the negative binomial distribution was found to be a good descriptor of passenger boardings and alightings over a range of ridership levels. Data from Lafayette, Indiana, were used to analyze the bus dwell time. It was found that the bus dwell time per passenger decreases with the natural logarithm of the boardings and alightings at the stop. From these findings, a procedure was developed to determine the resulting bus delay and its effect on operating speed.

The methodology was then tested by using data from Milwaukee, Wisconsin, and assuming different numbers of stops per mile. Analysis of the output revealed two major findings. First, a change in posted stops along a low-demand route will have only a minor effect on bus operating speed but will reduce the user's walking distance. Second, because additional posted stops along a high-demand route will save walking distance at the cost of greater in-vehicle travel time, an optimum number of posted stops per mile should be sought.

This methodology can be applied to all operating-policy changes that have an effect on the operating speed. Appropriate performance measures can then be used to examine the impact of the various policy options.

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Economics of Commuter Express Bus Operations

BRAD WILLIAMS AND BILL WELLS

With the recent cuts in federal subsidies for transit operations, planners are looking for ways to reduce their operating costs. One way of doing this is to allow the private sector to provide commuter express bus service at little or no subsidy. A study of commuter express bus operations is summarized in which it is concluded that the operating cost for a private carrier is only about half that of the public carriers in Southern California. After 22 public bus lines had been evaluated, the conclusion was that more than $5 million per year in subsidy could be eliminated if the 22 bus lines were operated by private carriers. The cost savings are attributed to more favorable work rules and the ability to use less costly equipment. One other factor is that private operators will continue operation of a bus only if it is nearly full. The analysis was based on operating budgets for the two transit districts in Los Angeles and Orange Counties and on a survey of private agencies in the region.

This paper is the product of a 10-month study that has focused on the respective roles of the public and private sectors in providing commuter express bus services. The study has examined two critical, interrelated issues affecting public policy decisions in this area. The issues are (a) the comparative economics of public and private agencies and (b) the institutional and regulatory framework within which services are currently provided and that constrain policy changes.

In this paper we concentrate on the economic analysis that was performed during the course of the study. The procedures that were used in obtaining cost and revenue estimates are described and the findings are summarized.

There are a number of events that have occurred from the local to the federal level that effectively created the arena in which this analysis was made. The net result of these events is that public transit agencies are facing severe budget constraints that are hampering expansion efforts and may soon necessitate some service cutbacks. At the same time the population growth in the region, much of which is in outlying areas where housing is less expensive, is creating a demand for more transit, both local and express.

From the outset the study was designed to address the concerns of public and private agencies as well as the regional planning community. To achieve this end, a special task force was formed to bring together the numerous and varied interests to give technical direction and policy feedback to the study.

Membership on the task force included public transit agencies and private commuter bus agencies plus planning, funding, and regulatory agencies. Participation by the entire membership was extremely spirited and productive despite often-conflicting goals. Input by the task force has proved invaluable in obtaining and interpreting the material used in this paper and in improving the overall quality of the entire study.

ECONOMICS OF COMMUTER EXPRESS BUS SERVICE

In this section we examine the costs and revenues associated with both public and private operations and compare them on a route-by-route basis. Operating-cost models are developed for each type of service and the estimated costs are compared. Revenues are estimated for both types of service with an adjustment to compensate for the fare elasticity of demand. A total of 22 existing Southern California Rapid Transit District (SCRTD) and Orange County Transit District (OCTD) bus lines are examined, which include peak-only, park-and-ride, and subscription-service categories.

Operating Costs

Careful attention was given to the estimation of operating costs for public and private agencies to ensure a realistic basis of comparison. Allocating the exact cost to a particular bus line is difficult, especially for public agencies. Therefore, some generalizations were made based on systemwide characteristics.

Public Transit Operations

Since the majority of public express service in the region today is provided by SCRTD and OCTD, in this analysis we concentrated on these two districts. The analysis was further restricted to a select number of express bus lines that operated exclusively during peak periods. Various cost-allocation models were examined and compared in order to find the most consistent basis on which to estimate operating costs.

OCTD Operations

OCTD has been using a cost-allocation model for the past few years that allocates unit costs to vehicle hours, vehicle miles, and revenue vehicles. This model was broken down into peak and off-peak periods for FY 1981 under the assumption that the peak-period service is more costly than off-peak service. The FY 1981-1982 model for peak-period service is

$$OC = 20.55\ (VH) + 0.95\ (VM) + 25{,}901\ (PV)$$

where

OC = fully allocated annual operating cost,
VH = total vehicle hours (revenue plus non-revenue),
VM = total vehicle miles (revenue plus non-revenue), and
PV = number of scheduled vehicles during each peak period (the model acutally distinguishes between a.m. and p.m. peak-period vehicles; to simplify the model, the two variables were merged into a single peak-vehicle variable with no loss of accuracy).

SCRTD Operations

Research disclosed three entirely different cost-allocation models for SCRTD. Although they came from different sources and represented different fiscal years, all three models were derived from SCRTD annual budgets.

A three-variable model, similar to the OCTD model, gave cost estimates consistently about 24 percent above those of the OCTD model. This relationship is very close to the relationship between unit costs for the two districts as shown in their short-range transit plans. SCRTD projected that in FY 1981 the operating cost per vehicle (revenue) hour would be $49.20, whereas OCTD projected a similar unit cost of $39.45. This indicates that SCRTD experiences unit costs about 25 percent higher than those of OCTD.

The model looks as follows for FY 1981-1982:

$$OC = 27.90\ (VH) + 1.22\ (VM) + 27{,}268\ (PV)$$

Private Transit Operations

Private bus agencies have some distinct advantages over public agencies that allow them to experience much lower costs for the same or similar services. Many of these advantages stem from the fact that most private agencies are not subject to the salary levels and operating restrictions that have recently characterized labor agreements in the public sector.

Survey of Agencies

Twenty-six questionnaires were sent to private agencies in the region asking for cost estimates for nine existing SCRTD and OCTD express bus lines. Because the purpose of the questionnaire was simply to determine the total cost, no breakdown or itemization was requested.

The comments of the various respondents to the questionnaire made it apparent that a generalization of private operating costs is very difficult. Issues such as the value of the vehicles, worker or professional drivers, and terminal locations can create situations where the cost per mile of two bus lines may be vastly different whereas the level of service as perceived by the riders may be identical. The following descriptions indicate the wide range of operating characteristics that determines a corresponding wide range in cost. These examples represent extreme situations. Most private services fall somewhere between these extremes.

1. Maximum-cost service could be provided by using a new intercity bus with all extras costing well over $150,000. These buses are returned to the storage facility after the run, which requires deadheading miles equal to or greater than revenue miles. Drivers are paid for each run from the time

the bus leaves the storage facility until it is returned to that facility.

2. Minimum-cost service could be provided with used buses that are still functional and comfortable, worth between $12,000 and $25,000. Worker drivers pick up the buses from a storage location near the origin point of the line and leave them at the destination point during the day. There are virtually no deadhead miles or nonrevenue hours for which the driver must be paid.

Except for the vehicle being used, the characteristics described above may be totally unknown to the rider. The cost of operating private express bus service, then, is not directly correlated with the level of service.

In some cases, worker drivers may be undesirable or difficult to find. Use of older equipment may be a cost saver for these cases. Finding worker drivers for a new service along a corridor not previously served by express bus may be particularly difficult. Most worker drivers have well-established patterns of commuting during specific hours in the morning and evening. Often they are transit users who have been riding on the particular bus that they later drive. When this type of contact is unavailable, new services may not always have the option of worker drivers. This might mean that the cost of providing a new service may be somewhat higher than that for certain already established services.

Private Agency Costs

Although only a small number of agencies responded to the questionnaire, the majority of their cost estimates were quite similar; they averaged $2.79/revenue mile.

One respondent, who operates a small agency that uses worker drivers exclusively, provided an estimate about one-third the magnitude of the others. The response indicates that it may be possible to achieve operating costs significantly below those estimated here with the exclusive use of worker drivers and perhaps older equipment.

One large agency indicated that they have contracts for commuter services that are significantly below the $2.79 value and others that are significantly above. This illustrates the variance that exists in the cost of private operations. It also indicates the problem in generalizing private costs for comparison with public costs. Every commuter express bus service has its own unique operating characteristics that must be considered when the service is evaluated. Although general comparisons are made in this paper, a more detailed study should be done on a line-by-line basis before any conversion from public to private operations is implemented.

Cost Comparison

By using the cost models described above, the cost of operating 22 existing SCRTD and OCTD bus lines was calculated for both public and private agencies.

Table 1 gives the results of the cost calculations. In general, the cost of providing commuter express services is 50 percent as expensive for private agencies as it is for public agencies. On a line-by-line basis, this ratio ranges from a low of 0.34 to a high of 0.76.

The results of this cost comparison are quite significant. A savings of 50 percent in the total operating cost of commuter express bus service could be achieved by using private rather than public carriers. As an indication of the magnitude of these savings, converting the SCRTD subscription and park-and-ride buses to private operation would save the district nearly $5 million a year. This is about 9 percent of their planned UMTA Section 5 operating subsidy for FY 1982, and 1 percent of the total operating budget for SCRTD.

Table 1. Comparison of public and private operating costs.

Type of Service	Cost ($) Private	Public	Difference	Ratio Private/ Public
Subscription	466,428	1,004,024	537,596	0.46
SCRTD park-and-ride	4,180,933	8,617,796	4,436,863	0.49
OCTD park-and-ride	574,697	925,489	350,792	0.61
Total	5,222,058	10,547,309	5,325,251	0.50

Operating (Fare) Revenue

The analysis of operating revenue focused on fares, ridership, and the sensitivity, or elasticity, of ridership to fares. Other ancillary revenue sources such as advertising were not considered, because they would have had only a marginal effect on the results.

Fares

Private agencies are in the business to make a profit and must compete with other private agencies as well as with subsidized public transit districts. Therefore, they tend to charge the lowest possible fare that will allow them to recover their costs plus a small percentage. Their fares are often calculated on a line-by-line basis. By minimizing the number of runs per line to ensure maximum ridership on each bus, they are able to keep the fare as low as possible. Generally, a bus less than 80 percent full loses money and does not remain in service for long without some revenue guarantees from a sponsoring firm or agency.

By using this individualized approach toward determining fares for private commuter express bus service, it is possible to have private fares that are higher than public fares in some cases and lower in others. In many instances today, the published fares for private services are close to the comparable public fare.

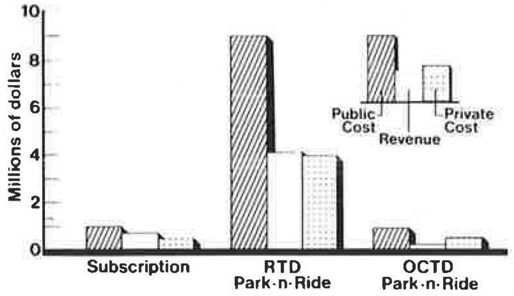
This economic analysis compares existing SCRTD and OCTD lines under public and private operating scenarios. The assumption is used that the private agencies would charge the same fare as the public agency whenever that fare would provide a revenue at least 6 percent above the cost. Fares for services where this does not occur are increased until the revenue, adjusted for fare elasticity, reaches that threshold.

Elasticity

A recent analysis of elasticities for SCRTD by the University of California, Los Angeles, has estimated a range of elasticities from -0.09 for system-level peak-period trips to -0.15 for all-day trips of more than 15 miles. This range is below the transit industry average of -0.28 and is consistent with averages for peak-period and work transit trips. The midpoint of this range, -0.12, was chosen as an appropriate approximation for estimating the impacts of fare increases on commuter bus ridership.

It is important to remember that every line that will be studied will have its own fare elasticity that will change for each station served along the line. A general elasticity parameter can, at best,

Figure 1. Economic comparison.



only provide a rough estimate of the actual impact that a fare increase would have on any particular line. Because there is no reasonable way to obtain elasticities on a line-by-line basis, the general parameter is the best approach to use. It is useful in obtaining order-of-magnitude impacts both on a systemwide and a line-by-line basis. The figure selected above will provide a reasonable estimate of fare-increase impacts on commuter bus ridership.

Ridership and Revenue

Both SCRTD and OCTD have estimates of ridership on each line that are periodically updated. At the time of this study the most recent OCTD estimates provided ridership numbers for November 1980. SCRTD's latest estimates were for June 1980.

The recent increases in fares by both districts were much greater than the current inflation rate and have had a detrimental effect on ridership. Therefore, the ridership estimates were adjusted by using the -0.12 elasticity assumption.

Total revenues for all of the bus lines under study are $5,042,523, or about 48 percent of the total public cost. Total subsidy for the 22 bus lines is $4,740,658.

Economic Analyses

The economic comparison of public and private operations is shown in Figure 1 and tabulated below (of the OCTD park-and-ride lines, three are not profitable at any fare level):

Type of Service	No. of Lines	No. Profitable Without Fare Increase	No. Requiring Fare Increase
SCRTD subscription	8	8	0
SCRTD park-and-ride	9	4	5
OCTD park-and-ride	5	0	2

This section summarizes the findings of that comparison and then develops a prototypical commuter express bus line that will provide an example for analyzing new services in markets not currently served at all.

Comparison of Existing Bus Lines

In the aggregate, the 22 transit district bus lines examined in the study would show an improvement in farebox recovery ratio from 0.48 to 0.97 by converting to all private carriers and keeping the current fare structure intact. Because of their lower costs, municipal agencies would experience results of smaller magnitude than those shown here. Subsidy per trip for the park-and-ride services would decrease from $2.39 to $0.18. There are large differences between subscription and park-and-ride service, as the discussion below indicates.

SCRTD Subscription Service

The SCRTD subscription buses are currently operating at a farebox recovery ratio of 0.67, which is far better than the system average. The service has an annual deficit of $335,624.

Private operation of the same service could be provided at a 43 percent profit. Because of the high farebox recovery ratio, however, it is unlikely that SCRTD would like to convert the service. Loss of these lines would have the net effect of reducing SCRTD's overall operating ratio, which would be undesirable for them.

SCRTD Park-and-Ride Service

Analysis of the nine SCRTD park-and-ride bus lines shows that they currently operate with a farebox recovery ratio of 0.49. This is slightly better than the systemwide average of 0.44 for FY 1981. However, the service still shows an annual deficit of more than $4 million and a subsidy per trip of $2.16.

Operation by private carriers shows a profit of 0.6 percent, or $27,080, when no adjustment is made to the fare. The subsidy per trip of $2.16 is totally eliminated. An increase in the fares for the entire service of only 6.2 percent would provide sufficient revenue for a 6 percent profit with a loss in ridership of 0.7 percent, or 59 trips. These findings are based on a private cost model that is biased upward. It may be possible that this entire service could be operated at an acceptable profit by private carriers with no change in fares.

On a line-by-line basis, four of the lines would be profitable with no increase in fares. Three more lines would be profitable with fare increases of less than 30 percent. The remaining two lines would require fare increases of greater than 50 percent. These two bus lines would probably need more than a fare increase to become profitable because the elasticity would most likely be greater than -0.12 for such large fare increases. Perhaps a combination of fare increases and service reductions would be warranted for these lines.

In general, the analysis of the SCRTD park-and-ride service indicated that the service could be operated profitably by private carriers. A fare increase to raise the profit margin to 6 percent might cause a drop in patronage of less than 1 percent, and some decrease in ridership due to service cutbacks might result. These negative impacts could be offset by the elimination of an annual subsidy requirement of $4.4 million, or $2.16/trip. The annual subsidy that could be saved for a person who rides the bus every weekday is $1,103.

OCTD Park-and-Ride Service

OCTD park-and-ride service operates with a high subsidy, as its 0.18 farebox recovery ratio indicates. This is slightly lower than their systemwide average of 0.20. This is due to low fares coupled with a ridership that averages about 24 riders per bus. Subsidy per trip averages $6.08/trip, or $3,101/yr for a person who rides the bus every weekday. A person riding bus number 291 every weekday is subsidized $7,655/yr.

Of the five bus lines examined, two could be operated profitably under private ownership. They

Table 2. Economic comparison of prototypical commuter express bus line.

Characteristic	Public	Private
Route description		
One-way route miles	31.0	31.0
Daily trips in and out	12, 12	12, 12
Monthly pass ($)	87.74	93.18
Ridership		
Daily	864	858
Per bus	36	36
Economic comparison		
Annual cost ($)	931,537	452,250
Annual revenue ($)	454,863	479,710
Profit ($)		27,460
Subsidy ($)	476,673	
Subsidy per trip ($)	2.16	0
Farebox recovery ratio	0.49	1.06
Annual subsidy per user ($)	1,103	0

would require fare increases of 70.3 and 140.6 percent, however, assuming that the fare elasticity would not change for these large increases. This would require the fares to be $96.00 to $136.00/month. Most likely, fare increases of this magnitude would result in a far greater loss in ridership than shown here. The other three bus lines could not achieve profitable revenues at any fare level without accompanying service cutbacks.

Raising OCTD fares by 67.1 percent to $94.00/month would make them comparable with SCRTD fares. Assuming this fare level for the private operations and constant elasticity, the annual subsidy for all five bus lines could be reduced from $759,379 to $408,587. This is $3.21/trip. It might be possible for small private agencies to provide the service by utilizing worker drivers exclusively. As indicated earlier, this might produce the kind of cost savings needed to put the service in the black.

Prototypical Commuter Express Bus Line

Evaluating the economics of any new commuter express services will have to be done on a line-by-line basis as opportunities arise. The following is an economic comparison of a prototypical bus line under both public and private operation that might be proposed in some corridor not currently being served by private or public carriers. The characteristics of the line are based on average characteristics of the nine SCRTD park-and-ride bus lines examined in this study. This comparison is given in Table 2.

The typical commuter express bus line has a route length of 31 miles and averages 26 mph. It provides 12 runs into an employment center during the morning peak and 12 away from the employment center in the afternoon. The public operator carries an average of 36 passengers per bus at a monthly rate of $87.74. The public operator receives a farebox recovery ratio of 0.49 and has an annual subsidy of $476,673. The subsidy per trip is $2.16. The annual subsidy to an individual who rides the bus every weekday is $1,103.

The private carrier operates the same service but charges a higher fare so that a 6 percent profit is achieved. The monthly rate is $93.18 and almost 36 passengers per bus are carried. Annual profit is $27,460. There is no subsidy per trip.

Operation by a private carrier saves the community the entire subsidy for the service, or $476,673. In addition, a $27,460 profit per year is being realized by a local enterprise. Therefore, the entire benefit to the community is $504,133. From this must be subtracted the additional $49,693 in fares paid by the 858 riders, an average of $57.92 per year per rider. Only six daily riders are lost due to this increase in fares.

The final analysis, then, is that choosing a private carrier over a public operator nets a financial benefit to the community of $454,440 at the cost of losing six riders per day. Since this is a new service, however, those six riders are not losing a service; they simply choose not to take advantage of a new service. The public operator has not been required to add $476,673 to its annual deficit and may choose to spend that money on another transit service somewhere else in the region.

Service Level and Subsidy Trade-Offs

With public transit operators facing conflicting needs to expand service yet decrease subsidies, the economic benefits of expanding private carrier service should be seriously explored. The subsidy per passenger of the SCRTD park-and-ride lines is 4 times the system average and more than 10 times the amount of some buses that operate in dense residential areas. As an example, data compiled in 1979 by SCRTD showed a subsidy per passenger of $0.12 for the Wilshire Boulevard local line (Line 83), whereas the park-and-ride line to Diamond Bar (752) was $2.07.

If some of the current public commuter express lines were converted to private carriers, the public operator could make the choice to expand local service in areas with high residential density (and many transit dependents) or to reduce the total system subsidy. Similarly, expansion of commuter express bus service through private carriers would have little or no effect on the existing budgets of the public operators. Either option allows the public operator to improve service for the entire region without adding any strain on the operating budget.

WHERE DO WE GO FROM HERE?

The findings that are summarized in this paper are significant and point toward the need for rapid policy actions by transportation planning and operating agencies in the region. The institutional and regulatory environment, however, is generally restrictive in providing for a major policy move toward private operation of a public service. State legislation, Public Utility Commission (PUC) regulations, federal regulations such as the Section 13(c) labor protection provision, and even the collective-bargaining agreements of local operators all tend to support the concept of public operations for commuter express bus service. Yet the economic benefits of expanding the role of the private carrier in this area may well be worth the effort.

