TRANSPORTATION RESEARCH RECORD

513

Formerly issued as Highway Research Record

Planning for Bus Transit

4 reports prepared for the 53rd Annual Meeting of the Highway Research Board

TRB

TRANSPORTATION RESEARCH BOARD

NATIONAL RESEARCH COUNCIL

Washington, D. C., 1974

Transportation Research Record 513
Price $2.00
Edited for TRB by Joan B. Silberman

subject areas
40 maintenance, general
41 construction and maintenance equipment
55 traffic measurements
84 urban transportation systems

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LIBRARY OF CONGRESS CATALOGING IN PUBLICATION DATA

National Research Council. Transportation Research Board. Planning for bus transit.

(Transportation research record; 513)

1. Motor bus lines—Congresses. 2. Local transit—Congresses. I. Title. II. Series.
TE7.H5 no. 513 [HE5606] 380.5'08s [388.4'1322] 74-32495
ISBN 0-309-02357-2

CONTENTS

FOREWORD

Highways and city streets are capable of accommodating large numbers of people on buses if proper bus planning and operation measures are employed. City officials are becoming increasingly aware of the great potential for good public transportation through the design of special facilities and control measures that can produce a high level of service to bus patrons. The four papers in this RECORD should assist planners and operators in improving transit service.

Levinson and Sanders develop a person-delay model that can be used in determining the feasibility and practicality for instituting a contraflow freeway bus lane in urban areas. The model deals with peak-hour trips. The authors show how planners can easily use it by way of a step-by-step procedure.

There is increased recognition by transportation planners that use of transit facilities depends on user preferences, which are not satisfactorily described in terms of the usual system performance variables of travel cost and travel time. Olsen and Smith report on research that examines the suitability of public transportation to the needs of the existing and potential user. The empirical basis of the research was obtained from attitudinal surveys conducted in Pinellas County, Florida. Their research concludes that psychological responses of people to transportation system characteristics are measurable.

The attractiveness of a bus rapid transit system is that it offers the possibility for a relatively high-speed movement of people on an existing arterial and street network without a very high initial capital investment. Meier, Vederoff, and Porter describe a method for assessing a regional bus rapid transit system at the macroplanning scale. The authors use Seattle as their test region. Operations between nodes would be on a nonstop basis. Feeder and local distribution systems would be required around some nodes. The study evaluates the system structure and loads, costs, and revenues and compares the authors' work with the full-scale bus transit planning study that has been completed for the same region.

Every transit property is faced with large maintenance operations of its bus fleet. Buses must receive proper routine maintenance checks and repairs with a minimum loss of time. De Hsu and Surti report on a study they conducted by using the Denver Metro Transit Company as a case study to apply queuing theory techniques for evaluating bus maintenance problems. A generalized model is presented that consists of submodels of the inspection shop, the repair shop, and maintenance minimization costs. Except for the cost optimization model, validity was established by comparing observed data and data produced by the models. The study provides much insight into the problems and complexities of bus maintenance operation.

RESERVED BUS LANES ON URBAN FREEWAYS: A MACROMODEL

Herbert S. Levinson and David B. Sanders, Wilbur Smith and Associates, New Haven

An increasing number of cities are becoming interested in operating buses on reserved lanes so that people can be moved more effectively. This paper develops a person-delay model that can be used in determining the feasibility and practicality for implementing a contraflow freeway bus lane in urban areas. The model deals with peak-hour trips on a six-lane, two-direction freeway, and it uses certain relationships (1) to demonstrate its applicability. The derivation of the model is shown, and the paper discusses, by a step-by-step procedure, how transportation planners can easily use it.

•RESERVED freeway lanes for buses provide a cost-effective approach to bus priorities in radial highway corridors with peak-hour congestion and heavy bus volumes. They apply freeway traffic operations and control techniques to reserve lanes for buses or other designated vehicles (e.g., emergency vehicles, trucks, and multiple-occupancy cars). They involve minimum physical construction, and they can speed bus service where interim access or stations are not required.

APPLICABILITY

Lanes may be reserved for buses in the normal or opposite direction of flow during the morning or evening peak periods; however, contraflow lanes are most common (2).

Contraflow freeway bus lanes are found along I-495 in New Jersey, the Long Island Expressway in New York, and US-101 in Marin County, California. A contraflow lane operation was intermittently operated on the Southeast Expressway, Boston, and one has been proposed for the Hollywood Freeway, Los Angeles. A short, normal flow bus lane exists on the Ninth Street expressway spur in Washington, D.C.

Normal flow bus lanes are usually not practical to implement because, where freeways are free-flowing in the peak periods, lanes are not usually needed to improve bus speeds. Conversely, where freeways operate near or beyond capacity, provision of bus lanes would substantially reduce person-capacity and increase total person-delay. Moreover, normal flow lanes are difficult to enforce.

Contraflow or wrong-way bus lanes can use portions of freeways serving relatively light traffic. Thus, they do not reduce peak directional highway capacity or efficiency. They are an adaptation of the reversible lane concept applied to urban freeways for more than three decades. Costs are minimal, and enforcement is easy because cars are highly visible to police patrols.

Buses can use single contraflow lanes where mixed traffic could not do so safely because (a) the bus lane traffic stream is homogeneous—variation in vehicle performance is minimal and there is no need for overtaking slower vehicles; (b) buses are highly visible to other drivers, especially if emergency flashers are used; (c) professional bus drivers are generally well-trained, experienced, and highly disciplined; and (d) bus lane volumes are relatively low (generally under 200 vehicles per hour); this makes a risk of a collision no greater than on an undivided urban arterial street or rural highway.

Publication of this paper sponsored by Committee on Busways and Bus Lanes.

Contraflow freeway lanes should be applied when the following conditions prevail:

1. The freeway is at least six lanes wide.
2. All normal freeway entrances and exits are to the right of the through traffic lanes.
3. The freeway preferably is illuminated wherever evening contraflow operations are envisioned.
4. Freeway travel in the off-peak direction can be accommodated in the remaining lanes at level of service D or better.
5. The contraflow bus lane generally produces bus passenger time-savings that exceed the time losses imposed on traffic in the opposite direction.

Meeting these broad criteria calls for a high imbalance in peak-hour traffic, an increase in the minimum number of peak-hour buses as traffic in the off-peak direction approaches capacity.

MODELING PERSON-DELAY

Analytical approaches can be used to determine the minimum number of buses required in the flow direction for varying traffic levels in the off-peak direction. The underlying objective is to save bus travelers more time than the time losses that are imposed on other traffic, minimizing total person-delay in both directions.

Assumptions in Model Formulation

The following assumptions underly the person-delay model:

1. The model deals only with peak-hour trips on a six-lane, two-direction freeway.
2. The median lane in the off-peak direction would be used by buses traveling in the peak direction.
3. Car and bus speeds relate to volume-capacity relationships (1, Fig. 9-1).
4. The maximum operating speed for private vehicles is 60 mph.
5. The maximum operating speed for buses when they operate in the contraflow lane is 45 mph.
6. Highway capacity is 1,800 vehicles per lane per hour.
7. In calibrating the model, there are occupancies of 1.5 persons per automobile and 50 persons per bus.
8. Total person-delay with a contraflow bus lane must be equal or less than total person-delay without the lane.

Person-Delay Minimization

The model assumes that the total person-delay after installation of a contraflow bus lane will be less than the person-delay before installation. (The various parameters used in the bus lane model and their notations are given in Table 1.) This concept of total person-delay minimization can be formulated and stated analytically as follows:

$$D_3 + D_4 \leq D_1 + D_2 \tag{1}$$

or conversely,

$$D_1 + D_2 > D_3 + D_4$$

From Eq. 1 it follows that

$$B_1L_1t_1 + A_1M_1t_1 + B_2L_2t_2 + A_2M_2t_2 \geq B_1L_1S_1 + A_1M_1t_3 + B_2L_2t_4 + A_2M_2t_2 \tag{2}$$

$$B_1L_1t_1 - B_1L_1S_1 \geq A_1M_1t_3 - A_1M_1t_1 + A_2M_2t_4 - A_2M_2t_2 + B_2L_2t_4 - B_2L_2t_2 \tag{3}$$

$$B_1L_1(t_1 - S_1) \geq A_1M_1(t_3 - t_1) + A_2M_2(t_4 - t_2) + B_2L_2(t_4 - t_2) \tag{4}$$

Table 1. Key parameters of the bus lane model.

Item	Peak Direction	Off-Peak Direction
Peak-hour buses, number	B_1	B_2
Peak-hour automobiles, number	A_1	A_2
Load factor for buses	L_1	L_2
Load factor for automobiles	M_1	M_2
Bus travel time, with exclusive lane	S_1	—
Vehicle travel time, before implementation of bus lane	t_1	t_2
Vehicle travel time, after implementation of bus lane	t_3	t_4
Total person-delay, before implementation of bus lane	D_1	D_2
Total person-delay, after implementation of bus lane	D_3	D_4

Note: Differences in bus and car travel times can now be defined as follows, assuming that $t \geqslant 0$:
Bus travel time change = $(\Delta t_1) = t_1 - S_1$.
Automobile travel time change = $(\Delta t_2) = t_4 - t_2$ in the off-peak direction.
Automobile travel time change = $(\Delta t_3) = t_1 - t_3$ in the peak direction.

Table 2. Approximate minimum bus volumes for contraflow bus lane.

TOTAL PEAK DIRECTION (VOLUME PER HOUR)	TOTAL OFF-PEAK DIRECTION (VOLUME PER HOUR) 900	1200	1500	1800	2100	2400	2700	3000	3300	3600	3900	4200	4500
3600	34	41	90	135	205	288	365	495	693	1701	3130	5355	7594
3900	14	22	36	54	82	115	146	198	277	680	1252	2142	3038
4200	10	17	28	42	63	89	112	152	213	524	963	1648	2337
4500	8	13	21	32	48	68	86	116	163	401	736	1260	1787
4800	5	9	14	22	33	46	58	79	111	272	501	857	1215
5100	4	6	10	15	23	32	41	55	77	189	342	595	844
5400	2	3	5	8	12	17	22	30	42	102	187	320	484
6300	1	1	2	3	4	6	8	11	15	37	68	117	166
7200	1	1	1	2	3	4	5	6	9	23	42	72	103
8100	-	-	-	1	1	2	2	4	5	13	23	40	57

I These bus volumes exceed most urban bus fleets and fall outside the domain of practical application.

II The domain of practical application--involves hourly bus volumes ranging from about 40 to 200 buses.

III Volumes of under 40 buses per hour do not usually warrant contra-flow lanes.

NOTE: Assumes an occupancy factor of 1.5 and 50 for automobiles and buses, respectively.

$$B_1 \geq \frac{1}{L_1(t_1 - S_1)} [A_1M_1(t_3 - t_1) + A_2M_2(t_4 - t_2) + B_2L_2(t_4 - t_2)] \tag{5}$$

This model assumes that $t_1 > S_1$, $t_1 > t_3$, and $t_4 > t_2$. Therefore,

$$B_1 \geq \frac{1}{L_1\Delta t_1} [A_1M_1(-\Delta t_3) + A_2M_2(\Delta t_2) + B_2L_2(\Delta t_2)] \tag{6}$$

But it can be assumed that $\Delta t_3 \rightarrow 0$ when $B_1 < 200$ and L_2 is negligible for off-peak direction. Therefore,

$$B_1 \geq \left(\frac{1}{L_1\Delta t_1}\right)(A_2M_2\Delta t_2) \tag{7}$$

$$B_1 \geq A_2\left(\frac{M_2}{L_1}\right)\left(\frac{\Delta t_2}{\Delta t_1}\right) \tag{8}$$

(This is approximate.)

Equation 8 states that the minimum number of buses needed to warrant a bus lane must be equal to or greater than the number of automobiles in the off-peak direction and must be factored by the ratio of car-to-bus passenger occupancies for the off-peak and peak directions respectively. This number is then further modified to reflect the expected change in travel time for the buses in their own reserved lane as well as the travel times for automobiles with less highway capacity. Equation 8 ensures that the total person-delay will be less after bus lane implementation than it was before.

Speed-Delay Concept

In applying Eq. 8 and solving for B_1, the independent variables must be assumed or determined. These independent variables include estimates of the changes in automobile and bus travel times that are due to the contraflow bus lane. Changes in operating speeds (and, therefore, travel times) are assumed to be a function of traffic volume-capacity ratios only. The approximate relationship expressing this is

$$\text{Speed}_1 = \text{Speed}_o - A\frac{V_1}{C} \tag{9}$$

where

Speed_1 = speed at designated volume,
Speed_o = maximum highway speed,
A = calibration constant,
V_1 = highway traffic volume, and
C = capacity of highway.