After carefully researching the institutional and regulatory environment in Southern California, the Southern California Association of Governments approved the following policy recommendations:

1. All transit districts and municipal operators in the region should review their commuter express bus operations and determine the potential cost savings to be achieved by conversion to private operations.
2. All transit districts, municipal operators, and planning agencies in the region should take immediate steps to remove any institutional barriers to converting to private operations, including pressing for new state or federal legislation, if required.
3. All transit districts and municipal operators in the region should cooperate to the fullest extent possible with private operators to make private service a part of the regional transit service. This could include (a) dissemination of

schedules and other operating data and (b) transfer discounts.

4. All transit districts and municipal operators should promote the expansion of private commuter express bus operations by (a) not contesting PUC certificate applications unless the proposed service would have a serious negative impact on the public system, (b) not expanding public commuter express services in areas where private operations appear feasible, and (c) assisting private operators in identifying new commuter express bus markets.

5. Expansion of privately operated services will need promotional, informational, and coordinative support, which might well be provided by Commuter Computer.

This paper documents the potential economic advantages of giving the private bus operator a much larger role in providing commuter express services. Rapid implementation of these recommendations has the potential to increase transit service while reducing annual operating subsidies paid by the public.

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Sources of Rising Operating Deficits in Urban Bus Transit

DON H. PICKRELL

Annual operating expenses incurred by U.S. urban transit systems rose more than $5 billion from 1960 to 1980, of which a rapidly declining fraction was covered by farebox receipts. As a result, the industrywide operating deficit approached $4 billion by the end of this period. Although rail transit systems first incurred large operating losses, by 1980 the motor bus segment of the U.S. public transit industry accounted for three-quarters of its aggregate deficit. Recent growth in bus transit operating deficits can be traced to escalating costs per unit of service, rapid service expansion despite declining utilization of existing service levels, and decisions to simplify and reduce fare structures. A detailed examination of each of these sources of rising operating losses is presented, and attempts are made to assess both their individual contributions to deficit growth and their respective underlying causes. Following this examination, an illustration of how these developments interacted to produce the explosive growth in bus transit operating deficits that occurred during the 1970s is given. Specific recommendations are made for bringing growing losses under control.

By many measures, the decade of the 1970s was a pivotal episode in the history of the American public transit industry. After declining steadily for more than 25 yr, total U.S. transit ridership began to climb slowly after 1972 and continued to grow throughout the remainder of the decade; by 1980, the annual number of riders carried by U.S. transit systems returned to the level of the early 1960s. Similarly, after nearly 30 yr of decline, the number of vehicle miles operated by the industry increased dramatically during the 1970s, so that by the end of the decade, nationwide transit service was restored to its level of 25 yr earlier. Much of this revitalized service was provided by using new, higher-capacity vehicles traveling at faster speeds and offering new amenities such as more spacious seating and air conditioning. By 1980, transit vehicles operated over nearly 125,000 track and route miles in the United States, more than a quarter of which were added during the 1970s. Thus despite the tremendous growth in urbanized land area that occurred during this time, both the density and coverage of transit routes in most major U.S. cities reached new postwar highs by 1980 (1).

Other developments, however, were less encouraging: Total operating expenditures incurred by U.S. urban transit systems rose more than $4.5 billion over the decade, of which a rapidly declining fraction was covered by farebox receipts. As a result, the industrywide difference between fare revenue and operating expenditures fell from a surplus of slightly more than $100 million in 1970 to a deficit approaching $4 billion by 1980 (1,2). The most alarming aspect of this growth was that operating costs and deficits not only grew quickly in the early part of the decade, when service and ridership continued their long-term decline, but rose even more rapidly as patronage and service grew throughout the remainder of the decade. By 1980, the motor bus segment of the U.S. urban public transit industry accounted for nearly 70 percent of service offered and total passengers carried nationwide, as well as three-quarters of the aggregate deficit incurred by U.S. public transit operators.

The recent explosion in bus transit operating deficits can be traced to four basic sources: escalation in the unit costs of providing transit service, rapid service expansion despite declining demand for and utilization of existing service levels, and operators' decisions to simplify and reduce transit fare structures. The effects of these trends on urban bus transit finances in the United States over the period from 1960 to 1980 are given below (computed from Tables 1-3):

Factor	Percentage of 1960 to 1980 Decline in Net Operating Income
Increasing real expenditure per seat mile of service	31
Growth in seat miles of service provided	24
Declining passenger miles carried per seat mile of service provided	14
Declining real fare revenue per passenger mile carried	31

Even after adjustment for inflation, rising unit operating costs were responsible for nearly one-third of the $3.2 billion drop in aggregate operating income over the two decades studied, and increases in the level of service provided contributed about another quarter. The remainder of the drop in aggregate operating income resulted from declining demand for transit service together with reductions in fares at which it was offered. Because fare levels clearly affect the use of transit services that are supplied, it is impossible to fully separate the influences of declining demand and fare reductions on transit operators' deteriorating finances; one estimate of the relative contributions of these two factors was presented above. The following sections examine each of these sources of rising bus transit deficits in detail, concluding with specific recommendations for bringing growing losses under control.

UNIT-COST ESCALATION AND ITS CAUSES

The most widely discussed cause of rising deficits in urban transit is escalation in the costs per unit of transit service provided. Nevertheless, after adjustment for the effects of inflation, operating expenditures per seat mile among bus transit operations actually fell during most of the 1960s and rose only slowly through 1975. These early reductions in unit operating costs were achieved largely through continued reequipping of bus fleets with higher-capacity vehicles in conjunction with slight increases in average vehicle operating speeds. Together these developments reduced the quantity of labor and other operating inputs required per seat mile of service sufficiently to offset the effects of rising wage rates and other input prices. Over the next 5 yr, however, rapid increases in labor compensation rates and fuel prices raised real expenditures per seat mile nearly 50 percent (3-5, Table 3-16; 6).

For the period 1960 to 1980 as a whole, rising unit costs for drivers and other labor were responsible for more than three-quarters of the total escalation in operating expenses per seat mile of bus service; increasing fuel costs accounted for most of the remainder. Unit labor costs increase when either the rate of labor compensation rises or the amount of labor required to produce a seat mile of service increases. Table 1 (2,3,7), which reports estimates of trends in each of these factors over the period studied, shows that after increasing slowly from 1960 to 1970, labor compensation rates--including wages, salaries, and fringe benefits--rose substantially during the next decade. Thus even after adjustment for the effect of rapid price inflation, annual compensation per employee in 1980 was nearly 80 percent above its estimated 1960 level (2,3,7).

Table 1 also reports that the annual number of seat miles produced per employee increased somewhat during this period, allowing some of this increase in compensation rates to be absorbed. During most of this period, labor productivity in the transit industry was apparently declining slowly as changes in the structure of demand for transit service--increased peaking during commuting hours and growing imbalances in directional flows of passengers--together with increasingly restrictive work rules governing driver assignments and maintenance procedures made it more difficult for transit operators to fully utilize drivers, mechanics, and other workers (8, pp. 22-25). By itself, this decline in labor productivity would have raised the amount of labor necessary to produce each seat mile of service; however, it was almost exactly offset by the industry's continuing acquisition of larger vehicles together with a slight increase in the average speed at which transit buses operated, both of which reduced the amount of labor time required to produce each seat mile of bus service (6). On balance, the annual number of seat miles produced per employee rose about 10 percent over the two decades; hence the entire increase in labor expenses per seat mile during this period resulted from escalation in wage and fringe benefit rates, nearly three-quarters of which occurred after 1970.

Table 1. Changes in compensation, productivity, unit labor costs, and unit operating expenditures for U.S. bus transit systems.

Year	Annual Compensation per Employee ($1980)	Annual Seat Miles per Employee (000s)	Labor Expense per Seat Mile ($1980)	Total Operating Expense per Seat Mile ($1980)
1960	14,560	564.4	0.0258	0.0361
1970	17,690	665.0	0.0266	0.0339
1980	25,930	620.8	0.0418	0.0569

Table 2. Estimates of seat miles of service supplied, passenger miles carried, and percentage of seat miles occupied for U.S. urban bus transit operations.

Year	Seat Miles Supplied (000,000s)	Passenger Miles Carried (000,000s)	Percentage of Seat Miles Occupied
1960	56,674.0	18,743.2	33.1
1965	60,597.4	17,470.1	28.8
1970	61,125.1	16,879.7	27.6
1975	70,074.5	17,820.5	25.4
1980	79,834.7	21,535.0	27.0

The other important component of rising operating expenditures per seat mile, increasing outlays for motor fuel, resulted from the two major oil price increases imposed during the 1970s by the oil producers' cartel, which together raised the average price paid by U.S. bus operators for diesel fuel nearly eightfold between 1970 and 1980 (3,9). The effect of rising fuel prices was aggravated by the increasing fuel consumption per seat mile of transit buses, which rose nearly 25 percent from 1960 to 1980, despite continuing increases in their average seating capacity (1,3,6). Nevertheless, some of this deterioration in fuel economy probably resulted from developments that upgraded the quality of transit service, including features such as air conditioning and more spacious seating, as well as from improvements in vehicle performance and safety characteristics. Hence, it can probably be regarded as a less serious source of unnecessary operating cost increases than rising labor compensation rates.

EXPANDING TRANSIT SERVICE AND DECLINING UTILIZATION

Rising real expenditures per seat mile were translated into even faster growth in outlays per passenger mile, because the fraction of available seat miles actually occupied by passengers fell slowly over most of the period studied. Table 2 (3-6; 10, Tables E and F; 11, p. 20; 12, Tables 3-21, C-36, C-40, and C-47) indicates that growth in the average seating capacity of buses more than offset early reductions in the number of bus miles operated, so that aggregate seat miles of bus transit service provided nationwide rose slowly through 1970. At the same time, the number of passengers carried fell steadily, so that despite the apparent lengthening of typical bus transit trips, the number of passenger miles traveled on urban bus transit systems declined slowly. The result was a significant reduction in the fraction of bus service that was actually used by passengers, from about one-third in 1960 to slightly more than one-quarter 10 yr later.

This fraction declined further after 1970 as earlier cuts in vehicle miles of service began to be rapidly restored with the advent of government operating-subsidy programs, whereas ridership continued to fall. After 1975, however, ridership grew significantly, and the upward trend in the average length of passengers' trips accelerated slightly; these two factors combined to produce a substantial increase in the number of passenger miles carried by bus transit systems. Although the level of service offered continued to grow, primarily as a result of rapid increases in bus miles operated, the fraction of bus transit seat miles actually occupied rose slightly from 1975 to 1980. This increase in utilization was superficially encouraging, but it probably occurred in response to widespread reduction in transit fares (average bus fares fell more than 25 percent on a per-mile basis between 1975 and 1980, after adjustment for the effects of inflation) in combination with rapid escalation in the real costs of operating private automobiles, which rose nearly 40 percent over the same period [3, 13 (adjusted to 1975 and 1980 values by using gasoline price data for those years reported as part of the consumer price index)].

The decline in transit utilization occurred partly because important economic and demographic trends caused significant reductions in the demand for public transit service while the spatial and temporal structure of transit was altered in ways that also made high utilization more difficult for transit operators to achieve. The most important of these trends was probably the ongoing dispersion of employment, residential development, and population-serving activities within U.S. metropolitan areas, which sharply reduced the number of trips for which public transit could offer costs and service levels that made it competitive with the private automobile. More than half of the population of major U.S. metropolitan areas lived in their densely developed central cities in 1960, yet by 1975 this figure had fallen to only about one-third; the remainder lived in much lower-density surrounding suburbs. Similarly, the fraction of metropolitan-area residents working in central city areas fell from nearly two-thirds in 1960 to just over one-half by 1975 and has probably continued to fall since that time. Partly as a result of these developments, the number of transit work trips within the central areas of major U.S. cities, the traditional stronghold of transit service and ridership, fell by more than half during the same period (14, Table 216, p. 526; 15, Table D, p. 3).

Much of this dispersion was the product of growing urban populations and rising personal incomes, which increased the demand for dwelling space and other amenities provided by lower-density residential locations. At the same time, the evolving technology and industrial mix of urban economic activity combined to produce similar, although somewhat less rapid, employment decentralization within U.S. urban areas. Rising incomes also increased the demand for total travel as well as for the particular characteristics offered by automobile transportation, including its minimal access and waiting times, scheduling and routing flexibility, guaranteed comfortable seating, and privacy. This was reflected in explosive growth in automobile ownership and use in urban areas as well as in urban residents' apparent willingness to finance substantial investments in road and highway capacity (16). Thus although total urban travel volumes grew rapidly throughout the postwar era, transit ridership continued to decline, at least until comparatively recently.

In addition to reducing total transit ridership, the ongoing decentralization of urban activities and growing demand for automobile transportation apparently left much of it concentrated on a relatively few specific types of routes. Because the geographic dispersal of residences proceeded more rapidly than that of jobs during the period, the number of work trips made from suburban areas into central cities increased substantially. In the radial corridors that carried much of this growing volume of commuting, public transit most often continued to offer travel times, service frequencies, and costs that made it competitive with private automobile commuting, particularly in older, congested urban areas that had low levels of street and highway capacity. Thus the only growing category of transit work trips in U.S. metropolitan areas after 1970, when the long-term decline in transit ridership was finally arrested, included those into central cities from their surrounding suburban areas, which grew about 5 percent in the first five years of the decade (15, Table D, p. 3).

Public transit travel also remained attractive to low-income residents of the densely populated centers of urban areas, whose automobile ownership levels and valuations of travel time tend to be lower and where high congestion levels and parking charges raise the cost of automobile travel (17, Table 2, p. 11). Transit service also remained less costly to provide in such areas because the greater variety of trip purposes and destinations it served resulted in passenger flows that were more evenly distributed along individual routes and throughout the day. On most other types of transit service, however, such as intersuburban or crosstown routes, the process of metropolitan decentralization and the accompanying dispersion of trip origins and destinations made it increasingly difficult for transit operators to offer service levels and fares that were competitive with the speed, scheduling flexibility, and low cost of automobile travel, particularly where it was accompanied by ambitious increases in street and highway capacity, as was common in newly developed suburban areas.

Still, the utilization of transit service declined even more rapidly than these developments in the demand for public transportation would by themselves have suggested, because operators' service policies failed to recognize and respond to them. From 1960 to 1980, when the number of urban travel corridors along which it could compete effectively with automobile travel probably declined significantly, aggregate route mileage served by bus transit in the United States increased 28 percent (1,2). Because the total number of vehicle miles operated declined slightly over the same period, the average level of service operated per route mile, an index of the frequency of typical bus transit service, fell significantly, especially after 1970 as the availability of government operating subsidies increased rapidly. Thus instead of carefully identifying types of routes where service that was sufficiently frequent to achieve acceptable utilization could be maintained at reasonable operating costs, transit operators apparently expanded service into widespread new markets. On such routes, most of which probably served suburban areas with lower densities of employment and population as well as high levels of car ownership and automobile accessibility, the service levels typically provided were thus unlikely to achieve satisfactory ridership, at least at fares that reflected the costs of providing them.

Urban decentralization, rising automobile ownership, and other accompanying developments also made it more difficult for transit operators to maintain high utilization levels by increasing the degree of peaking in demand while aggravating imbalances in the spatial patterns of ridership. In conjunction with rising income and automobile ownership levels, widespread relocation of retail and other population-serving activities into lower-density areas significantly reduced the number of nonwork trips for which public transit was used. At the same time, because it less drastically reduced the number of work trips for which transit travel remained competitive with automobile commuting, the effect of metropolitan decentralization on the use of public transit for travel to work was probably much less pronounced. For example, the number of work trips made by public transit in Chicago fell less than 10 percent between 1956 and 1970, yet the number of transit trips for all other purposes declined nearly one-third (18, Table 2.6). Because trips to work are usually more concentrated during morning and evening travel hours than those for other purposes, the changing mix of travel purposes for which public transit was used probably resulted in a significant increase in the fraction of all transit trips that took place during peak periods (10, Tables E and F; 11, p. 20). Increasing participation in the labor force also aggravated the degree of peaking in transit ridership because some of those who formerly used public transit service during off-peak hours for shopping, personal business, and other nonwork travel shifted to peak-hour transit commuting; most important, the labor-force participation rate among adult women rose from only a third in 1960 to slightly more than half by 1980 (19, Table B-32, p. 270).

Because transit operators tended to expand vehicle fleets to accommodate ridership increases that were concentrated during a few hours of the day and union work rules restricted the assignment of operators to shifts encompassing morning and evening peaks, the overall utilization of capital and labor inputs fell significantly. This increase in peak vehicle and labor requirements was probably aggravated by the fact that commuting trips are not only longer on average than trips for other purposes but were also increasing in length during this period in response to the decentralizing forces at work in urban areas as well as other developments such as the increasing number of multiple-worker households. The accompanying increase in the fraction of commuting trips on many routes probably also tended to concentrate ridership in a single direction at any hour, further complicating the problem of designing routes and schedules to maintain satisfactory utilization of drivers and equipment as well as reasonable passenger loads.

CHANGES IN TRANSIT FARE POLICY

Another major source of escalating transit deficits was the failure of fares to reflect the rapidly escalating real costs of providing transit service: After increasing slightly from 1960 to 1970, inflation-adjusted fare revenue per passenger mile fell by nearly half during the subsequent decade. This resulted from a combination of failure to raise fares to compensate for rapid general price inflation and lengthening of typical transit trips together with decisions by transit operators to stabilize--or in some cases even to reduce--overall fare levels, offer substantial fare reductions for specific groups of riders, and eliminate surcharges for more costly trips. Table 3 (3; 10, Tables E and F; 11, p. 20; 12, Tables 3-21, C-36, C-40, and C-47) documents the combined effects of the first two of these factors; it reports that the average fare per passenger more than doubled over the period studied when measured in current dollars yet fell steadily after 1970 when adjusted for the effects of inflation. As the table also suggests, another important reason for the decline in real fare revenue per passenger mile was the steady increase in the average length of bus trips over these two decades (from about 3.5 miles in 1960 to slightly more than 5 miles by 1980) (2,10-12). Thus, even had the average fare per passenger kept pace with inflation during this period, fare revenue per passenger mile would have declined by nearly one-third.

Table 3. Changes in unit-fare revenue yields for U.S. urban bus transit service.

	Revenue per Passenger Carried		Revenue per Passenger Mile Carried	
Year	Current Dollars	1980 Dollars	Current Dollars	1980 Dollars
1960	0.180	0.471	0.051	0.135
1965	0.205	0.493	0.054	0.130
1970	0.294	0.579	0.072	0.141
1975	0.320	0.469	0.071	0.104
1980	0.375	0.375	0.077	0.077

The rapid decline in inflation-adjusted fares may initially have been an unintentional development, stemming from transit operators' delayed response to the onset of rapid inflation and cost escalation in the early 1970s. Its persistence, however, clearly reflected their decisions to exploit the growing availability of government operating subsidies to defray cost increases and permit fares to be stabilized or even reduced. Indeed, this was an explicit goal of the federal operating-subsidy program, under which funds were distributed beginning in 1974, and it partly motivated some state and local assistance programs before that time. Declining revenue yields also reflected the widespread advent of selective fare reductions for several classes of riders, most commonly the elderly and the handicapped, although many transit operators extended discounts to students, children, and frequent riders (through monthly pass programs) as well. Although some of these developments in fare policy were motivated by important social concerns about the mobility of deserving groups, they proved extremely costly to transit operators in terms of the revenue loss they entailed and were certainly one important cause of the precipitous decline in fare revenue after 1970.

Still another cause of declining revenue yields was the widespread absence or even elimination of fare premiums for services that were particularly costly for transit operators to supply; this included zone penalties and other forms of distance-based fares as well as peak-hour fare surcharges. Because typical transit trips became considerably longer, the widespread elimination of distance-based fare surcharges was apparently an important cause of declining farebox yields per passenger mile of travel. Further, although peak-hour fare surcharges have apparently never been common in U.S. transit systems, most of the few cities that once imposed peak fares eliminated them during the latter part of the 1970s (20, Tables 6-8; 21). With a rising fraction of ridership probably concentrated during peak travel hours, the absence of fare premiums that reflected the significantly higher costs of expanding peak service was another important cause of the failure of fare revenues to keep pace with the rapidly escalating costs of providing transit services.

COMBINED EFFECTS ON TRANSIT FINANCES

As a consequence of these trends in operating costs, service utilization, and fare revenue, inflation-adjusted operating income per passenger mile carried by U.S. bus transit systems declined slowly throughout the 1960s (Table 4). This occurred largely because falling utilization of the level of transit service offset the economies in operating expenditures per seat mile achieved by the industry sufficiently to actually raise expenses per passenger mile. Hence despite a modest increase in real fare

Table 4. Changes in operating expenditures, revenue, and net operating income for U.S. urban bus transit systems.

Year	Operating Expenditure per Passenger Mile ($1980)	Fare Revenue per Passenger Mile ($1980)	Net Operating Income per Passenger Mile ($1980)	Total Net Operating Income ($000,000s 1980)
1960	0.1092	0.1346	0.0245	479.2
1965	0.1103	0.1298	0.0195	311.9
1970	0.1228	0.1412	0.0194	251.5
1975	0.1507	0.1041	-0.0456	-739.5
1980	0.1912	0.0765	-0.1147	-2,754.9

Note: Computed from data in Tables 1-3.

revenue per passenger mile, the gap between unit revenue and expenditures narrowed significantly. During the 1970s, real costs per seat mile grew rapidly, particularly during the latter half of the decade. Although the fraction of service utilized also rose after 1975, thus absorbing some of this unit-cost increase, expenses per passenger mile still escalated nearly 60 percent from 1970 to 1980. Coupled with the sharp decline in fare revenue, this produced a dramatic reversal in unit operating income: By 1975, bus transit operators on average lost 4.6 cents per passenger mile carried, a figure that jumped to 11.5 cents by 1980.

Table 4 also indicates that after declining slowly from 1960 to 1970, industrywide total operating income dropped by nearly a billion dollars in the next 5 yr, primarily because of this sharp reversal in operating income per passenger mile. After 1975, total net operating income plummeted another $2 billion because losses per passenger mile nearly tripled, whereas service expansions and fare reductions together increased the total number of passenger miles carried by more than one-third. Thus at the same time that input prices were escalating rapidly and important economic and demographic developments reduced the demand for urban transit travel, bus operators continued to implement massive service expansions while offering fare concessions intended to increase ridership. One predictable result was the swift increase in its aggregate deficit, which, as given in Table 4, approached $3 billion by 1980.

CONTROLLING TRANSIT DEFICITS

This analysis suggests that transit operators and urban transportation planners face several important challenges. First is the necessity of bringing the recent explosive growth of transit operating costs under control, particularly the labor-cost component. As indicated earlier, rising labor expenses accounted for about two-thirds of the recent escalation in unit operating costs for bus transit, which in turn was attributable to rising wage and fringe-benefit rates. Faced with almost certain curtailment of the growth in government operating subsidies for transit, management must adopt more aggressive and responsible positions in future wage negotiations in order to bring the rate of wage increases into line with labor productivity improvements in the industry. Another important avenue for controlling labor costs is improving the productivity of operator labor, primarily by changing the restrictive rules that currently complicate the assignment of driver work shifts and result in considerable inadequate use of paid driver time. For example, Chomitz and Lave (22, Tables E-4, E-5, and E-6) estimate that extending the 12-hr maximum on driver work shifts that governs many transit systems' driver assignments to 13 hr could reduce labor costs by as much as 20 percent, whereas requiring pay premiums after 12-hr rather than 10-hr driver shifts could reduce labor costs up to 7 percent. Similarly, permitting more widespread use of part-time drivers could bring important cost savings, because their shifts would include considerably fewer paid hours during which they were inadequately used than is currently the case for full-time operators. Although the potential productivity improvements and resulting cost savings from each of these work-rule changes depends on the degree of peaking in daily ridership patterns faced by individual transit systems as well as on certain other factors, these estimates do illustrate that significant cost reductions could result from relatively minor modifications.

Labor requirements entailed in providing transit service could also be reduced by the continued acquisition of larger buses, which have historically been a valuable means for reducing labor input per seat mile produced. In particular, the use of currently available double-deck and articulated buses, which feature seating capacities in the range of 60 to 80 passengers, on routes with high passenger volumes could provide important labor-cost savings without unacceptable reductions in service frequencies. Of course, any potential labor-cost increases from measures that in effect substitute capital for labor in transit operations must be balanced against the potentially higher capital costs they entail, such as those for new, larger buses. Increasing the speeds at which buses operate in revenue service could also produce some further economies in the use of driver labor. Here, local transportation planners have an important role to play, because this could be accomplished most immediately by using traffic engineering modifications and transit vehicle priority measures that improve bus operating speeds and minimize the interference they experience from other vehicles on urban streets. In addition, increased use of urban expressway and freeway rights-of-way by transit vehicles may be feasible on many routes, such as those connecting suburban areas to each other or to downtown areas, and could lead to significant reductions in vehicle round-trip times and thus driver hour and vehicle fleet requirements.

A second major challenge is to make service policies more responsive to the changing patterns of transit demand in order to improve the utilization of services that continue to be provided. This will require transit planners and operators to understand the continuing economic, demographic, and technological forces that alter the spatial and temporal patterns of transit ridership as well as to more aggressively adapt service policies to those changing patterns. It will also demand much greater willingness to reduce services for which demand is declining than the industry has historically demonstrated, although the task would be eased considerably by fare levels that more realistically reflected the costs of providing lightly used services. Although the continuing failure to reorient services to respond to changing demand circumstances has been motivated by understandable political and social concerns, maintaining or extending transit service in markets where attractive service levels are costly to operate and often lightly ridden appears to have been an important cause of the intensifying financial difficulties faced by transit operators.

On the positive side, it seems likely that ridership on some other types of routes could be increased by well-planned service improvements. The best example of these is probably the provision of more high-speed, direct express or limited-stop bus service from suburban residential areas to employment and commercial activity centers, particularly in the downtown districts of major U.S. cities. Along such routes, transit vehicles are often able to provide service that is competitive with automobile travel, in terms of both door-to-door travel times and passenger comfort levels. Although the demand for such service is likely to be concentrated during peak travel hours, making it costly to provide, travel by automobile in such corridors often entails high costs as well, because of the prevalence of congestion and high parking charges at the trip destination. Hence many more travelers than currently do so might be willing to use reliable, high-quality service of this type, even at the relatively high fares that would be necessary to cover the increased costs for providing these improved service levels.

Finally, the fare-setting policies of most transit agencies need serious revision if the contribution of current fare structures to escalating deficits is to be reversed. Transit operators must first begin to bring the overall level of fares into closer conformity with the cost of providing transit service; as presented in Table 4, the typical bus passenger now pays only about 40 percent of the operating cost that his or her trip imposes. Fare-setting practices should also more fully recognize the important variation in the costs of accommodating passengers who travel on different types of routes, at different hours of the day, and for different distances. Doing so will require transit operators to implement more sophisticated cost estimation techniques and to adopt surcharges for particularly costly types of transit service, despite the fact that they may be even less popular politically than general fare increases. The most important of these surcharges is probably higher fares for peak-hour travel, since the vehicles and driver shifts that must be dedicated exclusively to peak-period service make it particularly costly to provide. Peak-fare surcharges would not only help to defray these higher costs but should also help to shift some use to times of the day at which vehicle and driver capacity is now inadequately used, thereby reducing peak vehicle and driver requirements and thus the total cost at which given levels of service can be provided. Further, peak-period transit ridership probably consists largely of work commuters, relatively few of whom are poor, whereas off-peak riders probably include many who do have low incomes; hence higher peak-hour fares would transfer to riders having greater average incomes some of the added costs they impose and perhaps actually reduce the cost burden borne by some riders who are less able to pay.

Another important form of surcharge for more costly service that should be relied on more heavily by transit operators is distance-based fares; higher fares are charged for longer trips through the use of zone-fare systems or mileage supplements to basic fare levels. The previous analysis demonstrated that recent growth in the length of typical transit trips has been another important cause of the widening gap between operating expense and fare revenue collected per passenger, which could be narrowed substantially by charging fares that vary at least roughly with distance traveled. In addition, imposing considerably higher fares for longer trips might allow those for very short trips to be reduced, which on some routes could lead to significant increases in ridership and revenue without necessitating added service or expenditures. Implementing distance-based fares should also be eased by widespread experience with their use, both in the United States and other nations, and the ready availability of a variety of proven technologies--ranging from manual to fully automated--for charging them. Again, at the same time that they transfer more of the burden of financing particularly costly forms of transit service to those who use them, distance-based surcharges could actually reduce the fare burden borne by lower-income riders, who typically make somewhat shorter trips than higher-income passengers (23, Chapters 5 and 7).

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Home-Origin Transit Travel Analysis Model

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The major findings of a bus patronage forecasting project to develop a simple short-range planning model for bus transit demand analysis in Albuquerque, New Mexico, are presented. The model would be typically applied by an analyst lacking specialized mathematical expertise by using commonly available data to analyze the ridership impacts of proposed transit service changes. Analysis of the information needs of Albuquerque officials and of the ridership patterns of Albuquerque SunTran users revealed that a focus on residential service requirements should have the highest analytic priority. In response to this need, a linear home-origin transit generation model was developed that could be manually applied to predict ridership response to service changes. The model is sensitive to a wide range of service, policy, socioeconomic, and land use factors. Validation studies on the model indicate that the model predictions are quite accurate. The technique should be transferable to other urban areas, especially rapidly growing multicentered sunbelt cities lacking the radial structure and dominant core of older American cities.

Findings of a project conducted for the Middle Rio Grande Council of Governments (MRGCOG) in Albuquerque, New Mexico, to develop a simple short-range planning model for bus transit demand analysis are presented. The project team developed a linear home-origin transit generation model that could be manually applied by using a hand calculator to predict ridership response to changes in the service and in socioeconomic and land use factors known to affect transit demand.

Specific project objectives for the development of the simple forecasting procedure included emphasis on

1. Policy relevance,
2. Use of available data,
3. Simplicity,
4. Transferability, and
5. Accuracy.

The final model and application procedure satisfactorily meet each of these project objectives. The following discussion of the Albuquerque setting provides perspective on some eccentricities in the model approach.

Albuquerque, New Mexico, is a rapidly growing sunbelt city with a generally mild, but arid, climate. Albuquerque population in 1940 was approximately 35,000. By 1980 the city population had grown to more than 400,000. Like many sunbelt cities developed in the postwar automobile age, there is no single dominant activity core to Albuquerque. Since the late 1950s, virtually all retail activity has migrated from the downtown central business district (CBD) to the uptown malls in the heart of Albuquerque's Northeast Heights (Figure 1). CBD activity is currently limited to government offices and some corporate headquarters. The largest daytime concentrations of population are found at the University of New Mexico (UNM), several miles east of the CBD. The city's largest employment center is the Kirtland Air Force Base (KAFB), located on the southeastern edge of the city.

Public transit service in Albuquerque is provided by the city's SunTran system. SunTran operates 20 regular routes and 5 morning and evening "trippers" to KAFB. The SunTran fleet consists of buses; the peak-period requirement is 72 vehicles.

The SunTran system configuration conforms to the grid system of streets and multicentered activity pattern it is designed to serve. The service policy governing system design was a full-coverage model to minimize the number of areas in the city that are not within walking distance of transit. The system, although not a pure grid due to the existence of outlying routes with radial characteristics, is certainly a grid-and-radial hybrid. Buses serve virtually every major street on 0.5-hr headways. Because of the grid configuration, many bus routes do not directly serve any major trip attractors; transfers are required to reach major destinations. [A 1981 survey of SunTran passengers revealed that almost one-quarter of all trips (23.6 percent) made on the system require one or more transfers.] A flat fare of 50 cents is charged for adult patrons. Up to two transfers are free. However, because of the system configuration, it is possible to go almost anywhere from almost anywhere in the city for 50 cents with no more than two transfers and a 10- to 15-min walk at each end.

SOURCES OF DATA

Most formal travel demand models are based on a simple conceptual model of travel behavior: The travel decisions of individuals are based on the characteristics of the travelers and their travel alternatives.

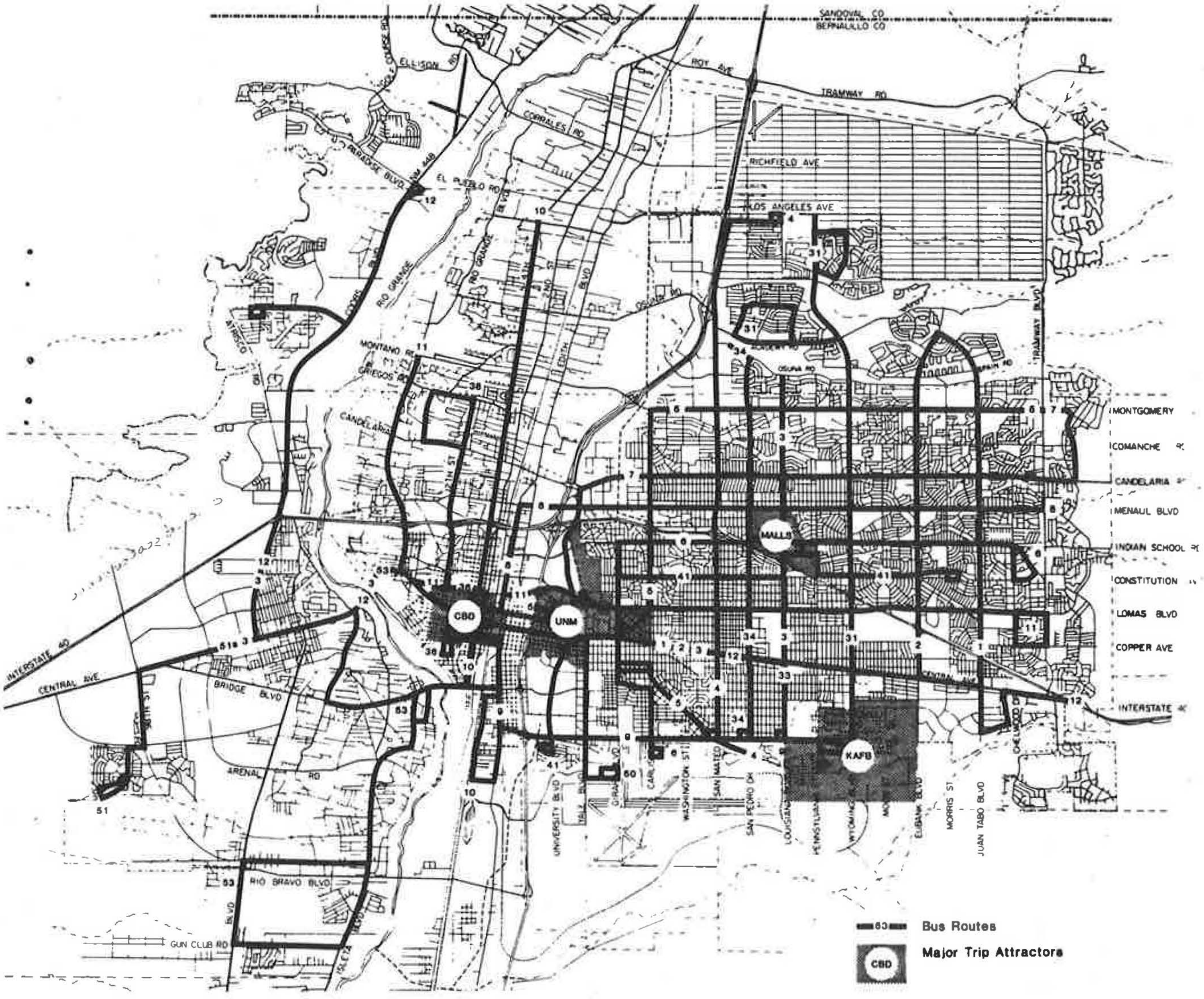
$$T_{ij} = f(SES_i, LOS_j) \tag{1}$$

where

T_{ij} = trips by individuals of class i by using alternative j,
SES_i = socioeconomic characteristics of individuals in class i, and
LOS_j = level of service offered by alternative j.

Consequently, three general types of data are required to develop formal mathematical models of travel behavior: travel, socioeconomic and land use, and level of service.

Figure 1. Albuquerque SunTran system: major destination areas.



Travel Data

The best available travel data were the 1981 on-board survey and ridership counts. From these data the project team developed accurate estimates of the geographic and temporal distribution of travel by trip purpose. Responses to the survey represented nearly 25 percent of total boardings and a substantially higher proportion of total linked trips (due to the high frequency of transfers). The project team expanded the survey results to represent a balanced profile of all riders by using ridership counts as control totals. No systematic comparable data were available about the extent or ridership characteristics of nontransit travel. This limited the modeling approaches that could be used; e.g., probabilistic choice models would have been impossible.

Socioeconomic and Land Use Data

A wide variety of data on population characteristics and land use was available from MRGCOG. These data are obtained and updated from a variety of sources, including U.S. Census reports, building permits, school enrollments, motor vehicle registrations, and aerial photographs. The unit of analysis for the socioeconomic data is the data-analysis subzone (DASZ). The Albuquerque urban area is divided into 419 DASZs ranging in area from less than 5 acres to more than 11 miles^2 in the outlying, less-developed areas. Each DASZ is generally an aggregation of several census blocks.

Level-of-Service Data

Level-of-service (LOS) considerations known to affect transit demand include in-vehicle travel time (IVTT), headways, walk time, accessibility, transfers, fares, schedule adherence, speed, and comfort and convenience. The policy relevance and analytic utility of a transit-forecasting model depend in large part on the number of factors explicitly reflected in the model specification. Therefore, a primary objective was to include as many service policy variables in the model as possible. However, the number of LOS components that could be considered was limited for several reasons.

First, in order to investigate statistical relationships between two variables, both must vary.

For some factors, such as fare, there was no variation corresponding to variations in ridership.

Second, there is the problem of multicollinearity. When there is high intercorrelation among independent variables in a cross-sectional forecasting model, the condition is known as multicollinearity. Some LOS factors, such as IVTT and walk time, are often highly intercorrelated. The impact of multicollinearity on model results is to confuse the true independent relationships between the correlated explanatory variables and the dependent variable. Parameter estimates for collinear variables will be biased, inefficient, and difficult to interpret. [For more information on multicollinearity, see Statistics for Economists (1, pp. 294-297).]

One suggested treatment for the condition of multicollinearity is to construct a composite explanatory variable from the intercorrelated variables to yield a single measure of the independent effects of the collinear variables. For this project, construction of composite variables was used with considerable success.

A third consideration limiting the number of LOS factors that could be included in the model was data availability. The only available service data were contained in the SunTran schedules and route map, from which the study team developed measures of IVTT, headways, required transfers, and overall accessibility of transit. However, no systematic data were available on walk times, comfort and convenience, or schedule adherence.

METHODOLOGY

The methodological approach to the modeling project was constrained, or jointly determined, by the considerations of the project objectives (especially easy application and high policy relevance), the project setting (multicentered hybrid grid-radial transit system), and the available data. This section briefly describes the methodology developed in response to these influences.

The selected model approach was a home-origin trip generation model that could be manually applied by using work sheets and a hand-held calculator to forecast ridership changes in response to changes in service, land use, or population. The model uses the DASZ as the unit of analysis. Fortunately, DASZ populations tend to be small and relatively homogeneous. (Fewer than 15 percent of all DASZ resident populations exceed 2,000 individuals.) This helps reduce the problem of aggregation error in the use of zonal data.

Circumstances influencing the selection of an aggregate model approach included the accuracy and currency of the DASZ data; the practice of regularly updating DASZ data; the unavailability of systematic data on nontransit users, required for individual-choice models; the unavailability of adequate survey data on frequency of transit use, required for individual trip-frequency models; and the easy application characteristics of aggregate models.

The selection of a zonal trip-generation approach was necessitated by the grid configuration of SunTran service, in which the possibility that users will substitute one route for another in reaction to service changes is much more salient than with radial configurations. Our approach to this problem is separate transit trip-generation and route-assignment procedures rather than a single route patronage forecasting model. The trip-generation model predicts transit ridership rates for DASZs as a function of all transit service offered to that area. The trips can then be apportioned by a route-assignment procedure that considers the relative service attributes of the routes. The advantage of a zonal trip-generation approach over a route-forecasting approach is that a direct route-forecasting model cannot handle the problem of users' substitutions of transit services as a response to changes in level of service. If a route is dropped, all ridership on the route is presumed lost with an ordinary route and zone trip analysis model. With a trip-generation model, all ridership is not lost; some users simply patronize the other route, which offers a lower level of service to their particular destination.