As a point of departure, the relation between speed and volume capacity (V/C) ratios was established (1, Fig. 9-1). The application of these ratio curves provided a basis for Tables 3, 4, 5, and 6 and calibration of the model (Eq. 8).

Model Results

The approximate minimum bus volumes that are required to warrant (from a person-delay standpoint) installation of a contraflow bus lane are given in Table 2. These bus volumes were estimated from Eq. 8. Basically, Table 2 defines the domain of practical application—hourly bus volumes between 40 and 200 buses—that most urban areas will be dealing with.

The data are also shown in Figure 1. The curves indicate the traffic volumes needed to warrant 40, 60, 80, 100, and 150 buses in a reserved lane; they are derived from Table 2. Because the results are related to travel time (speed) and volume, the number of buses required to minimize person-delay is nonlinear. Generally, as traffic becomes

Figure 1. Contraflow bus lane concept, six-lane freeway.

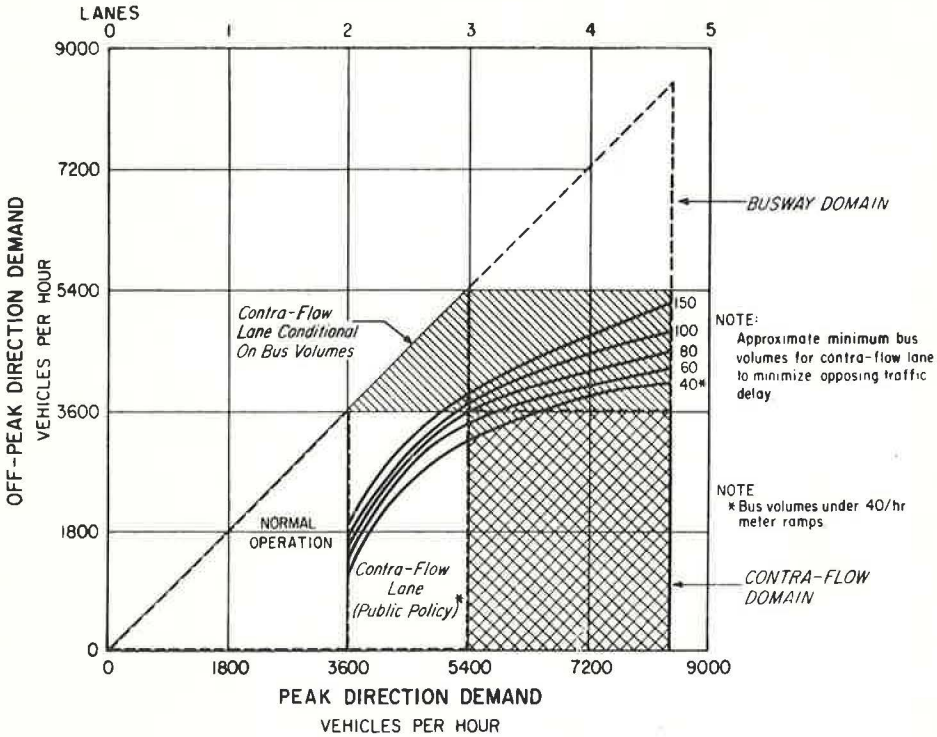

Table 3. Speed-volume relation, peak direction.

Demand (volume/ lane/hour)	$\frac{V}{C}$	Assumed Speed (mph)	Travel Time (min/mile)
300	0.17	56	1.07
400	0.22	55	1.10
500	0.28	54	1.12
600	0.33	52	1.15
700	0.39	51	1.18
800	0.44	50	1.21
900	0.50	48	1.25
1,000	0.56	47	1.28
1,100	0.61	46	1.32
1,200	0.67	44	1.37
1,300	0.72	43	1.43
1,400	0.78	41	1.46
1,500	0.83	40	1.50
1,600	0.89	37	1.58
1,700	0.94	34	1.69
1,800	1.00	30	2.00
1,900	1.06	24	2.40
2,000	1.11	22	2.76
2,100	1.17	19	3.16
2,200	1.22	17	3.43
2,300	1.28	15	4.00
2,400	1.33	14	4.29
2,500	1.39	12	5.00
2,600	1.44	11	5.45
2,700	1.50	09	6.67

Note: C = 1,800.

Table 4. Bus travel time-savings, peak direction, min/mile.

Demand (volume/hour in peak direction)	$\frac{V}{C}$	General Traffic (min/mile)	Bus Travel Time-Savings, Δt_1 (min/mile)
3,600	0.67	1.37	0.04
3,900	0.72	1.43	0.10
4,200	0.78	1.46	0.13
4,500	0.83	1.50	0.17
4,800	0.89	1.58	0.25
5,100	0.94	1.69	0.36
5,400	1.00	2.00	0.67
5,700	1.06	2.40	1.07
6,000	1.11	2.76	1.43
6,300	1.17	3.16	1.83
6,600	1.22	3.43	2.10
6,900	1.28	4.00	2.67
7,200	1.33	4.29	2.96
7,500	1.39	5.00	3.67
7,800	1.44	5.45	4.12
8,100	1.50	6.67	5.23

Notes: Maximum bus operating speed is 45 mph or 1.33 min/mile. Thus, where general traffic speeds are 1.37 min/mile, the savings from the bus lane are (1.37 - 1.33) or 0.04 min/mile. C = 5,400.

Table 5. Off-peak direction speed changes from lane reduction.

Total Volume, Off-Peak Direction	Without Lane Removed		With Lane Removed		
	$\frac{V}{C}$ (3 lanes)	t_2 (min/mile)	$\frac{V}{C}$ (2 lanes)	t_4 (min/mile)	Travel Time Loss, Δt_2
900	0.17	1.07	0.25	1.12	0.05
1,000	0.19	1.07	0.28	1.12	0.05
1,100	0.20	1.08	0.31	1.13	0.05
1,200	0.22	1.10	0.33	1.15	0.05
1,300	0.24	1.11	0.36	1.17	0.06
1,400	0.26	1.12	0.39	1.18	0.06
1,500	0.28	1.12	0.42	1.20	0.08
1,600	0.30	1.13	0.44	1.21	0.08
1,700	0.31	1.13	0.47	1.22	0.09
1,800	0.33	1.15	0.50	1.25	0.10
1,900	0.35	1.15	0.53	1.26	0.11
2,000	0.37	1.16	0.56	1.28	0.12
2,100	0.39	1.18	0.58	1.31	0.13
2,200	0.41	1.18	0.61	1.32	0.14
2,300	0.43	1.20	0.64	1.35	0.15
2,400	0.44	1.21	0.67	1.37	0.16
2,500	0.46	1.22	0.69	1.40	0.18
2,600	0.48	1.25	0.72	1.43	0.18
2,700	0.50	1.25	0.75	1.43	0.18
2,800	0.52	1.26	0.78	1.46	0.20
2,900	0.54	1.28	0.81	1.48	0.20
3,000	0.56	1.28	0.83	1.50	0.22
3,100	0.57	1.30	0.86	1.56	0.26
3,200	0.59	1.30	0.89	1.58	0.28
3,300	0.61	1.32	0.92	1.60	0.28
3,400	0.63	1.33	0.94	1.69	0.36
3,500	0.65	1.36	0.97	1.76	0.40
3,600	0.67	1.37	1.00	2.00	0.63
3,700	0.69	1.40	1.03	2.31	0.91
3,800	0.70	1.40	1.06	2.40	1.00
3,900	0.72	1.43	1.08	2.50	1.07
4,000	0.74	1.43	1.11	2.76	1.33
4,100	0.76	1.46	1.14	2.93	1.47
4,200	0.78	1.46	1.17	3.16	1.70
4,300	0.80	1.47	1.19	3.33	1.86
4,400	0.81	1.48	1.22	3.43	1.95
4,500	0.83	1.50	1.25	3.75	2.25

Table 6. Travel time change ratios.

Total Peak Direction (volume per hour)	Δt_1	Total Off-Peak Direction (volume per hour) and Δt_2												
		900, 0.05	1,200, 0.06	1,500, 0.08	1,800, 0.10	2,100, 0.13	2,400, 0.16	2,700, 0.18	3,000, 0.22	3,300, 0.28	3,600, 0.63	3,900, 1.07	4,200, 1.70	4,500, 2.25
3,600	0.04	1.25	1.50	2.00	2.50	3.25	4.00	4.50	5.50	7.00	15.75	26.75	42.50	56.25
3,900	0.10	0.50	0.60	0.80	1.00	1.30	1.60	1.80	2.20	2.80	6.30	10.70	17.00	22.50
4,200	0.13	0.38	0.46	0.62	0.77	1.00	1.23	1.38	1.69	2.15	4.85	8.23	13.08	17.31
4,500	0.17	0.29	0.35	0.47	0.59	0.76	0.94	1.06	1.29	1.65	3.71	6.29	10.00	13.24
4,800	0.25	0.20	0.24	0.32	0.40	0.52	0.64	0.72	0.88	1.12	2.52	4.28	6.80	9.00
5,100	0.36	0.14	0.17	0.22	0.28	0.36	0.44	0.50	0.61	0.78	1.75	2.97	4.72	6.25
5,400	0.67	0.07	0.09	0.12	0.15	0.19	0.24	0.27	0.33	0.42	0.94	1.60	2.54	3.36
6,300	1.83	0.03	0.03	0.04	0.05	0.07	0.09	0.10	0.12	0.15	0.34	0.58	0.93	1.23
7,200	2.96	0.02	0.02	0.03	0.03	0.04	0.05	0.06	0.07	0.09	0.21	0.36	0.57	0.76
8,100	5.34	0.01	0.01	0.01	0.02	0.02	0.03	0.03	0.04	0.05	0.12	0.20	0.32	0.42

Note: Off-peak direction volume = 2,400, Δt_2 = 0.16; peak direction volume = 5,400, Δt_1 = 0.67; ratio = 0.16/0.67 = 0.24.

balanced in both directions, a greater number of buses are required to warrant a contraflow bus lane. As the flow of traffic becomes imbalanced, fewer buses are needed. Figure 1 shows that with a flow less than 3,600 vehicles per hour in the heavy direction, buses can continue to operate normally because their speeds will already be about 45 mph or more. With traffic heavy in both directions, it becomes desirable to construct or use a separate busway.

The basic steps and relationships required to establish Table 2 and Figure 1 are given in Tables 3, 4, 5, and 6. Table 3 shows the relationship between speed and traffic volume. It shows a nonlinear decrease in speed (increase in travel time) as vehicle demand increases and approaches or exceeds the facility's capacity. Table 4, similar to Table 3, gives the expected changes in bus travel time (Δt_1) as a result of the exclusive bus lane. It assumes a maximum bus operating speed of 45 mph. Table 5 gives the vehicle travel time losses in the off-peak travel direction (Δt_2) resulting from the loss of one usable highway lane (designated for buses). It is assumed that travel by automobile in the peak direction is not changed because the removal of the buses to their own exclusive lane will not affect these vehicles. Table 6 gives the relation between Δt_1 and Δt_2 for various traffic volumes in the peak and off-peak travel directions. This relation is then used in Eq. 8 with assumed automobile and bus occupancies and traffic volume in the off-peak direction to establish the required number of buses to warrant an exclusive bus lane.

SUMMARY

Contraflow bus lanes should generally produce time-savings to bus passengers that exceed the time losses imposed on traffic in the opposite direction. Meeting this broad criterion calls for an increase in the minimum number of peak-hour buses as traffic in the off-peak direction rises and approaches (or exceeds) capacity. The model quantifies the number of buses required for a contraflow bus lane. As such, it represents a tool that urban and transportation planners may use in determining the feasibility for contraflow bus operations on urban freeways. The model should be tested under vehicle load factors, on traffic lanes (freeway width), and with volume-capacity speed functions to provide a more complete guide for practical applications. This information could then provide inputs to determine the model's sensitivity and range of application.

The procedure demonstrated one rational procedure for implementing an exclusive bus lane and assessing its potential benefits. Other policy factors should be considered in establishing bus lanes on freeways. The use of exclusive bus lanes is particularly timely in light of regulations that are being established to meet air quality and energy conservation needs.