Because Albuquerque has no single dominant activity center, the project team developed and used multiple LOS measures reflecting service to the variety of trip attractors. However, simply representing the multiple service measures to each destination separately, such as IVTT to each of four major destinations, is seldom possible due to multicollinearity. Instead composite variables were constructed to measure the joint impacts of IVTT, wait times, and transfers to major destinations. The major destinations most salient in analyzing Albuquerque transit demand were identified through analysis of the 1981 on-board survey and consultations with local officials. These destinations were described earlier in this paper (see Figure 1). The composite measures were constructed by taking the weighted average of each LOS measure (IVTT, wait time, and so on) to each destination for each DASZ. The composite weights were derived from the estimated total daytime population of each major destination area.

The two principal advantages of the composite LOS variable approach are, first, that it allows explicit consideration of level of service to multiple destinations without the complication of multicollinearity and, second, that it helps introduce greater variability into some LOS measures with relative low variance (e.g., wait times and transfers), thereby increasing the potential of detecting a statistically verifiable relationship (2).

MODEL DEVELOPMENT PROCESS

The dependent variable for the home-origin transit travel analysis model was home-origin transit trips per 1,000 DASZ residents, calculated by using the expanded on-board survey data. Model development was an exploratory process guided by general urban travel demand theory and the findings of previous researchers. Model calibration used an ordinary least-squares approach with the standard SPSS multiple-regression computer package.

The calibration data set consisted of 298 residential zones with accurate socioeconomic data; 102 zones with fewer than 25 households were eliminated from the calibration data set because of their generally nonresidential character and because trip rates and socioeconomic and land use measures are more influenced by sampling error when one is working with smaller populations. Nineteen other zones were eliminated because of their institutional character or unavailability of accurate socioeconomic data.

LOS Findings

In analyzing the level of service, a wide variety of variables was tested in alternative empirical specifications. Three principal criteria guided the valuation of alternative specifications:

1. Magnitude and sign of model coefficients: Conformance with a priori theory and research results was important.
2. Significance and stability of model coefficients: Estimated model parameters should be signif-

icantly different from zero. Parameter estimates should not change dramatically with the insertion or deletion of an unrelated variable.

3. Explanatory power of model: The best model explains the most variance in home-origin trip rates subject to constraints imposed by criteria 1 and 2.

Two graphic devices also provided guidance in the model-development process. First, bivariate scatterplots showing the relationship between independent variables and the home-origin trip rate were analyzed for insights concerning alternative variable specifications. Second, geographic plots of residuals by DASZ showed where the model fit worst and best. Residuals analysis suggested useful additions of both LOS and socioeconomic (SES) variables. In some instances, the residuals analysis indicated coding errors in the variables that, when corrected, helped improve the model's overall fit. Coding errors in the assignment of home-origin trips to DASZs were particularly critical.

After testing dozens of alternative variable combinations, transformations, and specifications, we determined that the most satisfactory LOS model was the simple linear combination of five LOS variables. Each variable is described below:

1. IVTTC: Composite in-vehicle travel time by transit to major destination areas based on SunTran system schedules (an excess travel-time penalty of 10 min was added for outlying zones more than 0.5 mile from the nearest bus route; 20 min was added for zones more than 2 miles out);
2. WAITC: Composite transit wait time based on one-half the peak-period headway on the minimum-path route to each major destination (a penalty of 10 min was added for each zone not contiguous to a transit route but within 0.5 mile);
3. TRNUMC: Composite number of transfers required to reach major destinations along the minimum transit path to each destination;
4. NUMRT: Number of transit routes serving the zone based on inspection of SunTran system map; and
5. EXTERNAL: A dummy variable assigned to zones at the end of each major regional transportation corridor to control for the coders' assignment of transit trips originating outside the study area and boarding at the route end point as originating in that zone.

Each parameter estimate had the theoretically correct sign and magnitude. All were statistically significant at the 0.05 level of confidence. [For more detail, see report by Nelson and O'Neil (2).]

SES and Land Use Findings

We systematically searched the SES data available from MRGCOG for significant correlations with the home-origin trip rate by using the same evaluation criteria and graphic data-analysis techniques developed for the LOS model component. SES factors affecting home-origin transit use were categorized into seven classes, described in the following discussion.

Density

More densely settled areas would be expected to provide a more hospitable environment for transit use because walk times would be reduced for many inhabitants. Therefore, several measures of zonal density were developed and tested. Inspection of the modeling data set's correlation matrix indicated multicollinearity problems between the more traditional density measures (e.g., population or households per square mile) and LOS measures. Consequently, a less traditional density measure, the percentage of single-family homes (PCTSF), was used. In bivariate analyses and multivariate model specifications, PCTSF had a significant negative relationship with the home-based trip rate and was included in the final model specification as a density measure and a surrogate variable for wealth.

Land Use

We hypothesized that the character of adjacent nonresidential activity in a neighborhood could have a significant impact on residential transit ridership. For instance, note that more thickly settled mixed-use areas with higher concentrations of population-serving (commercial, retail, and so on) activity tend to be more conducive to transit use. This may be due to a variety of influences and interactions, including the more pedestrian scale of such areas, the tendency of transit captives to locate where more population-serving activity is within walking distance, a possible ameliorative effect of store-front activity and visual stimuli in reducing the tedium of walking to and waiting for the bus, and finally a possible synergism between successful urban transportation nodes and population-serving activities (e.g., the corner convenience store is aided by the bus stop and the bus stop is aided by the store). Consequently, a measure of population-serving business activity was tested in the model development process. The measure, COMMERCE, was the density of population-serving jobs on a square-mile basis. Population-serving jobs were defined as any employment with a standard industrial classification (SIC) code of Retail and Wholesale; Service; or Finance, Insurance, and Real Estate. In all tests the density of population-serving activities was positively related to residential transit use.

Prototypical land use types that are not popularly associated with high residential transit use are industrial areas and outlying rural areas. Neither of these sorts of neighborhoods is at a pedestrian scale. Automobile ownership is required in such areas to meet the requirements of daily living. Observed ridership from industrial areas was consistently lower than predicted, which led to the development of a hypothesis of industrial land use and residential transit use correlative to the population-serving postulate. The study team determined that the ratio of industrial jobs (SIC code names: Manufacturing, Transportation, Communications and Utilities, and Construction and Contracting) to households best conveyed the notion of industrial intensity. This variable was called INDUSTHH. (Measures such as industrial jobs per acre would be inadequate because most industrial activity is rather land intensive.) Tests of INDUSTHH revealed a consistently strong negative relationship with the home-origin trip rate.

Labor-Force Participation

The analysts had mixed expectations concerning the relationship between labor-force participation and residential transit use. On the one hand, as employment increases, so would transit travel; there would be a general rise in travel and greater competition for household automobiles. It could also be argued that where larger proportions of the population hold jobs, incomes would be lower, which would lead to greater transit use. Child-care responsibilities could also be less common, which would lead to increased travel. On the other hand, it could be argued that increased labor-force participation would increase individual incomes, which would increase automobile ownership and decrease transit ridership.

Empirical evidence from Albuquerque suggests that increases in labor-force participation generally have a positive effect on transit ridership. In the final model specification, the selected labor-force participation measure is the percentage of persons over age 18 estimated to be employed (PCTEMP). This particular denominator was selected due to its good fit in the model and its accurate portrayal of the population at risk.

Dependent Population

It could be argued that the relationship among children, population, and residential transit use also shows mixed effects. On the one hand, as household size increases and there are more babies, children, and dependents, the chores of child rearing may reduce the household's mobility, which lowers overall travel. Also, as family size increases, the home economics of urban travel tend to favor automobile use, because the marginal cost of an additional private automobile passenger is often negligible for family-sized groups but substantially higher for bus travel. On the other hand, as household size increases, overall transit use could rise, because there would be more transit-captive adolescents on the SunTran system. Similarly, because family size would prevent purchase of a second family car, the bus would tend to serve this function.

The empirical results from Albuquerque support the former arguments that as the dependent population and average household size increase, transit ridership decreases. Several measures of the dependent population were developed from U.S. Census and Albuquerque Public School data, including a general measure of household size. Each of these measures of dependent population tended to be inversely correlated with the home-origin trip rate. The simple average household size measure (HHSIZE) was included in the final model specification due to its ease of calculation and generally intuitive appeal.

Elderly Population

Based on other experience, one would expect transit ridership to be positively correlated with the size of the elderly ridership base. Older retired individuals are often transit captives. In Albuquerque and elsewhere in the southwestern sunbelt, this conventional wisdom may not necessarily be true. As retirees have flocked to New Mexico over the last decade, the elderly population in Albuquerque has been growing 20 percent more rapidly than the population as a whole. These older individuals may be more affluent or less mobile than the average Albuquerquean, because no data in this study clearly indicated that the elderly are more or less likely to use transit than the average person.

Income or Wealth

Traditional wisdom in the transit planning field holds that income and wealth are generally inversely related to bus transit use. Bus transit is an inferior economic good, generally replaced by the luxury of automobile travel as incomes rise.

Several zonal measures of wealth or income were available. The most promising of these measures were derived from the 1980 Census questions on the values of owner-occupied homes and rents. From these data it was possible to create two housing-value or wealth measures: SFMEAN (average reported value of single-family home) and MFMEAN (average rent). These measures should be inversely correlated with the home-based trip rate. However, no significant relationships with residential transit use were detected in bivariate or multivariate tests. In the light of these results, the housing-value measures were dropped from the final model specification.

Automobile Ownership

Many researchers have discovered relationships between automobile ownership and availability and use of transit. The Albuquerque 1981 on-board survey data indicate that more than one-quarter (26 percent) of all transit trips are made by individuals living in households without automobiles. Clearly such individuals appear more likely to use bus transit. Consequently, the study team anticipated that the condition of being without an automobile would be negatively correlated with residential transit use. Measures were constructed by using current motor vehicle registration data; however, statistical tests revealed no relationship between automobile availability and transit use. The study team's interpretation of these results is that the measures of automobile availability were probably inadequate in that they contained significant errors and biases. [For more information, see report by Nelson and O'Neil (3).]

A set of five SES and land use variables was included in the final model specification:

1. PCTSF: the ratio of single-family homes to all homes in the zone times 100;
2. COMMERCE: the number of retail, wholesale, finance, insurance, real estate, and service jobs per square mile;
3. INDUSTHH: the total number of jobs in manufacturing, transportation, communications, utilities, construction, and contracting per household in the zone;
4. PCTEMP: the ratio of estimated employed residents to persons over the age of 18 times 100; and
5. HHSIZE: the ratio of total residents to total households.

Other factors are not included in the model due to insignificant or inconclusive statistical results. Errors in some explanatory variables, such as automobile ownership, are the principal reason for the failure to detect a usable statistical relationship.

FINAL MODEL SPECIFICATION AND RESULTS

The final model specification contains a total of 10 explanatory variables described in the previous section. The dependent variable is home-origin transit trips per 1,000 residents. As can be seen from the tabulations below, the model provides a rather good statistical fit; nearly 75 percent of the variance in trip rates is explained ($R^2 = 0.738$). Each of the model coefficients is statistically significant at the 0.05 level with the theoretically correct sign and a reasonable magnitude.

Variable	Parameter Estimate	SE of Estimate
IVTTC	-0.1011	0.0338
WAITC	-0.2721	0.1005
TRNUMC	-5.205	1.424
NUMRT	2.489	0.3624
EXTERNAL	22.42	3.027
PCTSF80	-0.0401	0.0198
COMMERCE	0.001625	0.00028
INDUSTHH	0.5203	0.1695
PCTEMP	0.3034	0.0501
HHSIZE	-3.766	1.003
Constant	16.97	Not available

Summary statistics are as follows:

Statistic	Value
Multiple R	0.859
R^2	0.7380
Adjusted R^2	0.7289
SE	7.0638

The analysis of variance statistics are given below:

Type	Df	Sum of Squared Errors	Mean Squared Error	F
Regression	10	40,339	4033.950	80.8443
Residual	287	14,320	49.897	

Partial validation of the model was conducted by using the model's predicted trip rates to calculate the anticipated number of trips originating in each zone and by comparing the model predictions with the actual numbers of home-origin trips recorded. The recorded daily average systemwide total was 7,918; the predicted daily average was 8,106 for a total error of 188 overestimated. The overall error rate equals 2.4 percent systemwide for the entire set of 419 DASZs. In only 58 cases (13.8 percent) was the discrepancy greater than 10 trips. In only 22 of these cases (5.2 percent) was the prediction error greater than 20 trips.

Figure 2 is a scatterplot of actual and predicted home-origin trips by zone. The correlation between actual and predicted trips is very strong (R = 0.931). The bivariate regression between actual and predicted numbers of trips indicates close correspondence; R^2 was 0.867, beta was 0.932, and the constant was 0.870. The SE of the estimate is 8.55 trips per zone. Although this level of performance may not be optimal, it represents a significant improvement over guessing or less-sophisticated analysis approaches that may require as much or more time to implement.

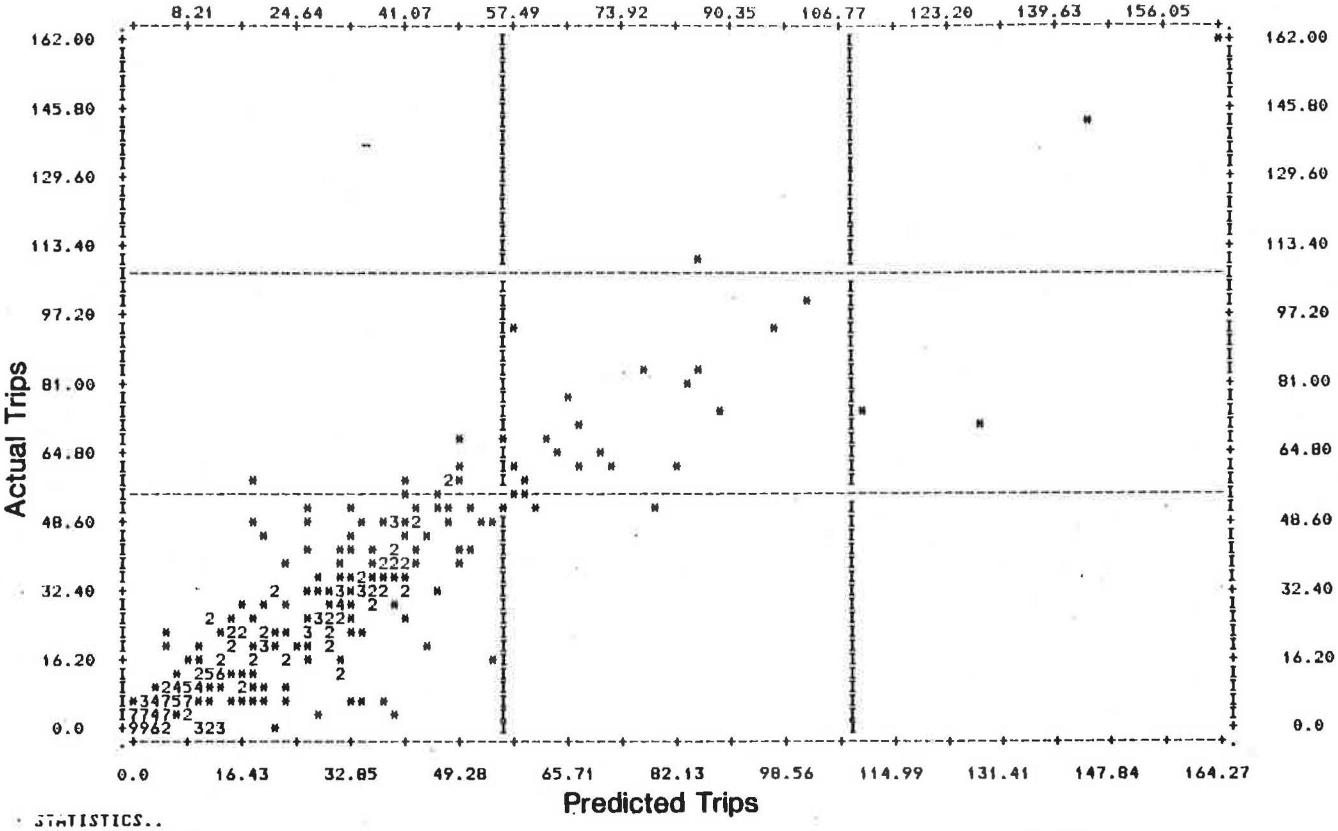
MODEL VALIDATION

The true test of a short-range planning analysis model is how well it predicts ridership response to changes in service or land use. This section documents the predictive validity of the forecasting procedure against the empirical results from an actual service change. The validation check results suggest that the procedure is quite accurate in predicting ridership changes due to changes in transit service.

Selected Service Change

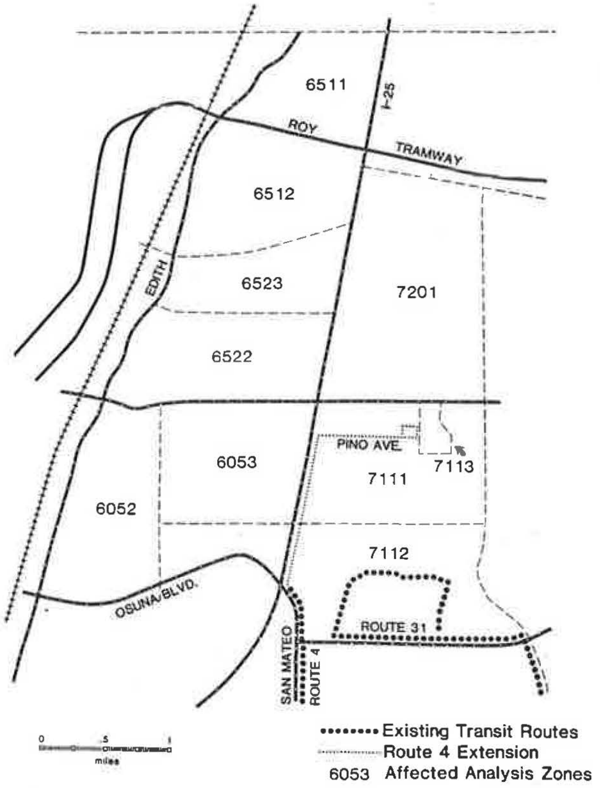
During the spring of 1980, service was extended north on Route 4 from its terminus on Osuna Boulevard to Pino Avenue (March 1980) and then east to Louisiana Boulevard (June 1980) (Figure 3). The change improved service to a total of nine residential DASZs. No substantial changes in land use or the SES characteristics of the residents accompanied the service change. The service extension had no impact on transit headways or travel times for other neighborhoods or routes. Consequently, this service extension can be conveniently analyzed as an isolated service change affecting only a single area or neighborhood.

Figure 2. Model validation scattergram: actual and predicted home-origin transit trips by analysis zone.



```
STATISTICS..
CORRELATION (R)-        0.93125     R SQUARED        -    0.86722     SIGNIFICANCE     -    0.00000
STD ERR OF EST -        8.54907     INTERCEPT (A)    -    0.87005     SLOPE (B)        -    0.93189
PLOTTED VALUES -      419           EXCLUDED VALUES-      0           MISSING VALUES   -    0
```

Figure 3. SunTran system: Route 4 extension.



Application Procedure

Because the route extension affected only transit LOS values, it was possible to use the model in a short-cut fashion to predict changes in ridership as a consequence of service improvements. That is, the change in level of service for each analysis zone could be calculated and multiplied times the relevant parameter estimate to determine the expected change in the zone's home-origin trip rate. This rate change could then be multiplied against the zone population to determine the expected change in zonal travel. Expected changes could then be summed for all affected zones and compared with observed changes in route ridership.

The predicted change in home-origin transit trips due to the Route 4 extension was 33.78 trips. This estimate must be doubled to get the anticipated change in all home-based trips, 67.56 daily trips. A final adjustment is then required to account for non-home-based trips. (Because non-home-based trips account for approximately 17 percent of all SunTran trips, an adjustment of 10-20 percent is probably appropriate for estimating the increased number of non-home-based trips.) With the adjustment, anticipated ridership responses range from 74 to 81 trips. This represents the best model estimate of induced ridership on Route 4 due to the service improvement.

Validation Results and Conclusions

The actual ridership change was calculated from monthly route ridership summaries for two 4-month periods: December 1979 to March 1980, before the service change, and July to October 1980, after the service change was completed. The average daily route ridership in the before period was 735 passengers. Afterwards, the count increased to 816 riders. This yields a net ridership increase of 81, which is within the predicted range of response.

These results are extremely encouraging. The model was easy to apply. Only a few hours were required to collect the necessary data and perform calculations. The model was also accurate in predicting the anticipated ridership change. It certainly would be sufficiently accurate for short-range bus service planning. The validation also highlights the need for a non-home-based travel analysis model to reduce uncertainty in making ridership predictions.

CONCLUSIONS

Based on the model results and validation exercise, the Albuquerque home-origin transit travel analysis model appears to be a valuable transit planning tool for analyzing the demand impacts of service, population, and land use changes. The model is intuitively simple, requires a minimum of data, and is flexible and easy to apply. It also appears that the model approach, if not the model itself, should be transferable to other urban areas, especially rapidly growing multicentered sunbelt cities that lack the radial structure and dominant activity core characteristic of older industrial cities.

ACKNOWLEDGMENT

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Analysis of Regional Park-and-Ride and Express Bus Service

THABET ZAKARIA, CH. ABDUL LATIF, AND PANAGIOTIS P. SALPEAS

The results of a study aimed at increasing the transit patronage, reducing the automobile travel, and improving the air quality in the Delaware Valley Region by introducing park-and-ride and express bus service are summarized. For this study, 45 bus corridors connecting 178 parking locations in major shopping areas with 500 or more parking spaces were initially identified. Many of these corridors were eliminated from further consideration to avoid duplication of service and frequent bus stops along the routes. A set of 21 corridors linking 47 parking locations was then tested by using UMTA's UTPS modeling package. Those park-and-ride locations that attracted more than 250 riders from the existing commuter and subway-elevated routes in the vicinity of the parking locations were not included. Other locations that attracted fewer than 50 riders from the use of automobiles were also dropped from further consideration. Based on these criteria, a final network of 14 routes and 25 parking lots is recommended for further detailed analysis and implementation studies. The impact on air quality and energy of the recommended facilities is also presented. Estimates for capital expenditure and operating cost for implementing the park-and-ride and express bus service are also included.

Multiple use of parking facilities in urban regions has occurred occasionally in the past. This limited use has ranged from contractual use of shopping center parking facilities to unauthorized roadside parking.

This study was initiated in 1981 by the transportation air-quality program of the Delaware Valley Regional Planning Commission (DVRPC) for the purpose of reducing automobile emissions and thus improving air quality. The purpose of this study is to select a number of parking facilities with reasonable proximity to major regional highways that, under agreement with their operators or owners, could be used for park-and-ride and express bus service. Basically, such an operation can have a measurable effect on automobile traffic volume and transit ridership. A reduction of the daily automobile trips will reduce highway congestion, improve air quality, and increase transit patronage, thus improving the operating revenues of the regional public transit carriers.

The term park-and-ride has been used in various ways. Some speak of express transit service between a suburban area and some activity center as park-and-ride service. Others use this term to refer to shuttle-bus services connecting parking lots located at the edge of a business district to that district. Still others refer to park-and-ride service as any operation that provides a parking lot at a point of access to any transit line. The terms park-and-ride, fringe parking, remote parking, and peripheral parking are often used interchangeably to describe similar operations. In this study, park-and-ride and express bus service is defined as transit service that encourages an individual to reach an express bus service by a private vehicle, usually an automobile, and permits this individual to transfer from to an express bus to reach his destination. At the point of transfer, the individual may (a) park the vehicle in the space provided or surrender it to an attendant or (b) be dropped off by another driver as in kiss-and-ride service. The return trip operates in the reverse, i.e., express bus to private mode.

As defined here, the express bus patronage may not always involve use of the park-and-ride facilities designated for this purpose. Patrons may reach the bus service by walking or by other modes such as paratransit services and kiss-and-ride service. The park-and-ride lot functions in a manner quite similar to that of a transportation terminal or railroad station.

The park-and-ride and express bus service is designed to link suburban communities with Philadelphia and Trenton central business districts (CBDs). The placement of parking facilities in suburban areas will ensure that suburban residents make relatively short trips to reach the express bus used for line-haul operation. It is assumed that the park-and-ride service will be accompanied by improved reliability of the transit service to deliver the rider to his destination on time and at faster overall speeds.

METHODOLOGY

The methodology followed in this study is divided into four phases: selection of park-and-ride lots, definition of the inner ring, preparation of network coding, and simulation of park-and-ride lots and route volumes.

Selection of Park-and-Ride Lots

The DVRPC 1975 Regional Parking Inventory, as updated, was used to identify the potential parking lots for this study. These parking locations were reviewed by the county officials for their suitability. The updated file of parking lots was used to plot the locations of potential parking lots on the regional map.

Because most of the travel from the outlying areas of the region is directed toward two major urban centers, highway corridors connecting the farthest parking lots in the region with Philadelphia or Trenton CBDs were then mapped. In delineating these corridors, the following criteria were considered:

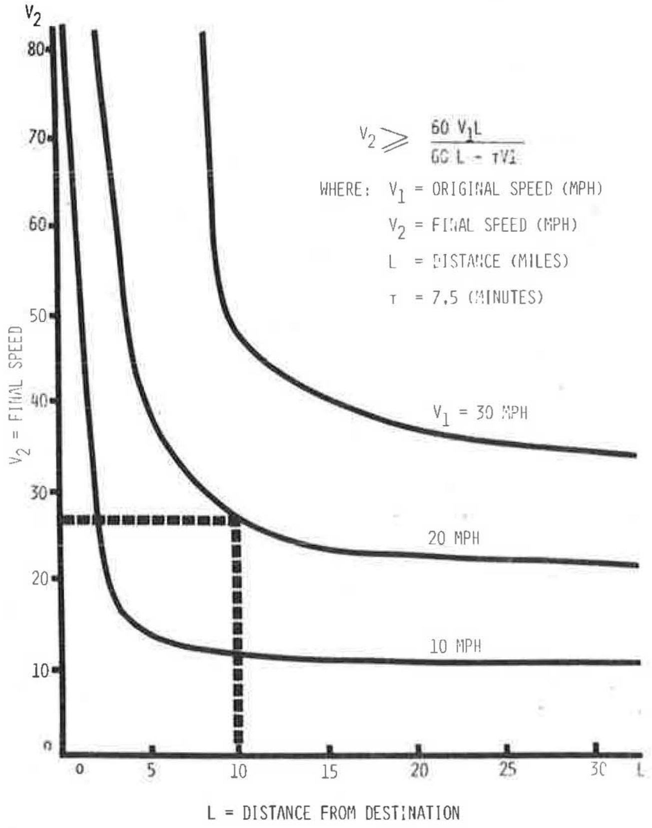
1. Routes with direct access in terms of alignment and speed were selected;
2. Parking lots of 250 or more spaces were linked with each proposed route, with particular emphasis on the lots recommended by county officials; and
3. Some cross-county routes connecting outlying urban centers were also identified.

This effort resulted in the identification of 45 corridors in the region connecting 178 parking lots. The routes were carefully selected to avoid competition with each other and with the existing transit service. The number of stops at the park-and-ride lots for each route was limited to 4.

Definition of Inner Ring

An important consideration in the selection of parking locations is the overall trip time. The use of park-and-ride service connotes a transfer from a car to a bus and therefore involves additional travel time. The total door-to-door time is a critical determinant in the choice of travel mode, and any transfer that would increase the travel time would

Figure 1. Determination of inner ring.



reduce the ridership. For the success of the park-and-ride service, therefore, it is important to increase the speed of the bus service from the parking lot to the place of destination to offset any time lost in transfers.

Assuming that a transfer from car to bus service takes an average of t min, a set of curves (Figure 1) was drawn to relate the final speed (V_2) of the commuter vehicle with the original speed of commuting (V_1) by car. These curves are based on the following relationship:

$$V_2 = 60\,V_1\,L/(60\,L - t\,V_1)$$

where

V_2 = final speed of commuter vehicle (mph),
V_1 = original speed of travel (door-to-door) (mph),
L = over-the-road distance between the lot and the destination (miles), and
t = additional time for transfer.

For Figure 1, t was assumed to be 7.5 min.

These curves show that when the distance L is small, the speed of commuting by the commuter vehicle V_2 is much higher than the original door-to-door speed V_1 by car. These curves were used to define a ring around the Philadelphia CBD based on the average speeds in various travel corridors. A similar ring was developed around Trenton. Figure 2 shows the location of these rings. Any park-and-ride location within these rings would be impractical due to the difficulty of attaining very high bus speeds.

Preparation of Network Coding

The original list of 45 routes was reduced to the 21 express bus routes shown in Figure 3 to avoid duplication of transit service and frequent stops along the routes. These corridors contain 52 park-and-ride locations, mainly at large shopping centers, totaling more than 42,000 parking spaces.

The express bus service in these corridors was coded for simulation according to the UTPS format and module. This simulation produced ridership on these routes and the number of parkers at each lot as well as the diversion of trips from other travel modes currently serving the corridor.

Simulation of Park-and-Ride Lots and Route Volumes

The preliminary park-and-ride and express bus system was simulated by the DVRPC modal-split and assignment models. The demographic and employment estimates used in the simulation were those for the year 1990 developed as part of the Year 2000 Transportation Plan. The 1990 transit and highway networks were used for this analysis, with the most recent estimates of transit fares and highway operating costs.

As mentioned before, the proposed bus lines were coded for simulation and evaluation. Travel time, headway, fare, and stop locations were used to describe the quality of the bus service. The commuter-shed areas were also identified for all the proposed facilities to identify the areas from which the ridership would originate. Based on the previous studies, the boundary of the shed area at the beginning of a bus route was defined as a hyperbola with a maximum trip length to the parking lot of 10 miles (Figure 4). The shed area for the other bus stops was assumed to be a circle with a 3-mile radius.

This definition of the commuter shed is based on the travel behavior of the commuters with regard to access time, which should be about 5 to 10 min to reach the park-and-ride location.

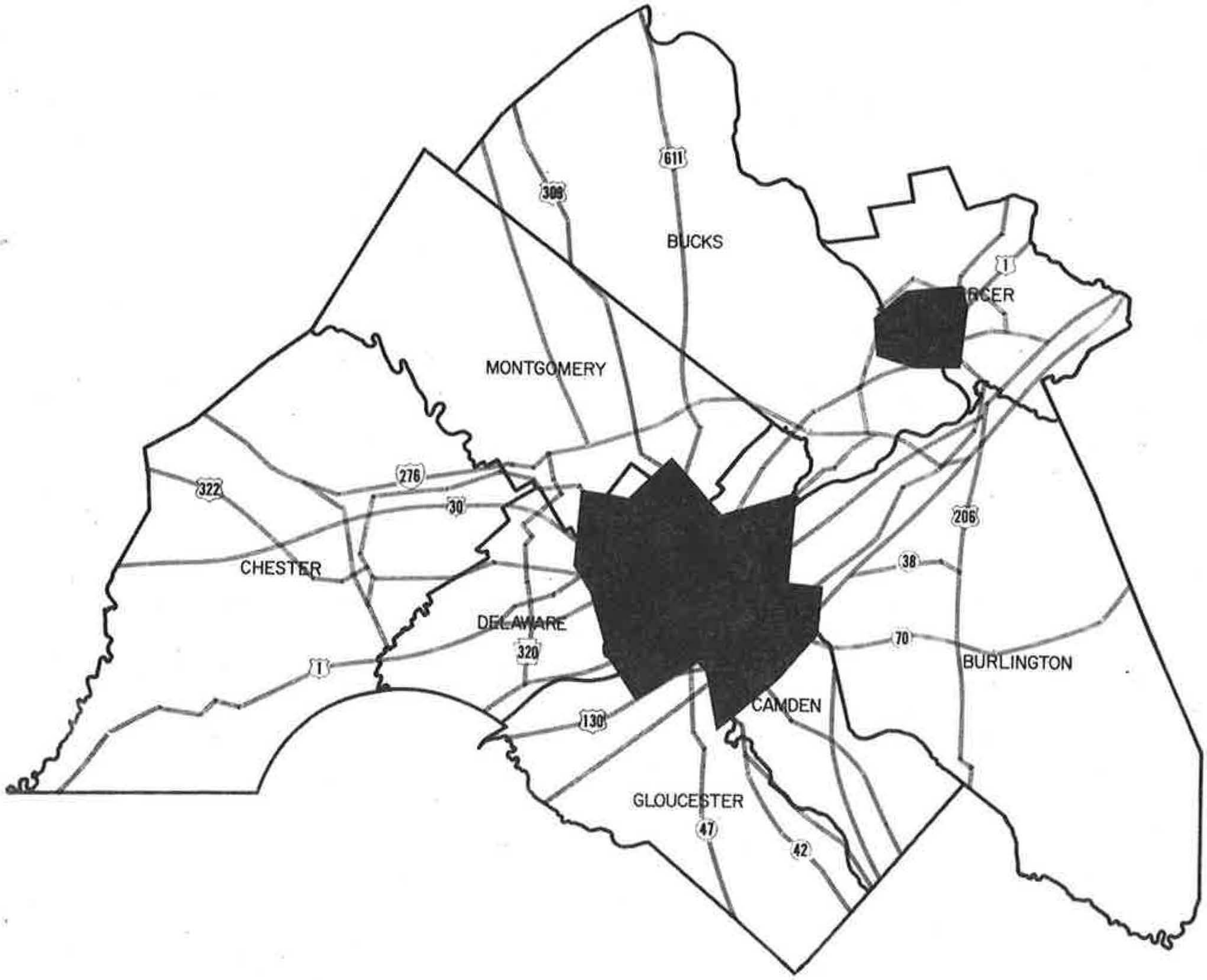
The modal-split and transit assignment models of the UTPS were then run to estimate the bus line and station volumes. The transit volumes on the express bus system were compared with those resulting from the transit network that do not include such a system to determine the diversion of trips from other travel modes.

SIMULATION RESULTS AND ANALYSIS

In Table 1, the daily transit ridership with and without park-and-ride and express bus service is summarized. The provision of these facilities results in an increase of 5,405 daily transit trips over the ridership without park-and-ride service. In Table 1 also, the overall daily ridership on the new express buses is 19,230 trips. In addition to the 5,405 trips diverted from automobile, this service would also divert 7,520 trips from the existing users of the commuter rail, 3,128 trips from the subway and elevated and high-speed lines of the Port Authority of Allegheny County (PATCO), and 3,177 from local bus. The reason for this massive shift from the existing transit modes is that the new express buses provide competitive and, in many cases, faster service. Table 2 presents patronage estimates at each park-and-ride facility on all 21 express routes. Major competition with commuter rail and subway and elevated modes is evident where the park-and-ride lot is located close to an existing commuter rail and subway and elevated station.

Because the objective of the park-and-ride and

Figure 2. Location of inner rings.



express bus service is to increase ridership on public transportation modes, it was necessary to modify the original park-and-ride network to exclude certain bus routes in order to avoid competition with other public transportation modes. Express bus routes or stations that attract more than 250 trips from competing commuter rail and subway and elevated lines were excluded from further consideration. In addition, the bus routes and stations on which the automobile trip diversion is less than 50 trips were excluded from further analysis, because they did not appear to have an effect on increasing transit ridership and improving air quality. As a result, four routes in Pennsylvania and three in New Jersey were eliminated. With some modification in the routing of the remaining bus lines, 14 lines were recommended for detailed studies (Table 3). Figure 5 shows the park-and-ride and express bus network recommended for further implementation studies.

The previous analysis indicates that the park-and-ride service will attract riders from the existing users of the commuter rail system and the subway and elevated lines and bus routes. In addition, some automobile users will also switch to the new bus service. To estimate parking space requirements, the following assumptions were made concerning the proportion of bus users who drive to the parking lots:

1. Bus users diverted from commuter rail, 80 percent;
2. Bus users diverted from subway and elevated lines, 30 percent;
3. Bus riders diverted from local bus, 10 percent;
4. Bus users diverted from automobile, 100 percent.

An average car occupancy of 1.3 persons per car was assumed in estimating the parking spaces required at each park-and-ride lot.

In Table 4, the total parking spaces required at each park-and-ride lot are shown as a percentage of the total parking spaces available at each facility. It will be seen that only 6 percent of the spaces in the parking lots will be needed for the park-and-ride service in Pennsylvania and 4 percent on the New Jersey side of the region.

AIR-QUALITY AND ENERGY IMPACTS

Any reduction in automobile driving will reduce automobile emissions, gasoline consumption, and operating cost. In Table 5, the impacts of the 14 park-and-ride facilities on person and automobile travel, hydrocarbon (HC) and carbon monoxide (CO) emissions, and fuel estimated for 1987 are shown. In Table 5, 1,710 persons living in Pennsylvania and 2,577 in New Jersey portions of the region would switch from automobile to park-and-ride service, resulting in a decrease of 19,800 daily vehicle miles of travel (VMT) in Pennsylvania and 28,900 VMT in New Jersey. This reduction will eliminate 52.6 kg of HC and 640.3 kg of CO emissions per day. In addition, there will be a daily savings of 2,633 gal of gasoline. On an annual basis, the emission re-

Figure 3. Park-and-ride and express bus network for simulation.

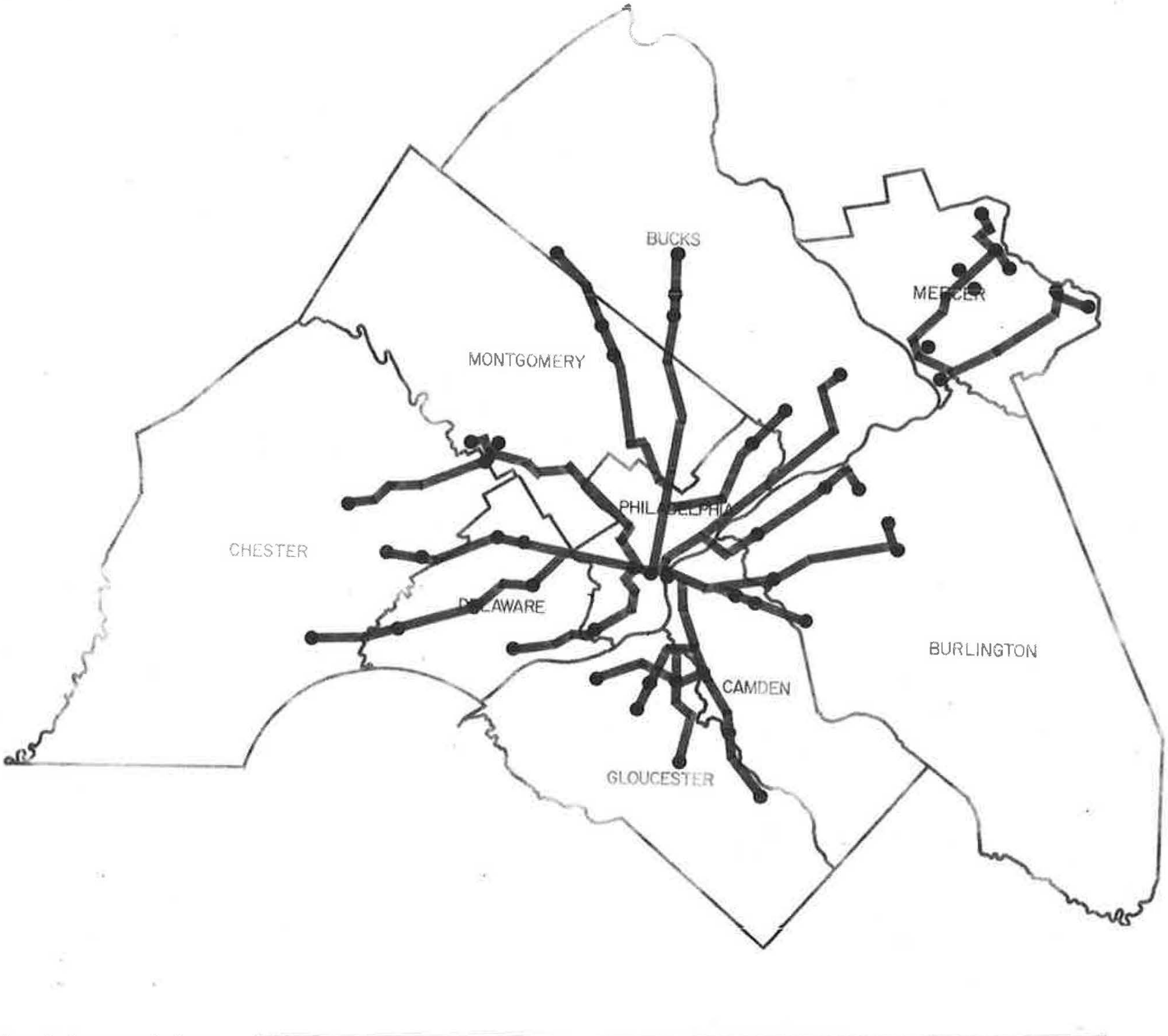


Figure 4. Commuter shed areas.