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VARIATIONS IN PSYCHOLOGICAL RESPONSES TO CHARACTERISTICS OF BUS SERVICE

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This study was undertaken as a part of a Florida Department of Transportation (DOT) bus demonstration project in Clearwater, Florida. It was intended to provide psychological data as inputs to analysis and design of public transportation systems. The bus system serviced a low-density urban region in which many elderly people lived. A survey for obtaining consumer inputs was administered at home to 145 users and nonusers of the bus system. Three other variables (in addition to user status) were studied: age, sex, and health status. Large differences were found on responses to various transportation-related concerns or annoyances. Nonusers were more concerned about injury and health risks, annoyances, and long-time pressures (e.g., delays). Oldest respondents were more concerned about injury and health risks and about short-time pressures (e.g., not being able to move quickly enough). Less healthy persons also reflected this latter concern. Because of the large number of persons in the elderly (sometimes infirm) category, it was suggested that consideration of the needs and limitations of these persons is clearly advisable in the design of transportation systems.

•IDENTIFICATION and measurement of various consumer inputs are currently receiving increased attention by transportation planners. The rationale behind this growing concern stems, in part, from recognition that use of public transportation facilities depends on user preferences that are not satisfactorily measured by usual system performance variables such as travel time, cost, and departure frequency. Previous studies of the ability of public transportation modes to meet the needs of and match the physical characteristics of existing and potential riders have revealed barriers for some people (1) and the importance of measuring preferences about system characteristics by users (2).

The need for this research is intensified by the increasing emphasis on planning public transportation services that meet the needs of relatively immobile or transportation-disadvantaged groups. Such emphasis is even a matter of national policy (3):

> It is hereby declared to be the national policy that elderly and handicapped persons have the same right as other persons to utilize mass transportation facilities and services; that special efforts shall be made in the planning and design of mass transportation facilities and services so that the availability to elderly and handicapped persons of mass transportation which they can effectively utilize will be assured; and that all Federal programs offering assistance in the field of mass transportation (including the programs under this Act) should contain provisions implementing this policy.

To ensure the possibility of effective use of public transportation by groups whose characteristics differ from the public at large requires that transportation planners make concerted efforts to mold the characteristics of public transportation systems

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to fit the specialized requirements of these groups. This does not imply that the needs of the many must be disregarded in favor of those of the few. The transportation system that is responsive to eliminating as far as possible all unnecessary physical and psychological impediments to travel probably will provide improved levels of service that can be appreciated by all its patrons. An appropriate concern, therefore, of those responsible for the planning and evaluation of transportation systems should be the identification and consideration of the activity needs, economic capacity, physical capabilities, and psychological reactions of population subgroups, particularly where these needs and reactions differ considerably among the various groupings.

METHOD

Clearwater Demonstration Project

The empirical basis for this research was an attitudinal survey of actual and potential users of a 1-year bus demonstration project conducted by the Division of Mass Transit Operations, Florida DOT. This project, known as the Clearwater Bus Demonstration, served a number of small communities just outside Clearwater, Florida, from October 1970 to October 1971. Alan M. Voorhees and Associates, transportation and urban planning consultants, were retained by Florida to operate the demonstration project, and they have reported on the monitoring and analysis of project performance (4, 5, 6).

The purpose of the demonstration project was to test the feasibility of providing fixed-route, inexpensive bus service in a low-density urban area that was populated largely by middle-income retirees and that had never been served by buses. According to the 1970 census, the percentage of the 522,329 Pinellas County residents 65 years of age or older was 29.4, three times the national figure of 9.8 percent. During the planning phase of the Clearwater project, a deliberate attempt was made to locate the bus routes so they would pass through the county's retirement population.

While the bus system was in operation, a home interview survey was conducted in which a random sample of households located within 1 mile of the bus routes was studied. The age of the 1,582 members of the 641 households surveyed was 40 percent over 60, 37 percent between 20 and 60, and 23 percent under 20 years of age. Thus, it can be assumed that a sizable proportion of the target population for the Clearwater project was elderly or retired or both. Those households surveyed were predominantly of middle-class status with a median family income of $7,000 and with car ownership averaging 1.32 per dwelling unit.

In addition to the home interviews, specific users of the demonstration buses took part in an on-the-bus survey. When questioned about the mode of travel used before the demonstration bus service was provided, 40 percent of the under 20-year-old bus users said they had been previously unable to make a similar trip. This illustrates significant latent demand for transportation. Although 46 percent of the over 60 age group indicated the automobile as the previous travel mode, only 10 percent of the persons in this group had both a driver's license and an automobile. Thus, most of the elderly persons who had previously used automobile travel apparently solicited rides from relatives and friends. A latent travel demand by those over 60 was also reflected by the 28 percent that had been previously unable to make particular trips.

Procedure

The survey was developed and analyzed under the joint sponsorship of the Urban Mass Transportation Administration and the Division of Mass Transit Operations, Florida DOT. It was an attempt to identify the feelings people have about traveling by public transportation as well as how such feelings vary among different people.

The survey questionnaire was designed to focus on psychological reactions of people to bus travel. Respondents were asked to select the answer that best described their feelings about various situations that occur often in bus travel. The situations specifically dealt with health, injury, annoyance, and time pressure. These categories and the specific travel situations assessed are as follows:

1. Injury risk—boarding the bus, bus moving before the passenger is seated, having to stand or move in crowds, having to stand during the ride, experiencing a bumpy ride, sudden changes in speed, alighting from the bus, alighting before other passengers, bus stops located on wide streets, and bus stops located near fast-moving traffic.
2. Health risk—uncomfortable temperature inside bus, uncomfortable temperature differential (inside-outside), being exposed to drafts, having to stand for extended periods of time, being in close contact with other people, experiencing a bumpy ride, having to wait outside in rainy weather, having to walk too far, and being exposed to exhaust fumes.
3. Annoyance—having to walk too far, delay time waiting for a bus, experiencing a bumpy ride, sudden changes in speed, cleanliness of the bus, being in close contact with other people, being forced to transfer, and having to stand during the ride.
4. Short-duration time pressure—boarding the bus ahead of other people, getting seated before the bus starts moving, moving from a seat to the exit door, alighting from the bus before other people, and interference with other people who are moving faster than you can (or want to).
5. Long-duration time pressure—having difficulty finding the bus stop, not knowing when the bus is scheduled to arrive, having to wait for a late bus, and experiencing unexplained delays enroute.

Those respondents who used the demonstration project buses were asked to answer on the basis of their experiences riding the buses. Respondents who were not bus users were asked to answer the same questions based on what they thought the situations would be like if they were to ride. In each case, the interview was conducted in the respondent's home and lasted about 30 min.

During the interview, the respondent was given a sheet of paper that indicated the appropriate scale to be used in answering each set of questions. A four-point Likert type of scale (7) was used with each numbered point representing a statement that expressed an extent of concern. For example, a scale from 0 to 3 would represent successively increasing concerns, as follows:

1. 0—not at all concerned about the situation,
2. 1—somewhat concerned about the situation,
3. 2—moderately concerned about the situation, and
4. 3—very concerned about the situation.

The interviewer described a situation, and the person being surveyed reacted by indicating the most appropriate numbered response. Interviewers were instructed to encourage the use of numbers alone rather than the corresponding statements. This way it was hoped that the respondents would have less reluctance to express possible fears or concerns.

Survey Respondents and Interviewers

Respondents for our survey were an essentially random subset of the larger sample from the Voorhees survey. Two differences existed, however. First, some of those selected were no longer available for inclusion, and second, so that the ability to compare user with nonuser behavior could be strengthened, a higher than existing proportion of users was sampled. A total of 145 persons participated, 74 of whom were riders on the demonstration bus system and 71 who were nonusers. Of the 145 respondents, 32 were less than 20 years old, 51 were between 20 and 60, and 62 were over 60.

The survey data were collected by 12 junior college students from the Clearwater area. They had been trained for and served as interviewers in previous Voorhees research.

Study Variables and Research Design

Four main variables were studied to see what differences they accounted for in survey responses: sex (male versus female), health status (excellent versus lesser),

bus ridership status (user versus nonuser), and age (<20 versus 20 to 60 versus >60 years). The three-way division of age provided for assessment of expected nonlinearity between responses and age.

In a classic experimental design, it is desirable to assign individuals to specific conditions in random or matched fashion so that causality of variables can reasonably be determined. Unfortunately, the four variables examined in this investigation were the sort in which a person's classification was dictated by his behavior or demography. Obviously, people who voluntarily use a demonstration bus project might differ from nonriders on such characteristics as car ownership and income. Hence, the observed relationship between ridership status and other behaviors might be caused by unidentified, extraneous factors. This is a limitation characteristic of all studies that use demographic variables as quasi-independent variables. Table 1 gives some of the main relationships between the quasi-independent variables of this study and various other categories. Note that several categories relate particularly to user status and age.

We tried to identify significant sources of variation in survey responses with a multivariate analysis of variance, i.e., use of a design that permitted unequal cell frequencies and disproportionalities. [The specific analysis of variance technique that was employed (BALANOVA 5, University of Illinois) uses an unweighted means technique for estimating all sources of variance.]

One consequence of using the combination of demographic variable classifications described is that the observations on each response variable must be subdivided into 24 cells (based on a 2×2×2×3 design). Unfortunately, limitations within the data set produced an insufficient number of observations in some of the cells and precluded the use of this design. These sparsely filled cells were primarily because of the young people surveyed who were almost all in excellent health. It was found, however, that a four-way classification design to examine the effect of health on survey response was possible if a two-category age breakdown (that resulted in a 2×2×2×2 cell design) was employed. So that the effect of age under the more desirable three-way age group breakdown could be tested, a second analysis of variance was designed that omitted the health category and consisted of user status, sex, and age (a 2×2×3 cell design).

RESULTS

A summary response score for each survey participant was derived for each of the categories: injury risk, health risk, annoyance, short-duration time pressure, and long-duration time pressure. The respondent's score (from 0 to 3) was recorded for each specific situation (e.g., sudden changes in speed) in the category. These, in turn, were averaged to provide an extent of concern score (ranging from 0 to 3.0). These various scores were analyzed, and the results are shown in Figures 1, 2, and 3.

In each of the graphs, the vertical axis represents the extent of concern dimension. The vertical displacement of a given point is the group mean that represents all of the members of that particular subgroup. The specific categories of concern are represented by points along the horizontal axis of each graph. The lines connecting the plotted points have been included to aid in recognition of the response profile of each demographic group.

Variations in response level that are attributable to user status are shown in Figure 1. These results are based on the three-way (2×2×3) analysis of variance design that excluded the health status variable. For all categories of response, the nonusers expressed greater levels of concern. Significant differences (in which probability of occurrence because of chance alone is 0.05 or less) were found in the injury risk, health risk, annoyance, and long-time pressure categories. Because nonusers were asked to respond according to how they thought the situations would affect them, these results presumably indicate the presence of a bias against bus transportation.

Variations in response level that are attributable to age are shown in Figure 2. These results are also based on the three-way design excluding the effect of the health status variable. As expected, the extent of concern about injury risk, health risk, and short-time pressure situations significantly increased with age. No significant differences among age groups were found for the annoyance and long-time pressure categories, but all age groups rated them as relatively important concerns.

Table 1. Significant relations between independent and descriptive variables (probability of occurrence < 0.05).

Descriptive Variables	User (U) Versus Nonuser (NU)	Excellent (EXC) Versus Lesser (LESS) Health	<20 Years Old (LO) Versus 20 to 60 (MID) Versus >60 (HI)
Distance between home and bus stop	NU > U		
Access to car	NU > U		MID > LO and HI
Possession of driver's license	NU > U		MID > LO
Years living at current address			LO > MID; HI > MID
Size of prior town or city	U > NU		HI > LO and MID
How often a transit user there	U > NU	EXC > LESS	MID > LO; HI > LO
School grade completed	NU > U		MID > LO and HI
Ability to get around physically		EXC > LESS	LO > MID and HI; MID > HI
Persons in excellent health			LO > MID and HI; MID > HI
Persons using the bus			LO > MID; HI > MID

Figure 1. Extent of concerns as function of user status.

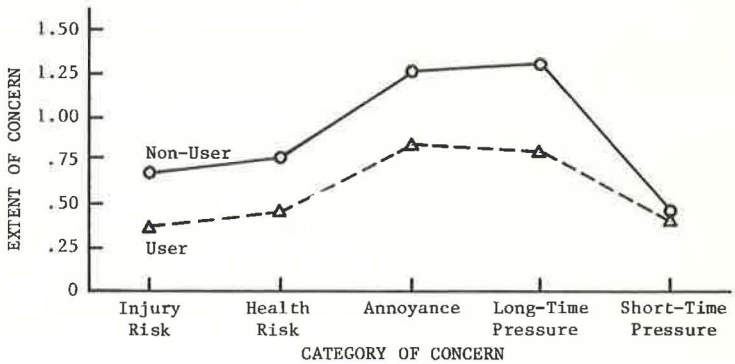


Figure 2. Extent of concerns as function of age category.