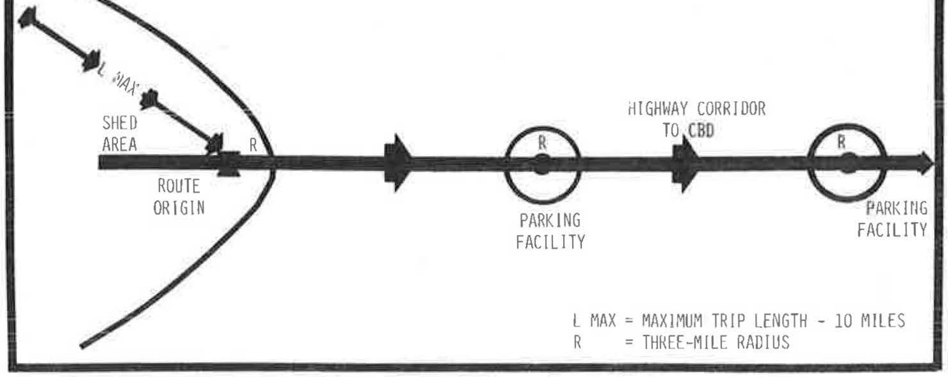


Table 1. Ridership with and without park-and-ride and express bus service.

	No. of Trips		
Ridership	Pennsylvania	New Jersey	Total
Without park-and-ride facilities	927,768	88,992	1,016,760
With park-and-ride facilities	930,376	91,789	1,022,165
Diverted from automobiles to park-and-ride service	2,608	2,797	5,405
Diverted to express bus from			
Commuter rail	7,188	332	7,520
Subway and elevated lines	2,140	988	3,128
Existing local bus	1,145	2,032	3,177
Automobiles	2,608	2,797	5,405
Total express bus trips	13,081	6,149	19,230

ductions would be 15 780 kg of HC, 192 090 kg of CO, and about 790,000 gal of gasoline.

The reduction in the amount of HC and CO emissions is based on the emission factors contained in the Mobile 2 model of the U.S. Environmental Protection Agency (EPA) for the year 1987. The savings in fuel consumption were estimated by using the consumption factors for the highway fleet average expected in 1987.

COST ANALYSIS

The state departments of transportation, transit operating agencies, or the counties may operate and maintain the parking facilities necessary for the service. They may also provide the capital cost re-

Table 2. Ridership estimates for park-and-ride and express bus service by location.

		Ridership Estimates		Ridership Diverted from			
Route Description	Park-and-Ride Facility Location	Park-and-Ride Facility	Route Total	Commuter Rail	Subway and Elevated	Local Bus	Automobile
Pennsylvania							
I-95/I-76	Chester CBD	3,152	4,584	2,467	158	284	243
	Philadelphia Airport (Cargo City)[a]	1,432		259	218	156	799
US-1	Longwood Gardens	196	941	136	0	22	38
	US-202 and US-1	104		92	0	10	2
	Granite Run Mall	366		255	55	29	27
	Springfield Shopping Center	275		74	145	14	42
PA-3	West Goshen Shopping Center	699	2,683	471	63	69	96
	Westtown Center	367		248	33	35	51
	Newtown Shopping Center	569		100	350	27	92
	Broomall Shopping Center	1,048		183	761	30	74
US-202/I-76	Exton Mall	643	844	397	0	69	177
	Valley Forge Music Fair	201		154	22	16	9
I-76	Valley Forge Park[a]	282	332	28	17	36	201
	King of Prussia	50		18	30	0	2
PA-309	Souderton Plaza[a]	174	423	99	0	19	56
	Montgomeryville Plaza[a]	147		75	0	16	56
	English Village[a]	102		0	0	14	88
US-611	Doylestown Center[a]	345	506	188	24	35	98
	Kings Plaza	56		31	6	6	13
	Warrington Shopping Center[a]	105		35	7	10	53
US-1/US-611	Neshaminy Mall[a]	651	1,108	235	91	64	261
	Red Lion Mall[a]	457		166	160	33	98
US-1/I-95	Oxford Valley Mall	1,660	1,660	1,477	0	151	32
Total			13,081	7,188	2,140	1,145	2,608
New Jersey							
US-130 (Hightstown)	Twin Rivers Shopping Center	91	170	0	0	47	44
	East Windsor Shopping Center	79		0	0	41	38
US-206	Whitehorse Bowling Alley[a]	282	282	48	0	122	112
US-1 (Mercer County)	West Windsor Shopping Center	102	200	27	0	39	36
	Penns Neck	98		23	0	39	36
US-1 (Princeton)	Princeton Shopping Center	106	176	26	0	42	38
	Mercer Mall	70		17	0	28	25
US-130 (Burlington, Betsy Ross Bridge)	Jefferson Ward Center (Dolran)[a]	233	561	0	17	112	104
	Willingboro Plaza[a]	328		0	24	158	146
US-130 (Burlington, Betsy Ross Bridge)	Cinnaminson Shopping Center[a]	1,005	1,005	191	242	197	375
NJ-38 (Mount Holly, Ben Franklin Bridge)	Fair Grounds, NJ-541[a]	202	1,230	0	44	82	76
	Lumberton Plaza[a]	478		0	105	194	179
	Moorestown Mall[a]	550		0	28	19	503
NJ-70 (Ben Franklin Bridge)	Marlton Plaza[a]	202	289	0	7	101	94
	Ellisburg Circle	45		0	41	2	2
	Garden State Park	42		0	40	1	1
NJ-42/North-South Freeway (Ben Franklin Bridge)	Williamstown Center[a]	294	505	0	18	144	132
	Jefferson Ward (Turnersville)[a]	211		0	36	91	84
NJ-47/North-South Freeway (Ben Franklin Bridge)	College Town (Glassboro)[a]	353	526	0	78	16	259
	Woodbury Plaza[a]	173		0	38	70	65
NJ-45/North-South Freeway (Ben Franklin Bridge)	Toll House Plaza (Mantua)[a]	261	582	0	58	106	97
	Acme Shopping Center (Woodbury)[a]	321		0	71	130	120
NJ-44/NJ-534/North-South Freeway (Ben Franklin Bridge)	Paulsboro Center[a]	438	623	0	100	176	162
	Deptford Mall[a]	185		0	41	75	69
Total			6,149	332	988	2,032	2,797
Regional total			19,230	7,520	3,128	3,177	5,405

[a] Routes recommended for detailed studies.

Table 3. Park-and-ride facilities and bus routes recommended for implementation studies.

		Ridership Estimates		Ridership Diverted from			
Route Description	Park-and-Ride Facility Location	Park-and-Ride Facility	Route Total	Commuter Rail	Subway and Elevated	Local Bus	Automobile
Pennsylvania							
I-95/I-76	Philadelphia Airport (Cargo City)	1,432	1,432	259	218	156	799
I-76	Valley Forge Park	282	282	28	17	36	201
PA-309	Souderton Plaza	174	423	99	0	19	56
	Montgomeryville Plaza	147		75	0	16	56
	English Village	102		0	0	14	88
US-611	Doylestown Center	345	450	188	24	35	98
	Warrington Shopping Center	105		35	7	10	53
US-1/US-611	Neshaminy Mall	651	1,108	235	91	64	261
	Red Lion Mall	457		166	160	33	98
Total			3,695	1,085	517	383	1,710
New Jersey							
US-206	Whitehorse Bowling Alley	282	282	48	0	122	112
US-130 (Burlington, Betsy Ross Bridge)	Jefferson Ward Center (Dolran)	233	561	0	17	112	104
	Willingboro Plaza	328		0	24	158	146
US-130 (Burlington, Betsy Ross Bridge)	Cinnaminson Shopping Center	1,005	1,005	191	242	197	375
NJ-38 (Mount Holly, Ben Franklin Bridge)	Fair Grounds–NJ-541	202	1,230	0	44	82	76
	Lumberton Plaza	478		0	105	194	179
	Moorestown Mall	550		0	28	19	503
NJ-70 (Ben Franklin Bridge)	Marlton Plaza	202	202	0	7	101	94
NJ-42/North-South Freeway (Ben Franklin Bridge)	Williamstown Center	294	505	0	18	144	132
	Jefferson Ward (Turnersville)	211		0	36	91	84
NJ-47/North-South Freeway (Ben Franklin Bridge)	College Town (Glassboro)	353	526	0	78	16	259
	Woodbury Plaza	173		0	38	70	65
NJ-45/North-South Freeway (Ben Franklin Bridge)	Toll House Plaza (Mantua)	261	582	0	58	106	97
	Acme Shopping Center (Woodbury)	321		0	71	130	120
NJ-44/NJ-534/North-South Freeway (Ben Franklin Bridge)	Paulsboro Center	438	623	0	100	176	162
	Deptford Mall	185		0	41	75	69
Total			5,516	239	907	1,793	2,577
Regional total			9,211	1,324	1,424	2,176	4,287

Figure 5. Recommended park-and-ride and express bus network.

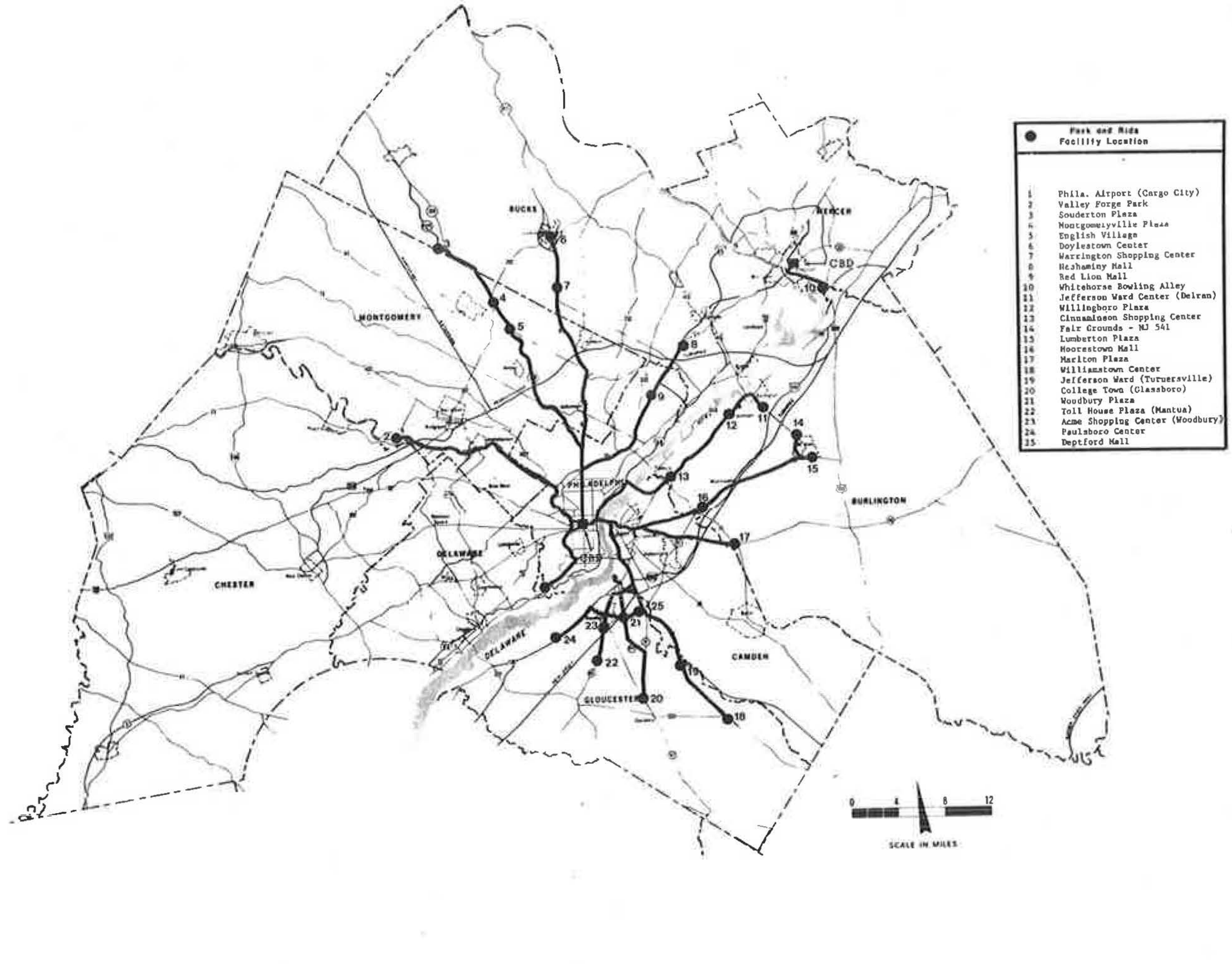


Table 4. Required parking spaces.

		Lot Capacity (no. of spaces)		
			Required for This Service	
Route Description	Park-and-Ride Facility Location	Total	Number	Percent of Total
Pennsylvania				
I-95/I-76	Philadelphia Airport (Cargo City)	1,800	418	23
I-76	Valley Forge Park	560	89	16
PA-309	Souderton Plaza	680	53	8
	Montgomeryville Plaza	585	45	8
	English Village	610	34	6
US-611	Doylestown Center	1,600	62	4
	Warrington Shopping Center	1,900	32	2
US-1/US-611	Neshaminy Mall	8,500	185	2
	Red Lion Mall	1,000	109	11
Total		17,235	1,027	6
New Jersey				
US-206	Whitehorse Bowling Alley	290	62	21
US-130 (Burlington, Betsy Ross Bridge)	Jefferson Ward Center (Dolran)	4,000	46	1
	Willingboro Plaza	4,300	65	2
US-130 (Burlington, Betsy Ross Bridge)	Cinnaminson Shopping Center	1,800	239	13
NJ-38 (Mount Holly, Ben Franklin Bridge)	Fair Grounds–NJ-541	1,165	37	3
	Lumberton Plaza	6,000	89	1
	Moorestown Mall	1,090	197	18
NJ-70 (Ben Franklin Bridge)	Marlton Plaza	1,500	41	3
NJ-42/North-South Freeway (Ben Franklin Bridge)	Williamstown Center	655	58	9
	Jefferson Ward (Turnersville)	990	40	4
NJ-47/North-South Freeway (Ben Franklin Bridge)	College Town (Glassboro)	1,475	109	7
	Woodbury Plaza	1,535	32	2
NJ-45/North-South Freeway (Ben Franklin Bridge)	Toll House Plaza (Mantua)	1,070	48	4
	Acme Shopping Center (Woodbury)	1,200	59	10
NJ-44/NJ-534/North-South Freeway (Ben Franklin Bridge)	Paulsboro Center	570	81	14
	Deptford Mall	5,500	34	1
Total		33,140	1,237	4
Regional total		50,375	2,264	5

Table 5. Estimated daily impact on trips, air quality, and energy of park-and-ride facilities.

			Reduction in				
Route Description	Park-and-Ride Facility Location	Distance to Destination (miles)	Daily Automobile Person Trips	Daily Automobile VMT	HC[a] (kg/day)	CO[a] (kg/day)	Fuel[b] (gal/day)
Pennsylvania							
I-95/I-76	Philadelphia Airport	7.4	799	4,500	4.8	48.9	243
I-76	Valley Forge Park	21.9	201	3,400	3.5	40.3	184
PA-309	Souderton Plaza	29.4	56	3,600	4.6	59.1	195
	Montgomeryville Plaza	22.6	56				
	English Village	20.1	88				
US-611	Doylestown Center	25.6	98	2,800	3.4	43.0	151
	Warrington Shopping Center	21.4	53				
US-1/US-611	Neshaminy Mall	21.0	261	5,500	5.4	66.6	297
	Red Lion Mall	16.5	98				
Total			1,710	19,800	21.7	257.9	1,070
New Jersey							
US-206	Whitehorse Bowling Alley	4.3	112	400	0.5	6.2	22
US-130 (Burlington, Betsy Ross Bridge)	Jefferson Ward Shopping Center	20.9	104	3,600	4.1	50.1	196
	Willingboro Plaza	17.6	146				
US-130 (Burlington, Betsy Ross Bridge)	Cinnaminson Shopping Center	9.8	375	2,800	3.4	42.3	151
NJ-38 (Mount Holly, Ben Franklin Bridge)	Fair Grounds–NJ-541	22.6	76	8,200	8.4	99.7	443
	Lumberton Plaza	20.0	179				
	Moorestown Mall	10.6	503				
NJ-70 (Ben Franklin Bridge)	Marlton Plaza	13.6	94	1,000	1.2	15.9	54
NJ-42/North-South Freeway (Ben Franklin Bridge)	Williamstown Center	22.5	132	3,300	3.5	41.8	178
	Jefferson Ward (Turnersville)	16.3	84				
NJ-47/North-South Freeway (Ben Franklin Bridge)	College Town (Glassboro)	19.2	259	4,400	4.5	53.5	238
	Woodbury Plaza	11.4	65				
NJ-45/North-South Freeway (Ben Franklin Bridge)	Toll House Plaza (Mantua)	15.2	97	2,300	2.8	36.6	124
	Acme Shopping Center (Woodbury)	12.4	120				
NJ-44/NJ-534/North-South Freeway (Ben Franklin Bridge)	Paulsboro Center	19.1	162	2,900	3.0	36.3	157
	Deptford Mall	10.4	69				
Total			2,577	28,900	30.9	382.4	1,563
Regional total			4,287	48,700	52.6	640.3	2,633

[a] Estimated on the basis of Mobile 2 model. [b] Amount of gasoline per day estimated on the basis of the estimated consumption factors for the highway fleet in 1987.

Table 6. Economic analysis of park-and-ride and express bus service.

Annual Cost	Pennsylvania	New Jersey	Total
Capital[a] ($1980)			
Vehicle fleet	531,000	841,700	1,372,000
Parking lots	171,000	225,000	396,000
Total	702,000	1,066,000	1,768,000
Operating and Maintenance[b] ($1980)			
Vehicle fleet	740,000	1,012,000	1,752,000
Parking lots	46,000	56,000	102,000
Total	786,000	1,068,000	1,854,000
Per passenger mile[c] (¢)			
Capital	10.49	10.89	10.73
Operating	11.74	10.92	11.25

[a] The capital cost of vehicles and improvements to the parking lots is expressed annually with an assumption of 10 yr of productive life, no salvage value, and 12 percent social rate of return.

[b] The operating and maintenance expenses of the vehicle fleet include labor, fuel, oil, and all other charges incidental to operating the vehicles. The charges for the parking lots are for snow removal, pavement upkeep and lighting, and so forth.

[c] This travel represents only the new riders switched over from the automobile. It does not include the riders using other transit modes who became attracted to the new service. Annual passenger miles per system are as follows: Pennsylvania, 6,691,000; New Jersey, 9,785,000; total, 16,476,000. Revenue per passenger mile by system is Pennsylvania, 10.50 cents; New Jersey, 19.90 cents; total, 10.70 cents.

quired for minor construction necessary to make the park-and-ride service operational. No land acquisition or other major improvements may be needed, however, because the recommended parking facilities are already functioning; their owners may permit their partial use for park-and-ride service with little or no charge.

It is estimated that the park-and-ride and express bus service will require 44 buses, of which 17 will be needed for providing service in Pennsylvania and 27 in New Jersey. This number is rather small and possibly could be arranged from the existing fleet of vehicles available with the operators of the transit service. The operators may, on the other hand, decide to acquire new, special vehicles for the service. The cost figures for the vehicle acquisition are therefore for illustrative purposes only.

The capital cost of 17 buses for the Southeastern Pennsylvania Transportation Authority (SEPTA) is about $3.00 million and for 27 buses for New Jersey, $4.75 million. The annual cost of operating these buses is estimated to be $740,000 for SEPTA and $1,102,000 for New Jersey operators. The operating cost of vehicles includes labor, fuel, oil, and other expenses for providing the service.

The capital cost for the park-and-ride service includes minor construction items required to improve the accessibility and the proper functioning of the parking lots. This includes clearing and grubbing, shaping the subgrade, shaping and clearing slopes, and fencing. It also includes the cost of park-and-ride signs, bus stop signs, and posting of weatherproof bus schedules. Some of the recommended facilities may require installation of new lighting poles, whereas others may require lighting improvements. The parking spaces designated for park-and-ride use would require identification by colored lines. Finally, every parking facility should provide a shelter for the bus riders to protect them from adverse weather conditions. It is estimated that a total capital cost of $2.2 million ($967,000 in Pennsylvania and $1,273,000 in New Jersey) will be needed to make the park-and-ride lots operational. Annually, the upkeep of the parking lots would require $46,000 from Pennsylvania and $56,000 from New Jersey.

The revenues that would be generated from the park-and-ride and express bus system depend on the fare level. Assuming a base fare of 65 cents (current fare level) and a charge of 8 cents/mile, the annual revenues collected from the fare box by SEPTA and New Jersey operators would be $824,000 and $1,218,000, respectively. Incidentally, the same fare structure was used in estimating the ridership for the new service.

These are the estimates of revenue only for the riders who are attracted from among the automobile users. Estimates for other riders who are attracted from existing transit modes are not included.

Table 6 presents a summary of capital and operating costs implicit in the provision of the service. For the sake of comparison, all capital costs were expressed annually. Table 6 also shows that the capital cost of providing the service is 10.73 cents/passenger mile. The running, maintenance, and operation of the service would cost 11.25 cents/mile. This compares favorably with revenues of 10.70 cents/mile.

AGREEMENT FOR USE OF PARKING FACILITIES

The review of the park-and-ride programs in several states indicates that it has not been difficult for governmental agencies to reach an agreement with the owners of shopping centers to designate a portion of their parking lots for the park-and-ride programs. Nevertheless, government commitments should be made for the proper maintenance and operation of the lots, such as extra lighting, surface maintenance, traffic control devices, and so forth.

Many of the suburban shopping centers have excess parking spaces that are not used on weekdays except perhaps during the holiday season. The park-and-ride service operates during working hours, when parking spaces are plentiful because most shopping is done after work.

The park-and-ride program is also beneficial to shopping centers, because the users of the park-and-ride service are more likely to shop where they have already parked. Furthermore, any advertisement and promotional programs for park-and-ride service may promote sales. The owners of the parking lots may receive benefits that will make the shopping centers more attractive to customers, such as an increase in police patrol and immediate snow removal.

There are various types of agreements that governmental agencies can reach with the owners of shopping centers for the park-and-ride program. The Metropolitan Washington Council of Governments (COG) signed an agreement with the owner of the Eastover Shopping Center to designate a portion of these parking areas for a park-and-ride service. This was formalized through a letter agreement in which it was stated that the shopping center would provide all normal maintenance, lighting, cleaning, and snow removal, whereas COG would provide insurance and Prince Georges County would provide signing and surveillance. A provision for discontinuance was included. A separate agreement was made between COG and Prince Georges County for the provision of trailblazing signing, surveillance, and installation of a shelter. Lighting was normally provided by the shopping center in the evening, although no provision was made for lighting in the morning. Pavement marking, originally planned for, was not deemed necessary because the fringe-parking site was sufficiently removed from the stores to avoid confusion.

IMPLEMENTATION STUDIES

As this study indicates, the provision of a park-and-ride and express bus service in selected corridors can be feasible for implementation because it contributes to the improvement of the air quality and diverts automobile users in the outlying suburban areas to the new service. Because the new express bus routes have fewer stops en route, overall travel-time savings accruing to the commuters will induce some riders from other existing transit modes. Location of such service in the corridors where good transit service, e.g., commuter rail, already exists should therefore be avoided.

The preceding analyses indicate that 14 corridors connecting 25 park-and-ride locations throughout the DVRPC region show promise for instituting the service. If all the routes are made operational, they will attract approximately 4,300 additional daily riders from the existing automobile users. Some shifts in the ridership of other transit modes will also result, diverting about 4,900 trips to the new service (Table 3).

The next step in this project is to advance the park-and-ride and express bus service to the implementation stage. In view of the fact that the financial resources are becoming increasingly scarce, the transit operating agencies may not be able to implement all corridors at the same time. The work described in this paper will then be expanded to study selected corridors in more detail and refine the demand estimation and operational and physical characteristics of the parking lots and routes. Operational agreements, if any, should be investigated with two or three owners of the parking lots falling in the corridor as well as with the transit operating agency that will provide the express bus service.

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Role of Quantitative Analysis in Bus Maintenance Planning

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Transit maintenance costs increased dramatically between the late 1970s and early 1980s. At the same time, transit funding assistance has become less available. These circumstances require that managers operate their maintenance systems more efficiently and that they adopt new cost-cutting policies. It is proposed that maintenance managers use quantitative techniques in planning the operations and policies of maintenance systems. The suggested quantitative techniques, commonly used in other areas of business, industry, and government, may be employed to plan transit maintenance system policies and operations. A simplified simulation model of a hypothetical maintenance system is presented as an example of the use of analytical techniques in maintenance planning.

More stress has been placed on the performance and efficiency of transit maintenance in the past few years. Although greater emphasis on maintenance is often attributed to the financial pinch between escalating maintenance costs and decreases in the availability of federal and local operating assistance, the reasons for paying more attention to transit maintenance are not so simple. Granted, transit industry maintenance costs have grown in recent years at a rate of approximately $400 million per year while at the same time funding assistance has been reduced; however, financial problems are only the most noticeable symptom of the basic problems facing transit maintenance (1).

Faced with this situation, transit maintenance managers must deal with the following basic questions:

1. What are the causes of escalating transit maintenance costs?
2. How can transit maintenance systems be made more efficient?
3. What are the cost trade-offs for various levels of maintenance service and bus dependability and availability?
4. How do maintenance policies and service requirements affect fleet life-cycle costs?
5. At what level can the transit industry afford to fund maintenance systems?

In this paper, it is shown how analytical tools can be used to aid transit managers in answering the first four questions. More specifically, it is proposed that once sufficient maintenance information exists, analytical planning tools can be used to better understand the relationships among maintenance policies, costs, bus availability (spare levels), parts availability, life-cycle costs, and other factors that can be used for a better understanding of the complex problems that maintenance managers face. The need for analytical planning tools is defined, their capabilities and limitations are described, and, last, a simplified example is given of a rudimentary maintenance simulation model.

NEED FOR ANALYTICAL MODELS

The escalation of maintenance cost has been more rapid than that of inflation in the past few years (1). Increasing labor, parts, maintenance-facility, and equipment costs have added to cost escalation, but because the rate of increase has outstripped the average inflation rate of labor and materials, other factors must be contributing to transit maintenance's rapid rate of cost escalation. These factors are probably related to recent changes in vehicle designs, to regulation of vehicle procurement and maintenance practices, and to other, less tangible factors such as changes in the makeup of the bus maintenance labor force.

In the past (1950s, 1960s, and early 1970s), bus designs remained relatively standard and design modifications were gradual. Maintenance managers developed a working knowledge of performance and reliability and maintainability. With the advent of advanced-design buses in the late 1970s, vehicle designs became more complex, equipment available for vehicles became more varied, and maintenance managers lacked familiarity with the reliability of the new buses. Because of lack of experience with these vehicles and the associated uncertainties, and for other reasons, some transit systems are designing and using the automated maintenance information system (MIS). These systems automatically summarize and analyze the maintenance status of buses, material, and labor. For example, the MIS will usually keep track of the date and mileage of repairs and mileage between failures and will automatically produce fleet averages for experiences with the same component. A notable example of an MIS is the one being designed and tested by the five members of the Western Transit Maintenance Consortium (2).

The MIS permits the maintenance manager to access a computerized data base that contains information related to the most current as well as historical information related to maintenance operations. Other information-summarizing options are often built into the data base, such as the flagging of exceptions, preventive-maintenance scheduling, work-order processing, parts and consumables inventory controls, and others. Note that what the MIS has given the maintenance manager is the information necessary to inventory existing conditions. An MIS only provides information to aid in the management of the maintenance operation under existing conditions. This capability is certainly an improvement over conditions without the MIS; however, it leaves the maintenance manager with only judgment and experience when evaluating the impact of new policies or when forecasting future needs. For example, a current MIS could not tell the maintenance manager what the trade-offs are between increases in the maintenance work force and the percentage of the bus fleet that should be held as spares nor does the MIS provide the maintenance manager with an estimate of the number of buses that will experience a specific component failure in the future so that the maintenance system can be prepared for surges in the failure rates of specific components.

The capability to estimate the impacts of policies and to make forecasts of failures, parts demand, maintenance labor required, and so forth, may be achieved through the use of planning models. Planning models extend rather than replace the MIS. In fact, planning models are calibrated and updated on the basis of information that is commonly produced by an MIS. The importance of adding planning capabilities to an MIS lies in the two general types of information that such a system would provide: (a) forecasts of the impacts resulting from changes in maintenance system policies or operation and (b) forecasts of future events while the maintenance system's policies and operation remain constant. The latter of the two types of information could be determined without planning modeling capabilities by simply waiting until events occur and using this experience in conjunction with the manager's judgment to project the occurrence of similar events into the future. Of course, one must assume that the maintenance manager will stay at the same position for an extended time, that bus designs will remain constant, and that the manager can keep track of the many events that occur simultaneously. On the other hand, a computer-based planning model can almost instantly forecast events (e.g., failure rates for several components) simultaneously, and the results will be completely consistent with whatever experience with the event is available. Such forecasts would be especially valuable in predicting surges in component failures so that the maintenance system and parts inventories could be prepared in anticipation of the surge; in the case of low failure rates of a particular type, resources could be devoted to other maintenance functions.

Computer-based planning models are particularly valuable in obtaining forecasts of the results of system changes (the first general type of information). Once a computer model is created to symbolize the system, the model can be used to experiment with the system. The user can ask what-if questions. For example, what impact will changing the number of mechanics have on the number of spare vehicles required to support the active fleet? Besides not disrupting the actual system with an experiment, a computer model has two important advantages. First, the results are obtained very quickly, perhaps within a few minutes, whereas the same experiment with an actual system might take years to produce results. Second, since all of the system variables in the model are controlled, the analyst knows that the results from the experiment were produced by the variable or variables manipulated. In other words, results obtained from an experiment with the real system may be affected by variables that cannot be controlled and that change during the course of the experiment, such as the weather or a union contract. These factors can be held constant in a computer model. Thus, a computer model can be less disruptive, faster, and more accurate than an actual experiment on the maintenance system.

Examples of the impacts on transit maintenance systems that could be estimated with the use of a computer model would include

1. Testing the impact of various alternatives for reducing the portion of the fleet used as spares (for example, one strategy that could be tested is to increase the number of mechanics devoted to various maintenance activities);
2. Determining the internal cost savings and reallocatable resources made available by sending buses to private repair shops for particular types of repairs (for example, testing the implications of sending buses to a maintenance contractor for brake repairs);
3. Testing the impact of varying preventive-maintenance policies (for example, a computer model

could determine the impact, in terms of in-service breakdowns and maintenance work load, of increasing or decreasing the interval between the preventive replacement of a particular part; the model could also test the impact of instigating a preventive replacement policy for a particular part); and

4. Analyzing the impacts on the maintenance system in shifting new purchases of buses to different models or to buses with different major components (for example, buses with smaller engines may experience less frequent transmission-related failures than buses with larger engines; however, buses with smaller engines may experience more frequent engine-related failures--the trade-offs between buses with different engines and failure rates can be tested).

The interests and concerns of individual maintenance managers may include those listed above or others. What is particularly important about the examples of tests listed above is that they illustrate the types of new policies and system changes that computer-based models can be used to analyze. As the maintenance manager seeks to improve the maintenance system's efficiency and productivity through various changes, changes can be tested before they are instituted by running a computer-based model that includes the proposed changes. If these changes do not cause the expected or desired result, the manager will know quickly. Then plans can be changed and the model run until the manager has the information required to choose the best of the available options and eliminate inferior changes in the maintenance system.

Given current conditions in the transit industry, the value of these types of planning models is great. Bus designs have changed substantially, and uncertainty about the reliability of components and maintenance requirements has grown dramatically. In addition, stricter regulations are being placed on vehicle-fleet spare levels and on bus-procurement practices. Thus, the decisions maintenance managers face have become more complex, the input to decisions has become more varied, and there is a greater degree of uncertainty about the results of decisions made. At the same time that uncertainty has increased, budgets have become tighter and thus less tolerant of error. Therefore, there is an increased need to develop computer-based planning models that can be used to summarize the outcomes of changes to the maintenance systems and aid the maintenance manager in instituting efficient system and policy changes.

COMPUTER-BASED PLANNING MODELS

Capabilities and Inabilities

Computer-based planning models are commonly used in many fields of private business and public service. Often these models take the form of simulations of systems. For example, in urban transportation planning, highway and mass transportation planners commonly use UMTA's UTPS simulation of urban travel to test the impact of transportation network changes. Traffic engineers have several traffic and highway operation simulation models (e.g., TRANSYT, NETSIM, FREQ, PASSER) to estimate the impact of changes in traffic control and in physical changes to highways. Simulation modeling has also gained in popularity in business as computing costs have dropped. Today, many general-purpose simulation packages are available for many types of computing systems.

Although computer-based modeling is a tremendously powerful tool to be used in estimating the outcomes of complex experiments, all computer models have limitations. A computer model is only a symbolic representation of the relationships between system variables. The relationships of all system variables are simultaneously considered in the computer model to determine the response of system variables to changes in one or more variables. For example, a relationship between wear and the failure of vehicle components could be estimated by modeling the distribution of observed failures and the mileage accumulated on actual buses until a failure occurred. Other relationships could be the distribution of time taken to make a repair or the interchangeability of facilities used to conduct various repairs. These relationships are measured from past experiences and are simultaneously considered within the symbolic structure of the model.

Computer models make forecasts by considering the impact of the manipulated variable on all other variables through relationships based on historical information. Although the model provides a highly ordered structure to extend observed relationships, it does not permit the prediction of the outcomes of changes where the model has no observed information upon which to base forecasts.

Sample Maintenance-Planning Model

In the following section, an example of a simplified, illustrative computer-based simulation model is described. The technique used is described elsewhere (3), and the mathematics of the approach is not described in detail here.

The model uses probability distributions of component failures as a function of accumulated bus mileage. From these distributions, and by using an average factor for miles accumulated per week, the simulation estimates the number of vehicles that will experience a failure during each week over the forecasting period. During any given week a fixed number of vehicles are repaired. Repaired buses are returned to active service and begin to accumulate wear. Unrepaired buses waiting in a maintenance queue and those being repaired are specified as spare vehicles. Once a vehicle leaves the maintenance queue and is repaired, all components (including those not repaired) begin accumulating wear.

The data used in the simulation and the assumptions made are purely hypothetical. However, the results of the example illustrate the utility of the technique. If the model were to be applied to an actual system, it would have to be carefully structured so that the model would accurately characterize the maintenance system analyzed. In this example, to make the illustration as general as possible and to make the explanation of the approach as understandable as possible, the assumptions made and the characteristics of the system are oversimplified. However, given the characteristics and peculiarities of an actual system, the model could be structured to simulate almost any situation. For instance, in the sample runs of the simulation model, it is assumed that components are only replaced after they fail. Many bus components are commonly repaired before they fail in anticipation of their failure and to prevent in-service breakdowns. If the model were used to simulate such a system, it would have to be structured to account for preventive repairs.

The inputs and assumptions of the model, for this example, are as follows:

1. The model requires that the number of vehicles to be considered in the experiment and their ages be specified. In this example, it is assumed that there are 500 buses in the fleet and that all are purchased (and begin wear) at roughly the same time.

Table 1. Hypothetical model parameters.

Component	Mean Distance Between Failures (miles)	SD of Between-Failure Mileage	Repair Rate (buses per week)
AC alternator	39,000	7,650	6
Brake lining			
Front	34,235	2,560	5
Rear	36,750	3,450	5
Brake relay valve	125,000	3,540	2
Chassis retro comp	30,000	4,525	6
Cylinder head			
Left	280,000	25,750	1
Right	240,000	12,500	1
Engine blower	145,000	12,300	2
Engine injector	94,000	7,250	3
Engine starter	80,000	5,206	3
Fluid fan drive	115,000	12,875	2
Leveling valves	64,000	5,500	4.5
Steering box	168,000	15,435	2.25
Transmission	95,000	15,000	3
Water pump and heater	150,000	8,750	2
Air-conditioner compressor	200,000	25,750	1.5

2. The model requires that the length of the experiment (in weeks) be specified. In the example, the experiment spans 12 yr, which is considered to be the entire life of the bus.

3. The model requires that the average wear (in miles per week) while in active service be specified. In the example, it is assumed that all buses travel an average of 700 miles per week.

4. The model requires that a repair rate be specified for every component considered. In the example, repair rates are specified as a maximum number of repairs that can be made for each type of component per week. The initial repair rates are listed in Table 1 (4).

5. The model requires the distribution of the mileage between failures. In the example, hypothetical distributions (and even hypothetical components) are used.

The reasons for using hypothetical distributions as opposed to actual information are as follows: (a) there is little available information on the distribution of bus part failures and (b) those that are available from empirically observed data do not distinguish between repairs made in anticipation of failures and repairs made due to actual failures (4,5). Therefore, to simplify matters, hypothetical data are used.

The parameters of the hypothetical distributions of wear between failures are shown in Table 1. All of the wear between failures is assumed to be Weibull distributed with a skew of 2. Weibull-distributed wear between failures is assumed partly due to the simplicity of using a Weibull distribution and partly because the Weibull distribution has properties that make it a popular choice to model the distribution of periods between failures.

Figures 1 through 6 show the predicted failure rates in buses per week for 6 of the 16 components examined based on the distribution parameters and repair rates shown in Table 1. (The remaining 10 failure-rate curves are not shown for the sake of brevity.) It is assumed in the estimation of these failure rates that while a bus is waiting for a re-

Figure 1. Weekly failure rate, front brake lining.

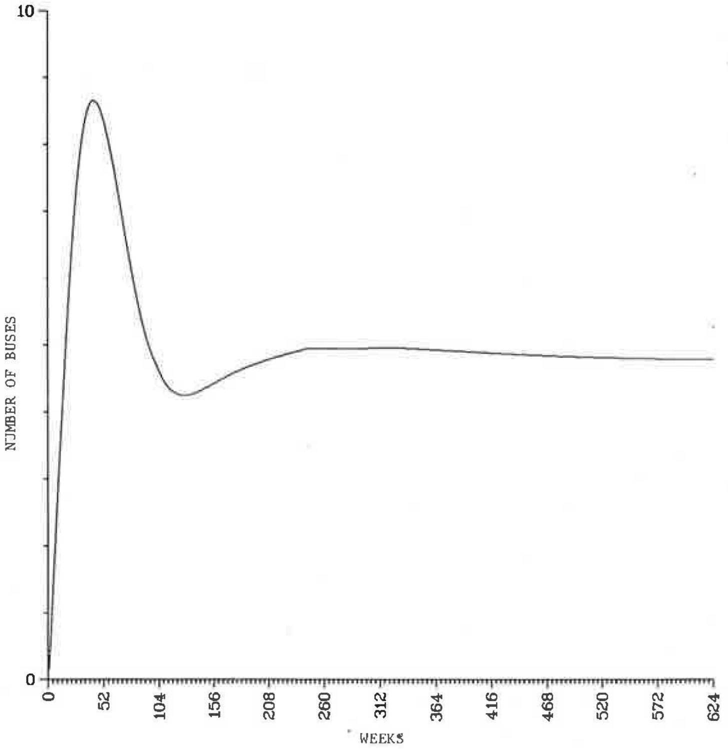


Figure 2. Weekly failure rate, rear brake lining.

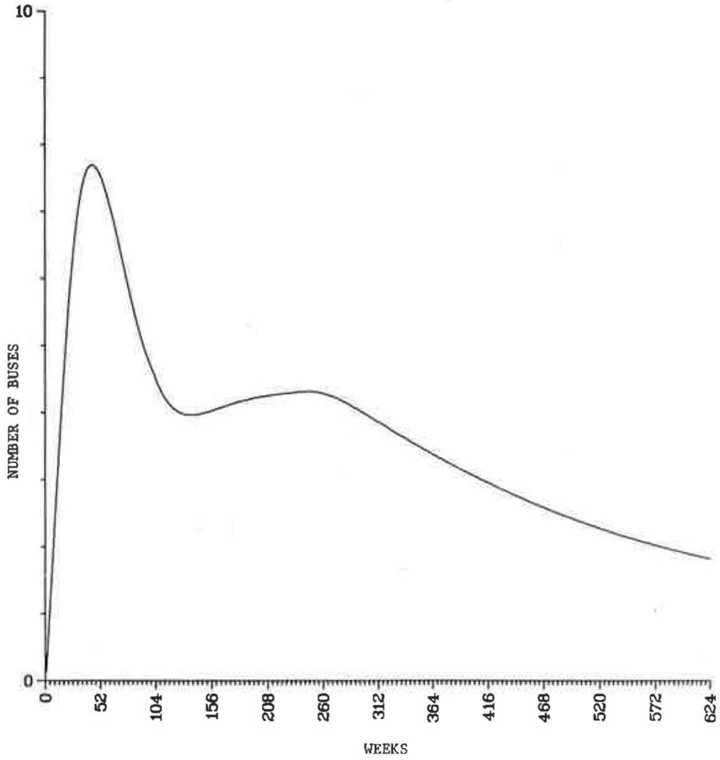


Figure 3. Weekly failure rate, chassis retro comp.