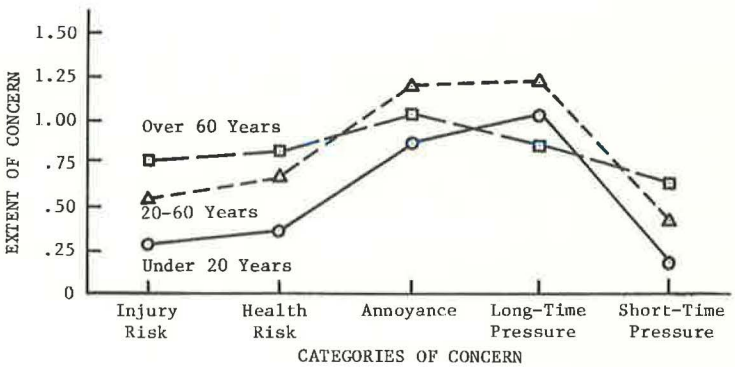
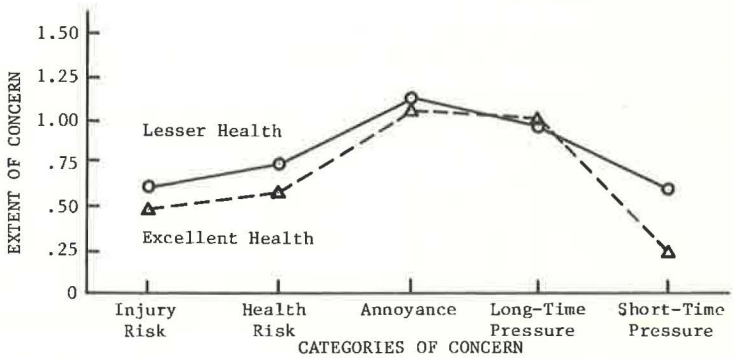


Figure 3. Extent of concerns as function of health status.



The variations in response level that are attributable to the perceived health status of the survey respondents are shown in Figure 3. These results are based on the four-way (2×2×2×2) design. The only significant difference in response level was in the short-time pressure situations, with poorer health respondents who indicated higher concern.

No significant differences in levels of concern based on sex of the respondents were found. User status and age, therefore, appear to be the two most important factors in explaining the variations in psychological response that were examined.

In addition to the main effects described above, there was a significant interaction between user status and age for the health risk concern measure. It was found that nonusers over 60 years old expressed considerably greater concern for health risk situations than did older users. This may indicate the true health status of the over-60 age group of nonusers, and it offers an additional clue as to why they chose not to use the demonstration buses.

CONCLUSIONS

This research represents a somewhat primitive attempt to provide psychological inputs to the analysis of public transportation service. The study was limited in at least two respects: (a) Budget and time constraints were responsible for the limited sample size; and (b) the Clearwater bus service was conceived as a demonstration program, and this could have led to findings atypical of bus service in general.

Nevertheless, the findings offer some useful insights and directions. The users and nonusers revealed sizable differences in many areas of concern. It would be expected (as found here) that nonusers would reflect their bias against bus riding in such areas as long waits, unexpected delays, unpredictable service, and general inconvenience. However, their concern about health and injury risks, as compared with users, is not so easily explained. There might be a need to consider public educational programs to offset this nonuser worry or bias.

The data showing the effect of age on transportation concerns appear quite important. Health and injury concerns were directly related to age: The oldest respondents were most concerned, the youngest the least. The elderly were also the most concerned about short-time pressure situations, e.g., where they could not move quickly enough to match situation requirements. Persons of poorer health in general showed this same concern. Because the elderly (and sometimes infirm) make up a major ridership group, only some of whom are currently likely to use typical bus service, their concerns strongly suggest possible equipment and systems-operation concessions. Notable among equipment considerations might be the design for safe and easy entrance and exit, adequate handholds and safety padding along all walkways and standing areas, and package and shopping cart capacity. A bus route that eliminates the need to cross fast, busy, wide avenues is an example of a system concession in the interests of wider ridership by the elderly and infirm.

The data show that people respond psychologically quite differently to various transportation equipment and systems characteristics according to their membership in relevant demographic groupings. We have tried to demonstrate that transportation service quality dimensions (which are "soft" in comparison to travel time) can be described, measured, and analyzed. Finally, we suggest that these kinds of information have considerable usefulness in the planning and evaluation of public transportation systems, which would then be more responsive to the needs of all potential consumers.

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MACROPLANNING APPROACH TO THE ASSESSMENT OF REGIONAL BUS RAPID TRANSIT SYSTEMS

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Bus systems provide the major public transportation services in the Seattle area. System viability has become a matter of increasing concern in recent years, in many urban areas, as ridership has fallen and operating deficits have increased. There is considerable sentiment, however, that public transit should not be allowed to collapse, because this would leave many people with no economical means of transportation and place even greater reliance than at present on the private automobile and freeways. An approach to the problem is bus rapid transit, which would provide a different route structure and operating philosophy than present bus systems. A bus-based system has merit because it offers the possibility for relatively high-speed movement of people on existing arterials, highways, and freeways without the very high capital investment required for a rail system.

•A CONFIGURATION for a bus rapid transit system that is composed of line-haul routes between activity centers or nodes is discussed. Feeder systems and local systems that would be required around some nodes are not considered. Operations between nodes are assumed to be on a nonstop basis as much as possible and are assumed to use arterials, highways, and freeways.

SYSTEM STRUCTURE AND LOADS

Nodes and links included in the bus rapid transit system (Fig. 1) reflect opinions of a number of individuals familiar with the area or of those engaged in traffic planning in the area. An outer beltway on the periphery of the system is not shown in the network because present traffic volumes are too small to warrant their inclusion. These could be added as required to accommodate growth in the future. The network encompasses the area from Puget Sound on the west to North Bend at the foot of the Cascade Mountains on the east and from Tacoma in the south to Everett in the north. Essentially all activity centers in the Seattle area with significant traffic densities are covered.

Projected traffic volumes for the region for 1975 were obtained from the Puget Sound Governmental Conference (PSGC). All PSGC planning analysis zones west of Puget Sound were excluded from the analysis, and the remaining 571 zones were allocated to the 56 nodes in the network. Total forecast trips between nodes were broken down into home-based work, home-based shopping, home-based school and college, home-based recreational, home-based miscellaneous, non-home-based, and commercial. For this study, commercial trips were excluded as were internal trips within each zone. Total daily trips in the region after these exclusions are approximately 2.29 million. The 24 most significant destination nodes were determined so that the analysis could be simplified. Total trips involving these 24 nodes are 1.84 million per day or 80 percent of the regional total trips.

Figure 2 shows a representative distribution of total trips through the day, which is based on operating data from bus system operations and traffic volume data for the Seattle freeway. The distribution is shown for an assumed 18-hour operating day. The

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hourly trip distribution generally indicates the pattern of the ridership that might be expected, although the exact shape is not critical for the analysis. Data of major importance in Figure 2 are the percentages of trips in the morning and evening peak hours that determine the size of bus fleet required. Each of these peak hours is estimated to be 15 percent of the total daily trips.

For this study, it is assumed that 10 percent of all trips are made on the bus network. A 10 percent modal split is used because it is consistent with the present experience of Seattle Transit and agrees with estimates of patronage from previous technical studies of rapid transit in the Seattle area for a bus system. It is also assumed that the modal split is uniform throughout the area. Although this is not likely to be true, the assumption affects only the relative loads on individual links and does not greatly affect total system operating characteristics.

From PSGC data, a table was constructed that shows peak-hour bus trips from the 56 origin nodes to the 24 major destination nodes. Total peak-hour trips are about 27,600 or 1.5 percent of the 1,840,000 trips per day that involve the 24 major destinations. This total reflects a 10 percent modal split for the bus system and peak-hour patronage of 15 percent of the daily total.

Inasmuch as exact routes are not specified for the links in the network, road distances for each of the links in Figure 1 were estimated at 1.25 times the airline distance between nodes. Approximate travel speeds for each link were estimated on a judgment of road conditions that might be expected on each link. Round-trip time estimates in minutes for each link are given in Table 1.

Minimum time paths from each of the 56 origin nodes to the 24 major destination nodes were constructed by using the link travel times and a minimum path algorithm in the interactive graphic simulation package available at the Urban Data Center, University of Washington. Peak-hour link loads given in Table 1 are the sum of the loads obtained from the 24 minimum time path analyses.

An analysis is given in Table 1 of peak-hour fleet requirements that are based on estimated 1975 travel times and peak-hour link loads and an assumed 10 percent modal split. In Table 2, all links have been analyzed separately as if each bus operates only between one pair of nodes in the network. The number of buses required for each link is rounded upward to determine an integral number of buses required to service a link. This results in a fleet size of 300 buses that is larger than the theoretical minimum but that allows for turn-around time and losses when actual schedules are developed. Neither of these is taken into account explicitly.

The fleet size in Table 1 is also based on trips to the 24 most important destinations in the network that account for 80 percent of total trips. No allowance in fleet size has been made for the missing 20 percent because it is felt that this additional load could be accomodated by capacity for standees and because minimum frequencies have been specified on a number of links where loads are small.

SYSTEM REVENUES AND COSTS

Estimates of system loads in Table 1 are based on an estimated 2,290,000 internodal, noncommercial trips per day in the Puget Sound region. With an assumed modal split of 10 percent, the bus system would carry approximately 230,000 riders per day. By using 300 equivalent full-time operating days per year as the basis for calculation, the system would carry approximately 69 million riders per year. In 1970, Seattle Transit received average fare box revenues of $0.27 per passenger. A minimum fare of $0.30 per ride, consequently, is consistent with fares on the present system. Annual revenues from a fare of $0.30 paid by 69 million riders would be $20.7 million.

Operating costs for the system are difficult to estimate because of lack of operating data for a comparable system. Current operating costs both in Seattle and nationally are about $1.00 per mile. On an hourly basis, operating costs are about $12.00 per hour and this reflects average speeds of 12 mph. For the network under study, operating speeds would be considerably higher than at present because service is essentially nonstop between nodes.

About 85 percent of current operating expenses in Seattle are wage-related; therefore, it is more reasonable to base an estimate of operating costs on hourly costs rather

Figure 1. Node-oriented bus rapid transit system.

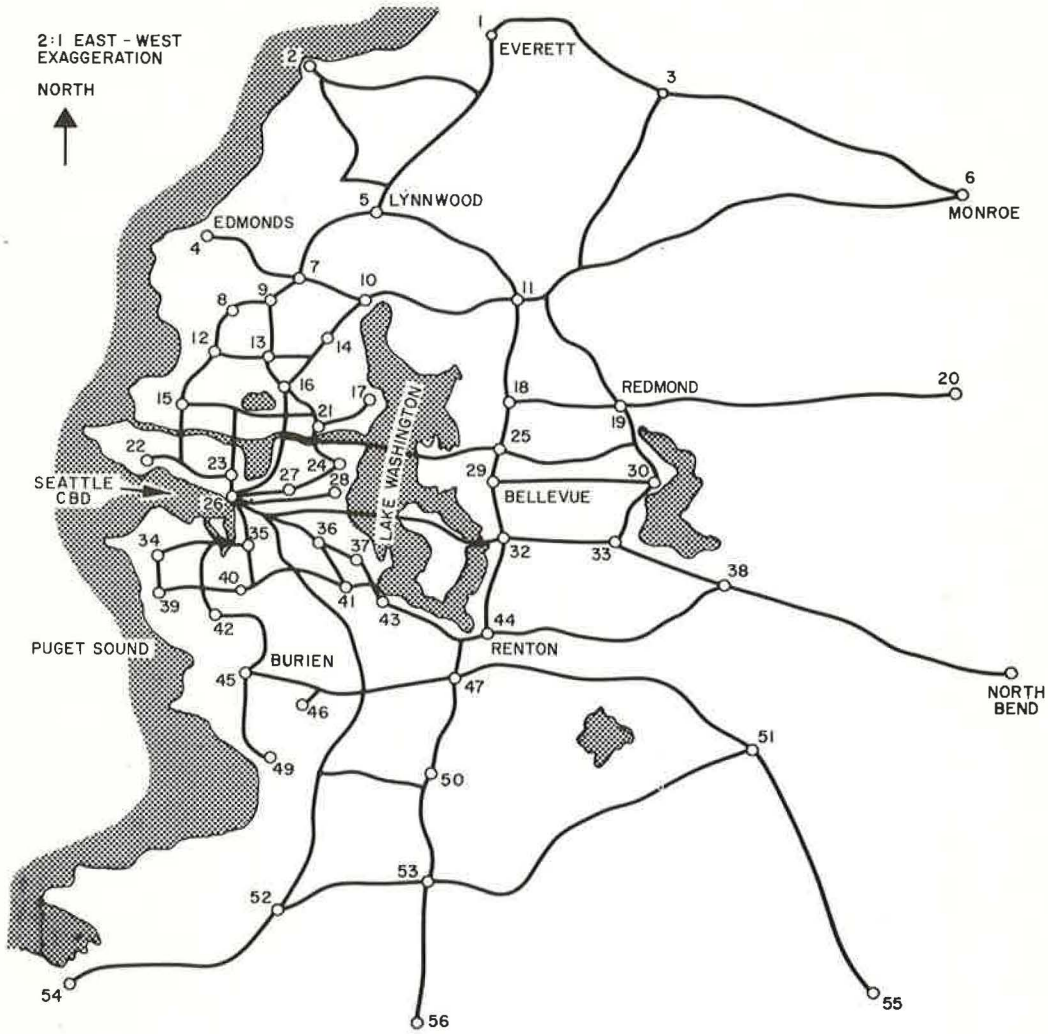

Figure 2. Daily trip distribution.