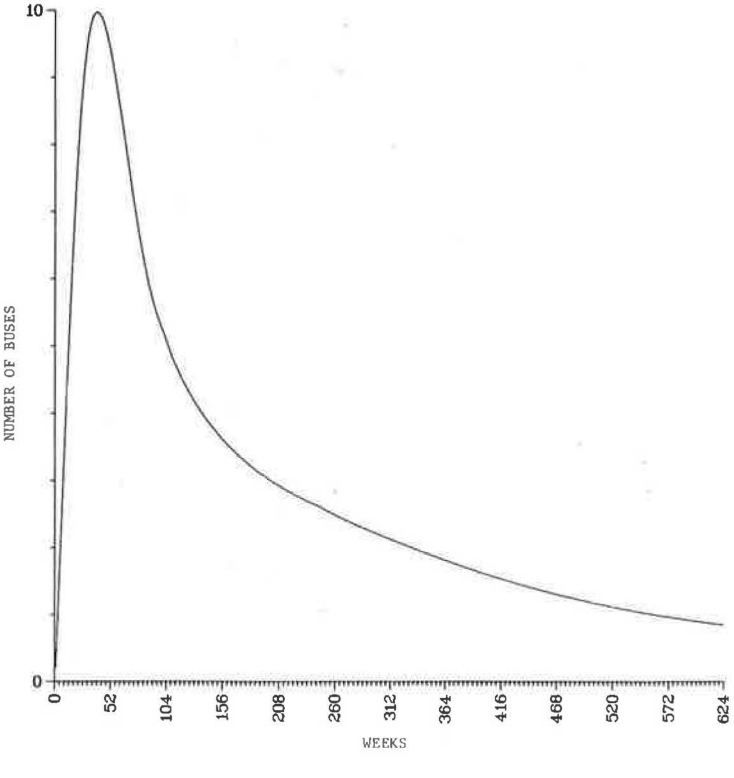


Figure 4. Weekly failure rate, left cylinder head.

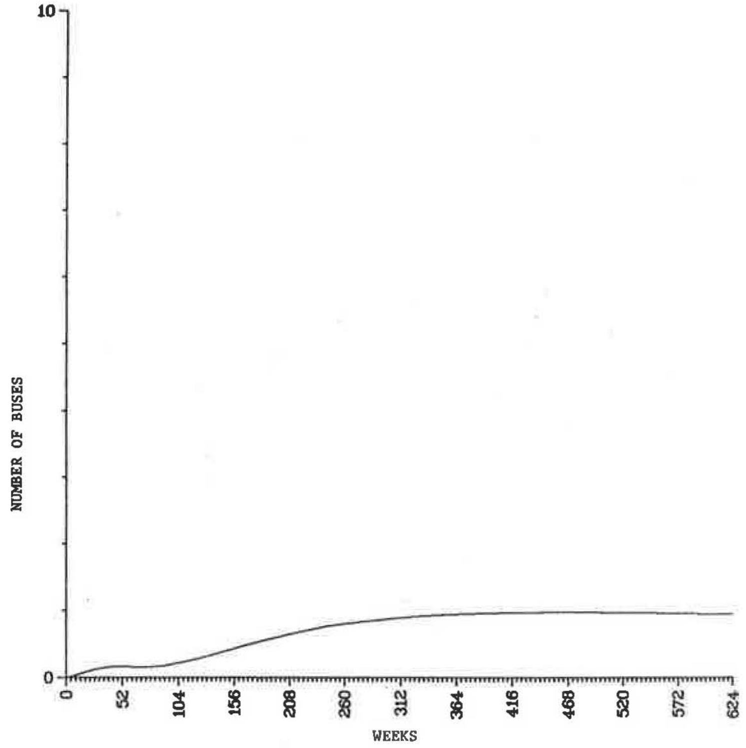


Figure 5. Weekly failure rate, leveling valve.

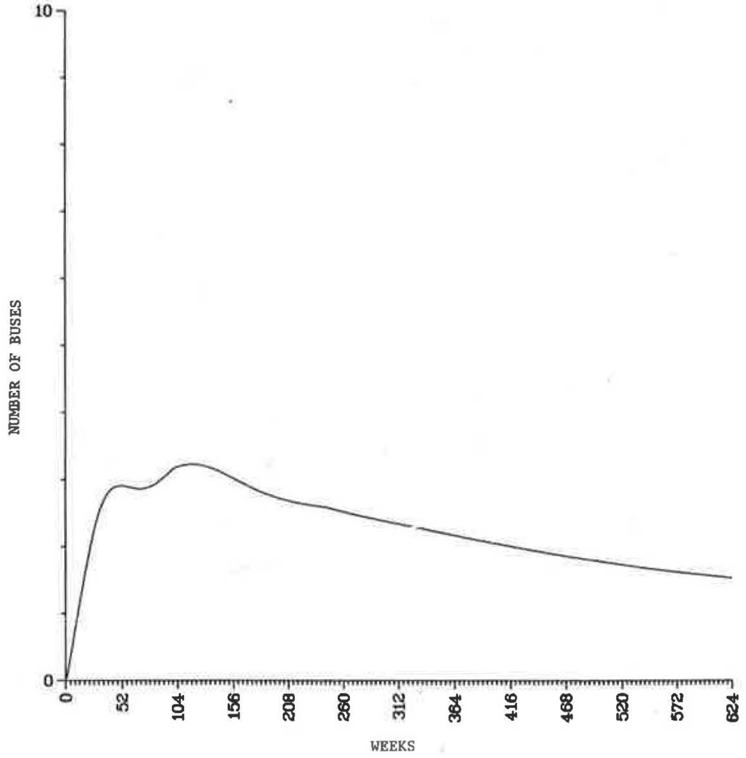


Figure 6. Weekly failure rate, steering box.

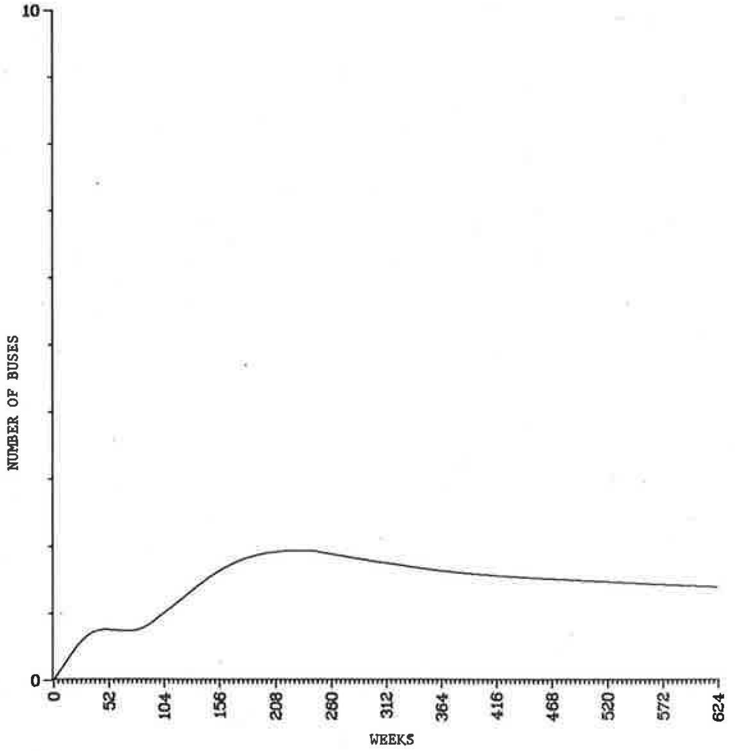
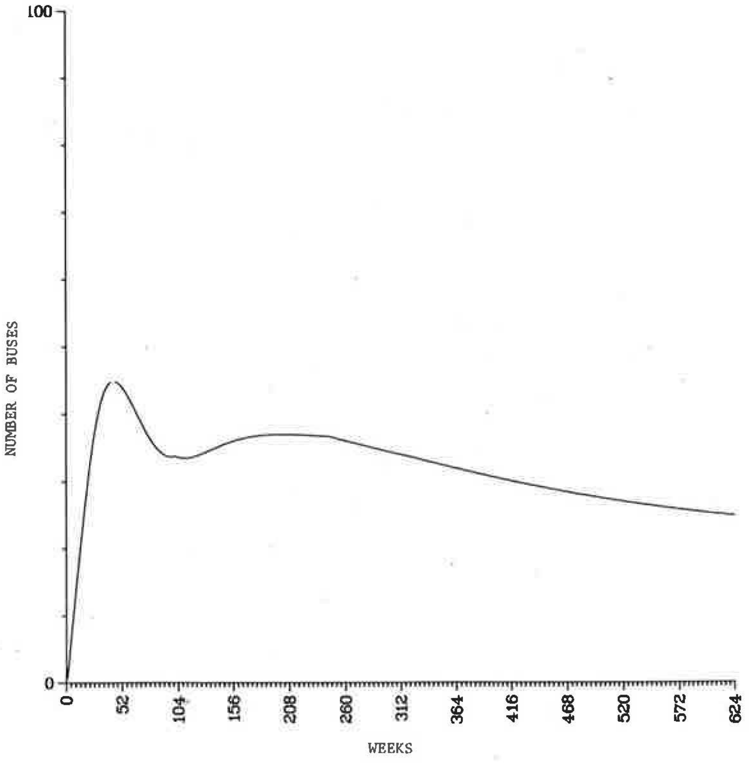


Figure 7. Total weekly failure rate.



pair, all other components do not accumulate wear and that wear on all parts begins once the bus is repaired and returned to active service. Note the relatively abrupt surge of brake-lining failures in Figures 1 and 2 around week 52 (remember that the assumed mean life is 34,235 miles and 36,750 miles for front and rear linings, respectively). Also note the abrupt surge of chassis retro comp failures in Figure 3. The reason for the surge around the 52nd week is that all have mean lives between 30,000 and 37,000 miles and all have relatively small standard deviations. A small standard deviation clusters a large amount of the distribution about the mean life. For example, front brake linings have a mean life of 34,235 miles and a standard deviation of 2,560 miles, which means that approximately 66 percent of all buses will experience their first front brake-lining failure after accumulating between 31,675 and 36,795 miles (34,235 ± 2,560). The surge in brake-lining failures may be contrasted with the relatively flat failure-rate curve of left cylinder-head failures shown in Figure 4, where left cylinder-head failures have a standard deviation of 25,750. The cumulative failure rate per week of all 16 components, as shown in Figure 7, tapers off after the mean ages of most components are reached and as the age of the components becomes more varied across the fleet.

In Figure 8 the number of vehicles waiting to be repaired (spares) is shown. In the first year the number of vehicles waiting to be repaired increases to more than 300 buses. This surge is mainly due to the sudden surge in brake-lining failures and chassis retro comp failures. Later, the number of vehicles waiting to be repaired begins to build slowly as later-occurring failures become more frequent.

In the first run of the model, there are as many as 300 out of 500 buses waiting for repairs at the peak (see Figure 8). This appears to be an unsatisfactory result. Hence, changes must be made in the system to relieve the surge and reduce the number of buses waiting for repairs to an acceptable level. Because brake-lining failures seem to be the main factor contributing to the early surge in buses waiting for repairs, the simulation model is run again with increased repair rates. Suppose that mechanics are willing to work overtime during the few weeks around the surge in brake-lining failures and that the maximum repair rate for both front and rear brake relinings per week is increased from five to seven.

The simulation model is rerun by using both a front and rear relining repair maximum rate of seven per week. The resulting quantity of buses waiting for repairs per week is plotted in Figure 9. Note that there still is a relatively sharp surge in the buses waiting for repairs around week 52, when there are as many as 200 buses waiting for repairs. This represents a drop of 100 buses per week from the peak in the previous run, but it still appears to be an unsatisfactory portion of the fleet waiting for repairs. Therefore, increasing the rate of lining repairs to seven per week did not decrease the early surge to a satisfactory degree.

Next, suppose that each week all buses with brake-lining failures that exceed the number of bus brake linings that can be repaired within the transit system's maintenance facility are taken to a private repair shop. This, in effect, increases the system's capacity to repair brake-lining failures to the point where all brakes can be repaired within the same week.

By using a brake-lining repair rate greater than

Figure 8. Weekly maintenance queue: first model run.

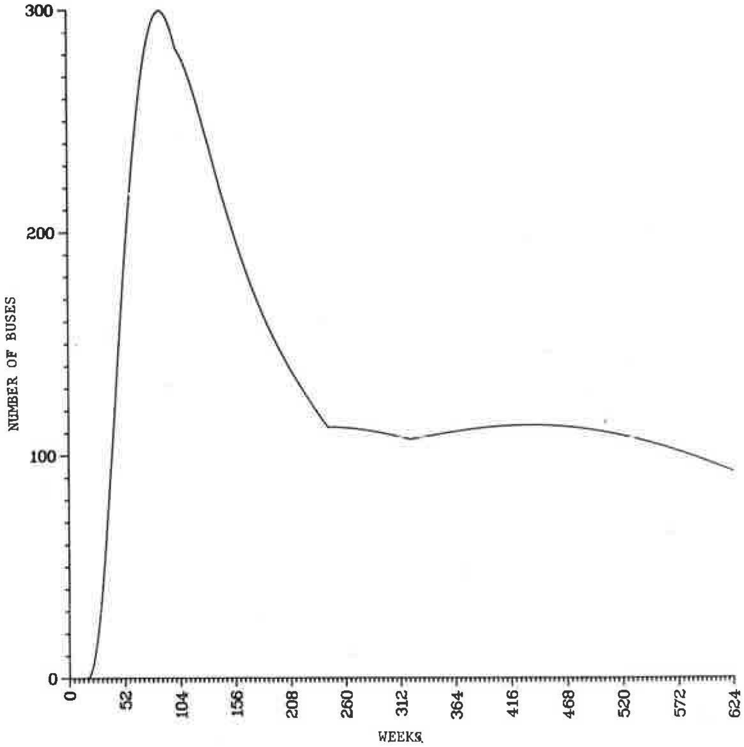


Figure 9. Weekly maintenance queue: second model run.

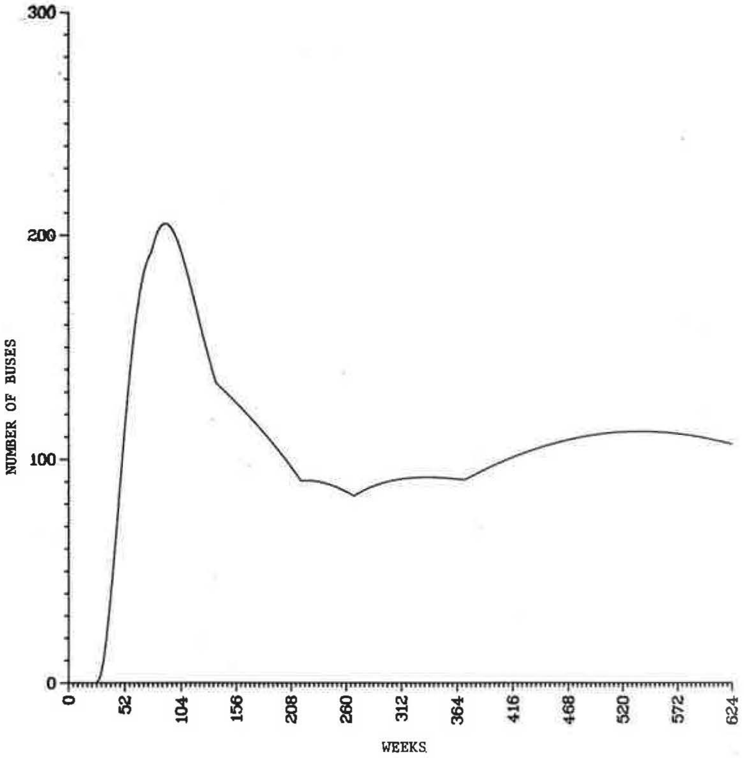
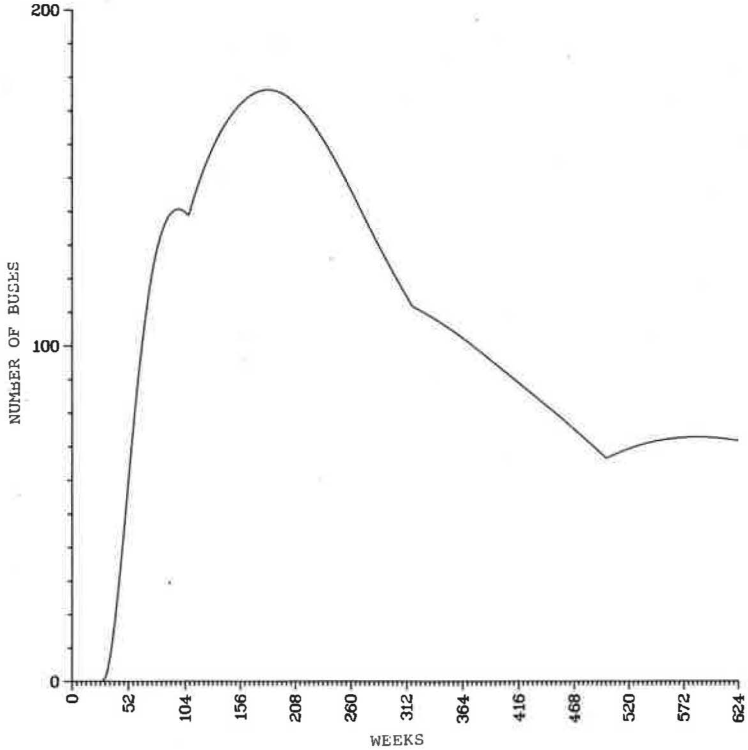


Figure 10. Weekly maintenance queue: third model run.



the maximum weekly failure rate, the simulation model is rerun; the resulting number of buses waiting for repairs during each week is shown in Figure 10. Note that the surge around week 52 has disappeared but is replaced by a nearly equal surge that takes place around week 180. At that time, the increase in buses waiting for repairs is brought on by the combined increase in the rate of failures of engine starters, transmissions, fluid fan drives, and brake relay valves. The surge around week 180 did not occur in previous experiments because in the first and second experiments, a large portion of the buses are waiting for brake-lining repairs. Because buses waiting in the maintenance queue do not accumulate wear, other components experienced a lower rate of failure. The model clearly illustrates that by relieving the problem of buses waiting for brake relinings, another problem is inadvertently caused in another portion of the maintenance system.

As can be seen from this simplified 16-component example of the use of a simulation model, changes in the maintenance system may have complex impacts on other parts of the system. As demonstrated by the third experiment, change in one portion of the system to relieve a specific problem may aggravate another portion of the system. Because of the complex and simultaneous relationships among vehicle wear, failure rates, repair rates, spare level, fleet size, and so on, all likely impacts of system changes are not obvious nor is it likely that they can be predicted by using intuition, hence the need to test for these impacts with a computer model. When one considers that the inputs to the examples are far fewer than those that would be considered in an actual application, the situation becomes more complex and the need for quantitative methods to predict the outcomes of system changes becomes even greater.

CONCLUSIONS AND RECOMMENDATIONS

Some of the contemporary issues in transit maintenance are described and reasons why transit maintenance managers should use quantitative tools to aid in addressing these issues are explained. Computer-based quantitative models are commonly used to aid in the planning of operations and policy in other fields of transportation and in other industries. In other areas, quantitative tools are often used to aid decision makers when the system of concern is too complex and varied to analyze by using intuition or hand calculations. As the problems faced by transit maintenance managers are made more complex by new and more varied bus designs, pressure for maintenance cost containment, increased demands on in-service vehicle reliability, pressure to decrease the number of spare vehicles carried to support the fleet, and so forth, it seems essential that maintenance managers use state-of-the-art quantitative techniques to aid in making decisions.

Quantitative planning models can be quite valuable in the decision-making process; however, a model is no better than the data used in calibration. Therefore, before maintenance-planning models can be tested and designed, there must exist data in sufficient quality and quantity to permit the estimation of true relationships between the relevant variables. The recent push toward the automated MIS is a step toward making useful and reliable maintenance data available. The next step is to use these data in the maintenance-planning process.

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