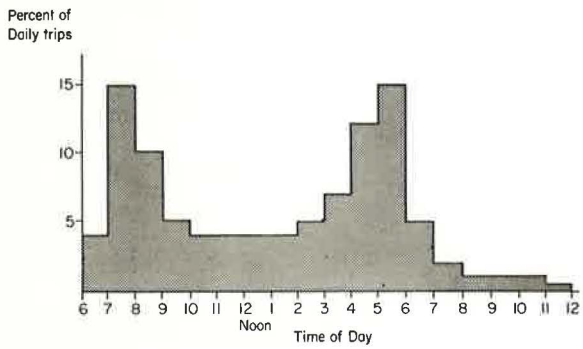

Table 1. Fleet size requirements for peak-hour service.

Link Pair	Peak-Hour Link Load	Round-Trip Time (min)	Buses Required[a]	Link Pair	Peak-Hour Link Load	Round-Trip Time (min)	Buses Required[a]
1-2	223	32	3	26-35	628	10	2
1-3	496	25	5	26-36	720	14	4
1-5	618	40	9	26-37	0	40	2[b]
3-6	50	35	2[c]	26-46	0	50	2[b]
3-11	34	45	2[c]	26-47	1,324	40	18
4-7	1,202	25	10	27-28	86	9	1
5-7	849	8	3	28-37	0	24	1[c]
5-11	186	25	2	29-30	204	14	1
6-11	0	25	1[b]	29-32	564	12	3
6-20	0	40	2[b]	30-33	0	17	1[b]
7-9	1,166	7	3	31-32	290	7	1
7-10	210	15	1	32-33	243	9	1
8-9	570	15	3	32-44	191	24	2
8-12	307	15	2	33-38	143	15	1
9-10	494	10	2	34-35	866	12	4
9-13	1,568	12	7	34-39	475	10	2
10-11	304	15	2	35-36	123	12	1
10-14	0	14	1[b]	36-37	403	7	1
11-18	312	20	2	36-41	287	14	2
11-19	0	36	2[b]	37-43	127	15	7
12-13	782	10	3	38-44	58	30	1
12-15	234	17	2	38-48	103	26	1
13-14	202	8	1	39-40	247	24	2
13-16	1,958	9	6	40-42	225	12	1
14-16	0	20	1[b]	40-43	240	22	2
15-16	122	24	1	41-43	551	15	3
15-21	150	26	2	42-45	897	20	6
15-22	158	20	1	43-44	277	14	2
15-23	330	26	3	44-47	868	8	3
16-21	2,461	10	9	44-50	261	17	2
17-21	691	12	3	44-51	177	42	3
18-19	0	14	1[b]	45-46	449	16	3
18-25	847	8	3	45-47	1,392	16	8
19-20	71	42	2[c]	45-49	843	22	7
19-30	0	20	1[b]	46-47	520	7	2
19-25	332	18	2	46-50	183	22	2
20-48	32	35	2[c]	47-50	262	17	2
21-24	180	15	1	50-53	746	26	7
21-25	501	26	5	51-53	72	51	2[c]
21-26	2,019	21	14	51-55	12	51	2[c]
22-23	237	18	2	52-47	398	42	6
23-26	1,492	12	6	52-53	477	18	3
24-27	325	15	2	52-54	840	24	7
25-26	495	34	6	53-55	190	51	4
25-29	545	8	2	53-56	263	26	3
26-27	575	9	2	54-56	801	22	6
26-28	490	12	2	55-56	0	51	2[b]
26-31	538	18	4				

[a]Buses required are rounded up to an integer number of buses. Total buses = 300.
[b]Number of buses on zero load links are set by policy of 30-min headway maximum on all links.
[c]Number of buses are increased to reduce headway to less than 30 min.

Table 2. Comparison of study scope.

Study Element	Macroplanning Study	Metro Study
Approximate total cost, $	<25,000	450,000
Time span	3 months maximum	1 year
Personnel requirement	1 to 2 persons full time	Approximately 8 people full time

than costs per mile. If one considers inflation and the effect of higher operating speeds, a cost of $15.00 per hour is a reasonable expectation. Current use of equipment by Seattle Transit is about 2,700 hours per year for each unit. Based on 300 equivalent days of operation per year, daily use is about 9 hours. Inasmuch as a conservative cost estimate is desired and improved off-peak service may be required to attract riders, 10 hours per day is used as the basis for cost estimation. Yearly operating hours for each bus in the node-oriented system are estimated at 3,000.

Table 1 gives a minimum required fleet of 300 buses for peak-hour needs. To this must be added some additional buses to provide for scheduling flexibility, maintenance, repairs, and so on. With a reserve of 50 buses for such contingencies, the total required fleet size is 350 buses. At 3,000 hours per bus, total operating hours per year are 1,050,000 and operating costs are $15.75 million per year, based on a cost of $15 per hour.

Although the $15-per-hour operating cost estimate includes some capital costs, it does not include full charges for expenditures for the bus fleet and other facilities. Assuming a 350 bus fleet and a life of 5 years, 70 buses must be purchased annually. Costs are about $50,000 for a 50-passenger bus, or an annual outlay of $3.5 million. Other capital improvements and facility costs have not been estimated in detail, but these might amount to $1.5 million per year, and this gives a total capital outlay for the system of $5 million per year. When these capital costs are included, annual costs for the system are $15.75 million in operating costs plus $5 million in capital costs for a total of $20.75 million. A comparison of this cost with the revenue estimate based on a $0.30 fare indicates that the system would just about break even.

It should be emphasized that the revenue estimate is based on an assumption that 10 percent of the noncommercial, internodal trips would be attracted to the system. If the modal split were less than 10 percent, revenues would be reduced accordingly. If a 10 percent modal split were not obtained, however, an offsetting factor would be a reduction in operating costs caused by a smaller fleet size and reduced number of operating hours.

Additional calculations with the basic data can provide other estimates of possible operating profits or losses. For example, with an average fare of $0.35 and an average modal split of 5 percent, revenues would be $12,075,000. A revised computation of the fleet size indicates that operating costs for a fleet of 240 buses would be $10.5 million, not including capital costs. Including capital costs of $3.9 million, annual costs would be about $14.4 million with a yearly loss of $2,325,000. Figure 3 shows estimated annual profits or losses for modal splits of 5 percent and 10 percent and various fare levels.

INTERPRETATION OF RESULTS

The analysis suggests that a node-oriented bus transit system is potentially an economically feasible method for providing regional public transportation in an area such as Puget Sound. Average fares necessary to attain a break-even level of financial operations assuming either a constant 10 percent or 5 percent modal split are well within the range of fares that could reasonably be obtained. Cost estimates are conservative because they include full internal funding of capital outlays. With federal or state assistance for capital expenditures, annual costs would be considerably lower.

Methodologically, this study has shown that initial feasibility assessments of node-oriented regional bus systems can be accomplished at low cost. Figure 4 shows the basic steps. With the exception of steps 2 and 4, all steps are accomplished by using easily obtainable parameters, informed judgment, and simple analytical procedures that can be carried out manually. Step 2, which requires the creation of an internodal trip table, may be a major task. In regions that have available trip data between principal origins and destinations, as in the Puget Sound region, only a summary of existing data is required. Because the resulting trip table may have over a thousand entries, a computer is useful, although not essential, for compiling the table and for determining peak-hour network link loads in step 4. Because a shortest path determination must be made for each entry in the trip table, automatic computation sub-

Figure 3. Estimated annual profits or losses.

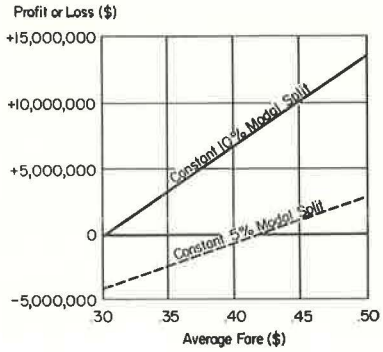

Figure 4. Major steps in node-oriented bus system study.

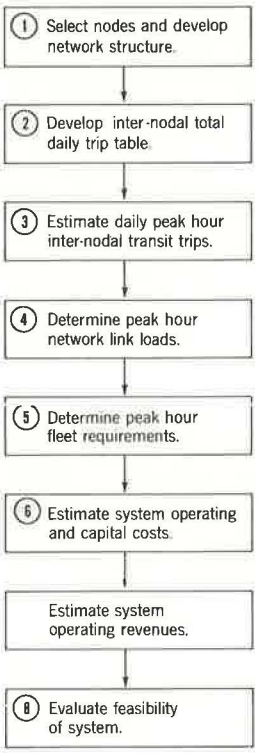

Table 3. Comparison of 1975 estimates of system costs.

System Element	Macroplanning Study	Metro Study[a]
Number of buses	350	325
Total bus operating hours	1,050,000	840,000
Bus miles	—[b]	10,937,000
Operating costs, $	15,750,000	11,816,000
Capital cost, $	5,000,000	6,000,000 to 7,000,000

[a]Calculated from Table 2-4-12 (10) by using an express bus-total system ratio of 0.5.
[b]Not required for macroplanning purposes but can be readily calculated.

stantially reduces the work involved. If no massive data collection is required to generate the trip table in step 2, a feasibility analysis similar in scope to the present study can be conducted for less than $25,000.

COMPARISON WITH FULL-SCALE PLANNING STUDY

The procedure used in defining the gross operating characteristics of a bus rapid transit system in the Seattle area is basically similar in concept to that used in a full-scale bus transit planning study for the same region. The full-scale study, which we will call the Metro study, was performed by a consultant firm in conjunction with the PSGC. Table 2 gives, in perspective, the differences in time and cost between the macroplanning study and the Metro study.

The macroplanning approach represents a simplification of the much more comprehensive Metro analysis. In both, trip assignment results from a step-by-step process of zonal identification, trip generation, trip distribution, and modal split. The major simplifying assumption that the macroplanning approach makes is of a system-wide, constant value of modal split that is judgmentally decided on. Thus the need for a modal-split model with its parameters is bypassed. A second simplification relates to the network and estimation of the number of buses required in the system. Buses are considered to run only back and forth between two adjacent nodes, and no consideration is given to actual routing of buses through the network.

Cost estimates obtained from the macroplanning approach are generally consistent with those obtained from the Metro study. The main difficulty in making straightforward numerical comparisons is that the Metro plan covers a combined express and local bus service, whereas the macroplanning study included only an express bus service. Table 3 gives a rough comparison of macroplanning and Metro estimates of system operating costs. The Metro estimates given in Table 3 are one-half of the values stated in the Metro report because the Metro express systems and local systems are approximately equal in size.

On the revenue side, the Metro study estimated total system patronage of 35.7 million passengers in 1975. Of these, about half—some 13 million—would be express bus riders. This figure is only one-quarter of the 69 million riders obtained from the 10 percent across-the-board modal split used in the macroplanning approach. The large difference is because the off-peak bus patronage is proportionately much less than during peak hours. Peak-hour loads must be used in sizing the bus fleet, and the 10 percent modal split used in the macroplanning study is a reasonable upper bound on peak-hour patronage, but it is too high for off-peak hours. Adjustment of the 10 percent modal split during off-peak hours to a more typical level would bring the ridership estimate in the macroplanning study much closer to the Metro study results. No such adjustment was made in the macroplanning study because the 10 percent modal split was viewed at the time of the study as a goal of the system rather than a forecast.

Aside from the discrepancy in revenue estimates discussed, results of the macroplanning study and the full-scale Metro study are quite comparable. This similarity suggests that the macroplanning approach may be a useful tool in assessing the gross operating characteristics of proposed transit systems.

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EVALUATION OF BUS MAINTENANCE PROCEDURES THROUGH SYSTEMS ANALYSIS: A CASE STUDY

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The purpose of this study was to apply different systems analysis techniques, especially the queuing theory, to evaluate the bus maintenance problems of a large transit company. The case study centers around the Denver Metro Transit Company. The maintenance facility of the company is analyzed, in terms of storage capacity, service rates for the various types of repairs, and other pertinent data, to arrive at a statistical service distribution. The statistical distribution of bus arrival for maintenance and channel configuration of the repair shop are established. The results indicate various effects on waiting time, the broken-down rate, arrival rate by changing facility capacities, and maintenance policy. At this stage of study, most efforts were concentrated on the facility aspect of the problem. The study established the theoretical basis for the maintenance procedure.

•EVERY transit company is faced with maintenance operations of buses. Each bus that is in the garage is a loss of revenue. For a transit system to operate in an efficient manner, the buses must receive proper maintenance and repairs with a minimum loss of time. This study is an attempt to gain an understanding of the bus maintenance procedures of a large transit company and to apply the systems analysis techniques, specifically the queuing theory techniques, so that the bus maintenance problem can be evaluated. The Denver Metro Transit Company (DMT), which is owned and operated by the City and County of Denver, is used as a case study.

GENERALIZED MODEL OF VEHICLE MAINTENANCE PROCEDURES

Model Construction

It is hypothesized that a generalized model of any maintenance shop can be developed through analysis of the maintenance procedures of DMT. A complexity arose because of the numerous types of vehicles in use at DMT and their requirement for specific parts, which are not necessarily interchangeable among the various vehicles or even needed on all of the vehicles. With this in mind, a simplified model of vehicle maintenance procedures is developed based on the following assumptions:

1. The company operates with one type of vehicle, totaling V.
2. Each vehicle contains P number of major parts per vehicle.
3. Preventive maintenance procedures (referred to as inspections) of vehicles are performed every m_o miles. There are K different types of inspections; Kth is the most complete. These K inspections are carried out on a cyclic basis. The maintenance mileage at the i th inspection, m_i, is im_o. After the Kth inspection, the mileage on the vehicle is recorded as zero, and the sequence of inspections is repeated.
4. A maintenance period is assigned to each major part. Because all parts get maintained only when vehicles get inspected, the maintenance period for part i, I_i, will be nm_o, where n is a positive integer.

Publication of this paper sponsored by Committee on Maintenance and Operations Systems.

5. The probability density function of the failure of part i at mileage m, $f_i(m)$, is Erlang-distributed. The lifetime distribution function $F_i(m)$ or the probability that part i breaks down before mileage m is expressed as

$$F_i(m) = \int_0^m f_i(x)dx \tag{1}$$

6. For the convenience of vehicle dispatching, a predetermined number of vehicles V_k is assigned for the k th type of inspection each day according to time allowances for that particular inspection. If the number of vehicles requiring the k th type of inspection exceeds the capacity of the maintenance shop, those vehicles with the highest mileages are assigned, and the remainder continue in operation.

7. There are J maintenance channels and an equal number of crew members in the inspection shop. Each channel can handle all types of inspection at a service rate η_k with k = 1 to K.

8. Vehicles that break down on their routes are pulled into the repair shop. There are R repair channels. Each repair channel specializes in the repair of one major part. The number of spare units of the i th part are equal to S_i with i = 1 to P.

9. Vehicles break down in a random fashion (Poisson distribution), the time to repair part i is Erlang-distributed with mean μ_i, and the time to remove a worn part and replace it with a new part is relatively short and negligible.

In this study, the model is constructed with special emphasis on the facility aspects. Two other related aspects, manpower and cost, should be taken into consideration in the future to make up a complete model.

Inspection Queue

The concept of the inspection queue is somewhat different from what one might think of first. Service rate of this queuing system is the assignment rate, rather than the actual inspection rate. Consequently, the service channel is referred to the assigning process, rather than the actual inspection channel. From this viewpoint, the system of the inspection shop can be thought of as K single-channel queues. The input for the k th queue, or the vehicles that reach the maintenance mileage of the k th inspection, is Poisson-distributed with mean λ_k, where k = 1 to K.

$$\lambda_k = \frac{m_t}{m_k} \tag{2}$$

where

m_t = total daily operating mileage, and
m_k = total operating mileage from k th inspection to the next k th inspection = Km_o.

The service rate of the k th queue, or the assignment rate for the k th inspection, is constant and equal to A_k. Then the average additional operating mileage, M_k, is

$$M_k = \frac{T_k m_t}{V} \tag{3}$$

where T_k = average additional daily operating time per day before vehicles can get inspected.

Effect of the Input Distribution

The values of T_k depend on the input rate λ_k, the assignment rate A_k, and the types of input distribution. For the fixed λ_k and A_k, T_k is determined by the distribution function of the input.

1. If the input is Poisson-distributed, then

$$T_k = \frac{\rho_k}{2A_k(1 - \rho_k)} \tag{4}$$

where $\rho_k = \frac{\lambda_k}{A_k}$.

2. If the input is uniformly distributed ($\lambda_k < A_k$) and a steady-state system exists, then $T_k = 0$.

Thus, a uniform or regular dispatching would be preferred to a random dispatching. Also, if M_k is greater than zero, the possibility of failure of parts would increase from $F_i(I_i)$ to $F_i(I_i + M_k)$. Therefore, the best dispatching rule is that the input rate of inspection can be kept uniform.

Broken-Down Rate

Because broken-down rates are involved with several calculations in this study, they are examined here in detail. If part i with expected life mileage $E_i(m)$ undergoes maintenance at mileage $(I_i + M_k)$, then the average operating mileage of part i before it breaks down or goes in for maintenance is

$$D_i = \int_0^{I_i+M_k} mf_i(m)dm + \int_{I_i+M_k}^{\infty} (I_i + M_k)f_i(m)dm \tag{5}$$

$$D_i = E_i(m) - \int_{I_i+M_k}^{\infty} (m - I_i - M_k)f_i(m)dm \tag{6}$$

$$D_i = (I_i + M_k)\,[1 - F_i(I_i + M_k)] + \int_0^{I_i+M_k} mf_i(m)dm \tag{7}$$

Thus, the daily number of part i to come to the maintenance shop for either inspection or repair is

$$VM_i = \frac{m_t}{D_i} \tag{8}$$

The broken-down rate B_i and the number coming for inspection VI_i are respectively

$$B_i = VM_i F_i(I_i + M_k) \tag{9}$$

and

$$VI_i = VM_i\,[1 - F_i(I_i + M_k)] \tag{10}$$

Effect of the Assignment Rate

Although the assignment rate is constant, service time of inspection is not. Realistically the rates are assumed to be exponentially distributed with mean η_k for k = 1 to K. The time to serve the assignment rate A_k, t_k is Erlang-distributed with

$$f(t_k) = \frac{t_k^{(A_k-1)}}{(A_k - 1)} \exp\left[-\frac{A_k t_k}{k}\right] \tag{11}$$

Let TN be the total working time for all the channels, then

$$P\left(\sum_{k=1}^{K} t_k \le TN\right) = \int_0^{TN} \int_0^{TN-t_1} \cdots \int_0^{TN-t_1-\ldots t_{k-1}} \sum_{k=1}^{K} P(t_k)dt_1 \ldots dt_k \tag{12}$$

The probability that the inspection crew cannot finish the assigned vehicles and have to work overtime is

$$P\left(\sum_{k=1}^{K} t_k > TN\right) = 1 - P\left(\sum_{k=1}^{K} t_k \le TN\right) \tag{13}$$

The average overtime length TM is

$$TM = E\left[\left(\sum_{k=1}^{K} t_k - TN\right) \middle| \left(\sum_{k=1}^{K} t_k > TN\right)\right] \tag{14}$$

The expectation is taken over the summation of t_k.

By increasing A_k, M_k will be reduced as will the broken-down rate, while the same time TM will be increased. From the viewpoint of minimizing cost, the optimal A_k will be as follows:

$$\text{Opt. COST} = \underset{A_k}{\text{Min}}\,[(\text{average overtime labor cost}) \times TM + (\text{average cost per repair for part i}) \times B_1] \tag{15}$$

Inspection Crew Size and Number of Inspection Channels

It was assumed in the model that the number in the inspection crew was equal to the number of inspection channels J. If the number of channels is increased, then the number of the crew size must also be increased; therefore, there will be an increase in total working time for all inspection channels and a decrease in overtime. The optimal number of inspection channels will depend on the availability of a night shift, the wages of mechanics, and the cost of increasing channel capacity. One can also increase the number of mechanics in each channel to reduce the service time, but the marginal savings gained on the service time by increasing the crew will eventually decrease. The optimal number of members in each channel would be reached when (marginal savings on overtime work) × (labor rate of overtime) = (wages of increased number of mechanics).

Determination of Maintenance Mileage for Individual Parts

In the case when m_o is given, the optimal maintenance mileage for part i, I_1, would be such that

$$\hat{I}_1 = \hat{n}m_o$$

$$\begin{aligned}\text{Opt. COST} &= \underset{n}{\text{Min}}\,[(\text{avg. cost/repair}) \times B_1 + (\text{avg. cost/inspection}) \times VI_1] \\ &= \underset{n}{\text{Min}}\,\{(\text{Avg. cost/repair}) \times VM_1 \times F_1(nm_o) + (\text{avg. cost/inspection}) \times VM_1 \times [1 - F_1(nm_o)]\}\end{aligned}$$

where n is positive integer. If the average additional operating mileage M_k is known,

B_i in the above equation becomes $VM_i \times F_i(\hat{n}m_o + M_k)$ instead of $VM_i \times F_i(\hat{n}m_o)$. VI_i becomes $VM_i \times [1 - F_i(\hat{n}m_o + M_k)]$.

Repair Queue

If the time required to remove a worn part and replace it with a spare unit is comparatively short and negligible, the repair shop system can be described as having P single-channel queues, where P is the number of types of major parts. The input of each queue is Poisson-distributed with mean B_i. The service time or the time needed to repair part i is assumed to be Erlang-distributed with mean μ_i and Erlang constant ℓ_i. The average number of vehicles idle in the repair shop E(n) is equal to

$$E(n) = \sum_{i=1}^{P} E_i(n) = \sum_{i=1}^{P}\left(\frac{\ell_i + 1}{2\ell_i} \times \frac{B_i}{\ell_i\mu_i(\ell_i\mu_i - B_i)} + \frac{B_i}{\ell_i\mu_i}\right) \tag{16}$$

and if no spare parts are available, the average expected waiting time at the repair shop $E_i(w)$ would be equal to

$$E_i(w) = \frac{\ell_i + 1}{2\ell_i} \times \frac{B_i}{\mu_i(\mu_i - B_i)} + \frac{B_i}{\mu_i} \tag{17}$$

Effect of Providing Spare Units

If S_i spare units are provided for part i, then the probability that a vehicle arrives and finds a spare unit available is equal to the probability that a vehicle arrives and finds the total number of failed parts i in the system less than S_i.

$$P(s_i < S_i) = \sum_{s_i=0}^{S_i-1} P(s_i)$$

$$= P(s_i = 0) + \sum_{s_i=1}^{S_i-1} P(s_i)$$

where

$$P(s_i = 0) = 1 - \ell_i\alpha_i$$

$$\alpha_i = \frac{B_i}{\ell_i\mu_i}$$

$$P(s_i) = (1 - \ell_i\alpha_i) \sum \alpha_i^{\beta}(-1)^i\binom{\beta}{i}\binom{\beta+j-1}{j} \quad \text{for } s_i > 0 \tag{18}$$

where the summation is taken over the partitions of s_i such that $s_i = \beta + i\ell_i + j$.

The average time saved from waiting by providing S_i spare units $TS(S_i)$ is

$$TS(S_i) = \frac{P(s_i < S_i)}{\mu_i} \tag{19}$$

and the average waiting time is reduced to $[E_i(w) - TS(S_i)]$. The average number of vehicles at the repair shop idle because part i failed can be reduced to

$$E_i(n) = \sum_{s_i=1}^{S_i-1} s_i P(s_i) - S_i[1 - P(s_i < S_i)] \tag{20}$$

The benefits gained from providing an additional spare unit decrease with the increasing number of spare units already on hand. If we have $(s_i - 1)$ spare units for part i, then the time that can be saved by providing an additional unit is

$$\begin{aligned} \Delta TS(s_i) &= TS(s_i) - TS(s_i - 1) \\ &= s_i \mu_i P(s_i - 1) \end{aligned} \tag{21}$$

The time decreases with an increase in s_i.

If the capital cost for one spare unit of the i th part is C_i and the expected life mileage is $E_i(m)$, then the optimal $\hat{S}_i$ is such that

$$\text{Opt. } C_i = \underset{S_i}{\text{Min}} \, [E_i(m) \times B_i \times \Delta TS(S_i)] \tag{22}$$

The flow chart of the model is shown in Figure 1.

PROBLEMS CONCERNING RELAXATION OF ASSUMPTIONS

Operation With Many Vehicle Types

It is assumed in the model that bus companies operate with only one type of vehicle, but in the real world a bus company would operate with a variety of vehicles. This fact affects almost every aspect of maintenance procedure.

First of all, daily operating mileages are different for each type of vehicle. One of the reasons is that some models are more suitable to serve some specific area or route to meet various passenger capacities. Table 1 gives the mileage variation on different models.

Next, one might argue that there may be different optimal inspection mileages for the various models, but this causes some complications from the viewpoint of management. Except for a few extreme cases, all models are inspected at the same mileage.

From the nature of the Poisson distribution, the distribution of the sum over several Poisson-distributed random variables is still Poisson. If the number of vehicles due for inspection for each model is Poisson-distributed, then the total number of vehicles due for each type of inspection is also Poisson-distributed. The average time needed to get through each inspection is almost the same, without significant differences for each model. Therefore the analysis discussed in a previous section still holds.

More complications arise, however, in the repair shop. It is not unusual to find that parts (e.g., the engine) are not interchangeable among the various models. Time to replace and time to repair are also different for some models. For most parts the time required to replace or to repair varies from case to case, but it is independent of the model.

Another problem that arises is the provision of spare units. The inability to change parts from one model to another requires the provision of spare units for each model. To solve this problem, parts from different models can be treated as different parts. The total number of parts in the system would therefore increase sharply, although the methodology would remain the same.

Assignment Discipline

The assignment discipline might be different from one company to another, and depends on the maintenance capacity, the maintenance system, and the management viewpoint of each company. For instance, a company might not run overtime for inspection at night. Those buses that were assigned for inspection but could not get through are left to be finished the next day. The assigned number for the next day is consequently

Figure 1. Vehicle flow of model.

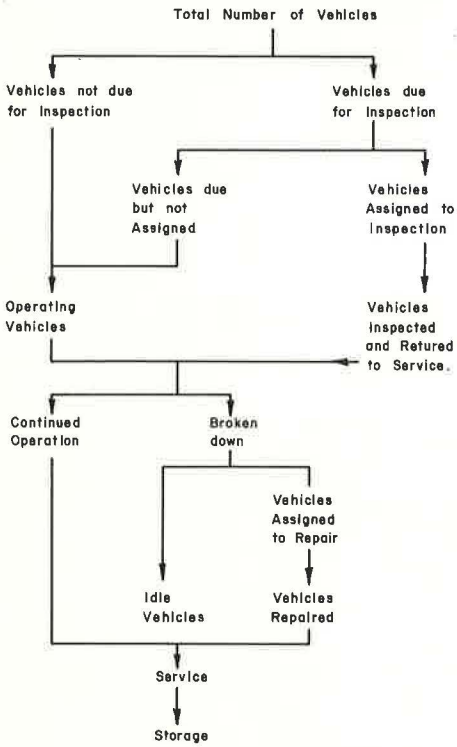


Table 1. Average monthly mileage for DMT (July 1972).

Vehicle Model	Mileage per Month (miles)
Stickshift, GMC 47	1,560
GMC 51	1,704
MACK 45	1,758
GMC 45	2,810
GMC 53	2,988
FLEX 53	2,894

Table 2. Proposed daily inspection assignment rate.

Type of Inspection	Assigned Vehicles per Day					Total per Week
	Mon.	Tues.	Wed.	Thurs.	Fri.	
A	5	5	6	6	4	26
B	6	6	5	5	4	26
C and D	9	9	11	11	12	52

reduced. If the distribution of the service rate P(n) is Poisson-distributed then the assignment rate becomes a truncated Poisson distribution with

$$P'(n) = P(n) \quad n = 1, 2, \ldots, N - 1$$
$$P'(N) = 1 - P(i) \tag{23}$$

where

N = predetermined assignment rate,
P(n) = distribution of service rate, and
P′(n) = distribution of actual assignment rate.

There is no analytical solution for such a problem thus far, but by the use of a random number generator, the problem can be analyzed through computer simulation.

Significant Removal and Installation Time for Vehicle Parts

In most cases, the time required to replace the part was less than the time required to repair it. This is the assumption made in the analysis. Logically, to what extent can one argue (a) that the time needed to replace the part is negligible and (b) what to do if it is significant? It was found that if the time needed to replace parts is negligible, then the analysis is independent of the number of service channels. If, however, time is significant, then the number of service channels plays a central role in the analysis.

Usually the service channels in the repair shop can be classified as hoists, pits, and stalls, which are suitable to serve some specific parts. If the number of one of these channels is greater than or equal to the number of parts that needed this type of channel to replace it, then the analysis described previously is still applicable. If the number of channels is less than the number of parts (after the parts are removed), the vehicles can be withdrawn from the channels and thus leave channels ready to serve other vehicles; the analysis is still applicable. The problem occurs when the number of channels is less than the number of vehicles needing service, and the vehicle being served has to remain in the channel until a repaired unit is installed. The analysis then would not hold.

Preventive Maintenance

In the previous model, the time required for preventive maintenance of all parts is included in the inspection time. It is noted, however, that maintenance of some parts takes longer time periods and sometimes needs special facilities. Therefore, the maintenance of these parts is not performed at the inspection shop but at the repair shop.

Suppose for part i, the time required for maintenance is Erlang-distributed with mean q_i and Erlang constant ℓ_i'. If the maintenance mileage is I_i, the arrival rate VI_i for preventive maintenance is

$$VI_i = VM_i[1 - F_i(I_i + M_k)] \tag{10}$$

The distribution of arrivals can be tested to determine whether it is Poisson if the number of vehicles is large.

The repair rate μ_i and the preventive maintenance rate q_i can be the same or different depending on the nature of the part and on the Erlang constants ℓ_i and ℓ_i'. If $u_i = q_i$ and $\ell_i = \ell_i'$, the arrival rate for repair B_i and preventive maintenance rate VI_i can be combined into

$$B_i + VI_i = VM_i \tag{24}$$

This new arrival is still Poisson-distributed. If $\mu_i \neq q_i$ or $\ell_i' \neq \ell_i'$, then one should treat them as two different sources for the repair queue system but use the same spare units.

CASE STUDY—DENVER METRO TRANSIT COMPANY

General Description

The general philosophy of DMT is to provide a second car for a family, to improve service, and to increase ridership. The facility was originally designed for motor coaches by the Tramway Company in 1956, which was privately owned and operated. It was purchased in April of 1971 by the City and County of Denver and renamed the Denver Metro Transit Company.

DMT operates with 9 different types of models for a total of 250 vehicles. The peak-hour morning run requires 234 vehicles, and the peak-hour afternoon run requires 235 vehicles. This leaves 15 vehicles in reserve for inspection, repair, and overhaul.

Routine Maintenance

DMT requires four types of inspections (A, B, C, and D) for its vehicles. The A inspection requires 30 to 45 min and four crew members. It consists of a brake adjustment and visual inspection of parts. The B inspection requires 1 to $1\frac{1}{2}$ hours and two crew members. It consists of a brake adjustment, lubrication, visual inspection of parts, oil and filter change, battery hydrometer check, stall test on the engine and transmission, voltage regulator volt test, and a check of the oil-cooled alternators. The C and D inspections require 10 min each and consist of a brake adjustment and rapid visual inspection. Inspections are required at 1,500-mile intervals: C at 1,500 miles, A at 3,000 miles, D at 4,500 miles, and B at 6,000 miles. Before inspection, the engine is washed a day or two in advance so that oil leaks may be checked for on inspection. Table 2 shows the proposed inspection assignment rate.

Overhauls are assigned according to compression ratings and oil consumption. If the inspection area falls short of work, the inspectors report oil consumption and highest mileages, and these vehicles are inspected. If work due to breakdowns and accidents offsets inspections, those vehicles scheduled for inspection are scheduled for split shifts and the shortest runs, so that they can be pulled in during the middle of the day for inspection and be returned to service by the afternoon run. The inspections are made so that most of the vehicles can be on the road; shortest repairs are done first, and these vehicles are back on the road first.

DMT provides three maintenance channels for inspections. There are two short pits and one long pit at these channel locations. These channels will permit four vehicles to be inspected at one time.

The inspection vehicles are selected on the basis of mileage. They are scheduled two days in advance. The inspection rate for July, August, and September of 1972 gives a general feel for system operation (Table 3). The actual arrival rate for inspection for July is given in Table 4 as a comparison.

Analysis of Inspection Queue

The model is constructed so that all rates, such as arrival rate and service rate, are measured with the unit of number of vehicles per day. It is further assumed that vehicles assigned can get through inspection by the next morning because there is a night shift crew provided in the DMT maintenance shop. (The service discipline of concern is how vehicles get assigned rather than how vehicles get inspected.)

In principle there exists a fixed and predetermined assignment rate. If the number of vehicles ready for inspection on a specific day exceeds this assignment rate, only a number equal to the assignment rate will be inspected on that day. The rest are left for the next day. On the other hand, if the number ready for inspection is less than the assignment rate, the inspected number on that specific day will be equal to the arriving number. In practice, however, the assignment rate is more flexible. From the experiences of DMT, one can see that the inspected number sometimes exceeds the assignment rate. In other words, the assignment is somewhat random, and no explicit decision rule is followed. In Figure 2, the number of daily inspected vehicles at DMT is fit to the inverse Erlang distribution. Several simulations were run on the computer so that differences between fixed and random assignment rates could be compared.

Table 3. Inspection rate.

Type of Inspection	July					August					September				
	Mon.	Tues.	Wed.	Thurs.	Fri.	Mon.	Tues.	Wed.	Thurs.	Fri.	Mon.	Tues.	Wed.	Thurs.	Fri.
A	5	—	5	5	5		5	5	6	4					4
B	5		5	4	5		6	4	5	4					4
C and D	10		8	11	9		13	10	11	9					8
A	5	5	5	5	5	5	5	6	6	4	—	5	6	7	5
B	5	5	5	5	5	6	6	5	5	4		6	5	4	4
C and D	10	11	10	9	8	11	12	10	11	8		11	9	10	10
A	5	5	6	5	5	4	6	6	6	4	5	5	5	4	5
B	5	5	5	6	5	6	6	5	5	4	5	7	5	5	4
C and D	12	12	11	11	9	11	11	11	11	8	9	4	9	11	10
A	5	5	6	6	5	5	6	5	6	4	5	5	6	6	4
B	4	6	5	5	5	5	6	5	5	4	6	6	5	5	4
C and D	9	9	9	10	8	11	11	11	11	7	11	10	11	10	8
A	3					5	4	7	5		4	7	6	6	4
B	6					6	6	5	5		6	6	5	5	4
C and D	12					12	11	10	9		11	11	9	10	8

[a]Independence Day. [b]Labor Day.

Table 4. Actual arrival rate.

Type of Inspection	Sun.	Mon.	Tues.	Wed.	Thurs.	Fri.	Sat.	Sun.	Mon.	Tues.	Wed.	Thurs.	Fri.	Sat.
A	0	2	7	1	9	1	2	1	2	2	4	0	7	7
B	1	0	4	5	4	3	4	2	3	2	5	5	2	4
C and D	2	2	8	3	9	2	14	2	1	9	8	7	11	10
A	1	0	8	11	4	6	2	2	0	3	5	2	4	5
B	2	1	2	7	6	5	2	0	2	4	5	2	4	4
C and D	5	3	11	7	11	9	8	4	1	9	4	7	9	10
A	1	2	1											
B	2	1	4											
C and D	3	1	7											

Note: From July 1972 operations of DMT.

Figure 2. Distribution of inspection rate.

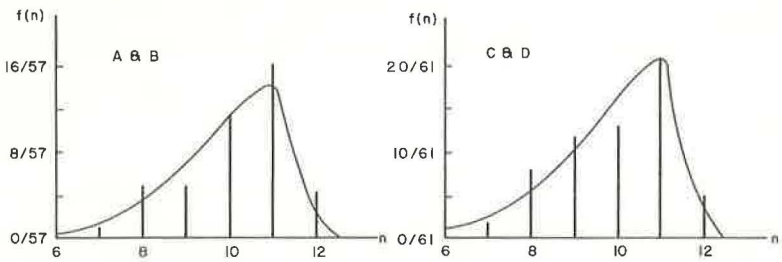


Figure 3 shows the observed data for inspections C and D at DMT from July to September 1972. The curves are from simulation based on the assumptions of Poisson arrivals and constant assignment rate. Because the arrival rate data fits Poisson distribution well (Fig. 4) and the assignment rate is basically constant, they are used in the following analysis. Input data for the inspection queue are

1. Number of vehicles—250;
2. Average daily operating mileage—89.9 miles per day per vehicle;
3. Inspection period—every 6,000 miles for all types of inspection;
4. Assignment—constant with rate 5.20 per day;
5. Assignment discipline—first arrive, first assigned; and
6. Inspection rate—exponentially distributed with the following means: $\eta_A = 40$ min, $\eta_B = 75$ min, $\eta_C = \eta_D = 10$ min.

By applying these data to the model, the following results:

1. Arrival rate—4.25 per day;
2. Average waiting time—0.25 days; and
3. Average additional operating mileage—19.33 miles per day per vehicle.

Both the number of buses and average daily operating mileage are beyond control of the maintenance shop, and the rest of the factors are determined either by the facility capacity or by the maintenance policies. The resulting average additional operating mileage is what we are most concerned with, because it has a direct effect on the broken-down rate. We have to increase the assignment rate, i.e., to speed up the actual inspection rate to reduce the additional operating mileage. Another alternative to reduce this mileage is to prolong the inspection period. However, this will increase the broken-down rate sharply. These relationships are shown in Figures 5, 6, and 7.

Repair Shop

The input for the repair shop is determined by the pull-ins and road calls. Road calls are received, and it is determined at this time whether or not it is necessary to send a replacement vehicle or a repair vehicle to the scene. DMT has three pick-ups and one tow truck to answer these road calls; three of the four vehicles are radio equipped for easier dispersion to disabled buses. Not more than 5 min in route time is lost before a repair vehicle meets the bus on route for a road call. The repair vehicles meet the buses along their scheduled runs so that service is never disrupted. A completely stopped bus requires a replacement; therefore within 20 min after the call, a replacement is at the scene to complete the run of the disabled vehicle. A bus will continue in service as long as it is operating properly with no danger to the passengers or operator.

A pull-in is taken to the repair shop and checked. There are six lanes with no hoists or pits. If a major repair is indicated, the bus is taken to the overhaul or body shop for repair. The repair shop has a crew that is taken from the inspection area as needed.

Repair Shop Analysis

Currently, DMT operates nine different types of buses; this fact makes the problem of repair and maintenance much more complex and the analysis more difficult. Differences between the various types of buses are ignored here so that more insight into the mechanism of the repair shop may be obtained. A computer simulation should be used to accommodate the problem of operating with many vehicle types.

There are 29 major parts listed in the file of the DMT repair shop. Although a maintenance mileage is suggested for each part, no preventive maintenance is carried out at the present time. From the DMT repair records, a life-mileage curve, according to the vehicle type, is fitted for each part without further breakdown. Some examples are shown in Figure 8. The detailed data, including the life-mileage curve, time required for replacement and repair, number of square units, and maintenance mileages suggested by DMT, are given in Table 5. Among these 29 parts, four parts that occupy the repair shop for the longest period of time were chosen for detailed analysis. These four parts are the engine, the transmission, the transmission governor, and the cylinder head.

Figure 3. Observed and theoretical inspection rate.

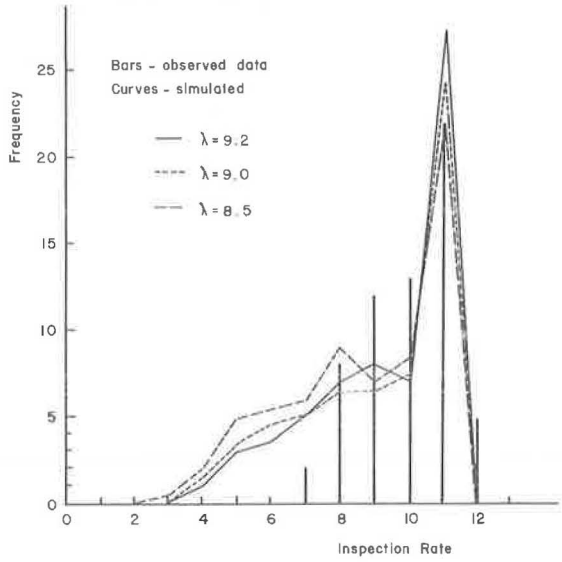


Figure 4. Distribution of arrival rate.

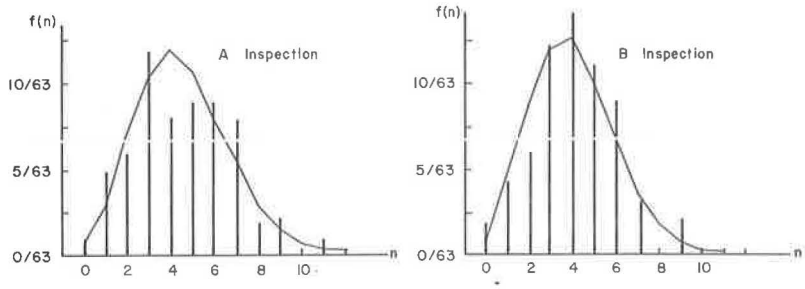


Figure 5. Effect of assignment rate on additional operating mileage.

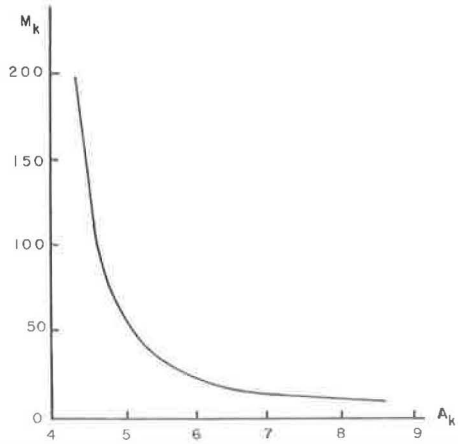


Figure 6. Effect of inspection period on broken-down rate.

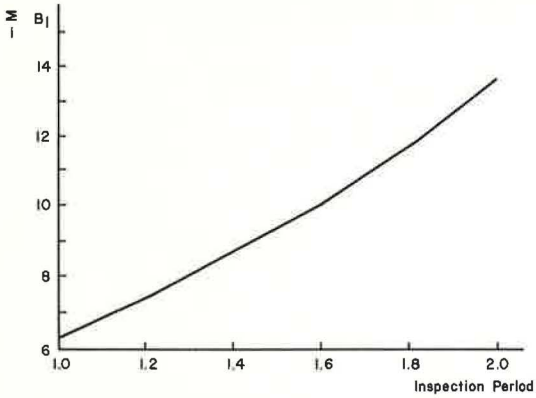


Figure 7. Effect of inspection period on additional operating time.

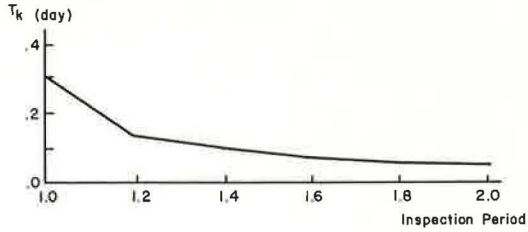


Figure 8. Cumulative distribution of life mileage (10^4 miles for transmission, engine, and cylinder head; 10^3 miles for transmission governor).

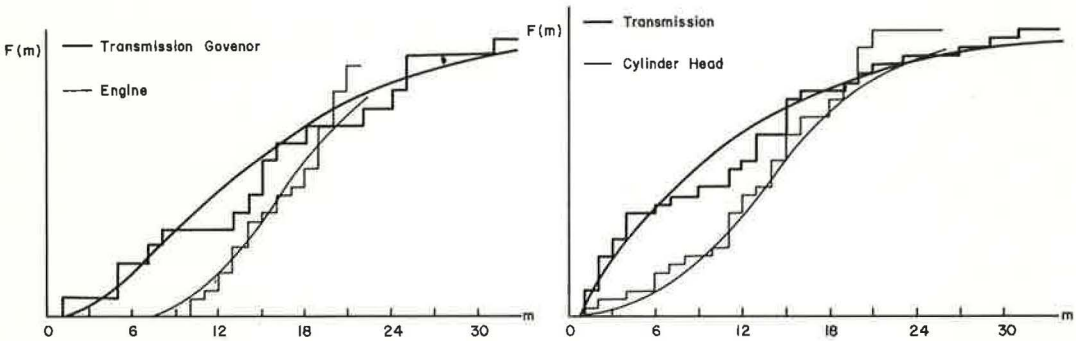


Table 5. Major part characteristics.

Parts	Life Mileage: Erlang Constant	Life Mileage: Expected	Proposed Maintenance Period	Time (hours): Remove	Time (hours): Repair
Engine	10	180,000	—[b]	8	192.5
Transmission	1	105,000	200,000	8	32
Trans. gov.	2	16,000	36,000	12.5	32
Starter	1	60,000	150,000	2.4	1
Generator	6	140,000	125,000	1	1.5
N/S solonoid	—[a]	—[a]	—[a]	1	1
Compressor	2	70,000	150,000	1.5	5
Comp. gov.	3	75,000	125,000	0.5	0.5
Comp. lub. valve	—[a]	—[a]	—[a]	0.5	1
Shutter stat.	1	40,000	78,000	0.5	1
Shutter cylinder	3	90,000	125,000	2	1
Injectors	1	60,000	—[b]	—[a]	—[a]
Clutch cylinder	2	36,000	155,000	0.5	0.25
Throttle cylinder	—[a]	—[a]	—[a]	0.5	0.5
Water pump	3	45,000	125,000	0.5	2.5
Alarmstat.	6	32,000	78,000	0.5	—[c]
Fuel pump	6	140,000	—[b]	1	0.5
Cylinder head	6	140,000	—[b]	7	4.5
Blower	6	140,000	—[b]	3	11
Eng. gov.	2	120,000	—[b]	2	1.5
Clutch mag. valve	—[a]	—[a]	—[a]	0.5	1
Eng. thermo.	—[a]	—[a]	—[a]	1	0.5
Throttle lip	—[a]	—[a]	—[a]	0.1	0.5
Radiator	1	90,000	—[a]	4	8

[a]Not available. [b]Overhaul. [c]Disposable.

At the DMT repair shop, including the overhaul shop, there are four pits, four hoists, and numerous stalls. Because the number of channels of each type is greater than the number of parts needing this specific type channel and also because each of these four parts goes to four different mechanics for repair, the analysis from the previous section can be applied here.

Another interesting aspect is that the time required for repair is the same for either the broken-down vehicle or the vehicle that comes in for preventive maintenance. Therefore, the actual arrival rate at the repair shop is the sum of these two cases. VM_i, the average arrival number at the repair shop, and B_i, the average number of broken-down vehicles due to failure of part i, were shown previously in Eqs. 9 and 10. Both of these rates are the function of the maintenance mileage, I_i. The broken-down rate is a monotonic increasing function of I_i, and the arrival rate, including the broken-down vehicle and vehicles for preventive maintenance, is a convex function of I_i. They are shown in Figures 9 and 10. It was observed that the optimal maintenance mileage for the lowest arrival rate occurs at from 70 to 110 percent of the expected life mileage. However, a minimum arrival rate could probably mean a high broken-down rate because the broken-down rate curves are monotonically increasing. For example, the arrival rate due to failure of the cylinder head reaches minimum at 70 percent of the expected life mileage, and the broken-down rate at this mileage is 0.35, which is much higher if compared to 0.08 of the transmission. Therefore the optimal maintenance mileage should be located at some time when the broken-down rate is thought to be tolerable.

The optimal number of spare units that should be provided for each part is also a management decision. Five parts are chosen to test the effects of the spare number provided. It is observed that the decreasing rate of the number of idle vehicles depends on the value of α, the ratio of arriving rate to the service rate of $\ell\mu$. For the engine, the radiator, and the compressor (they all have small values of α), the effect of providing one spare unit is significant. Both the transmission and the transmission governor have high values of α; the effect of the provision of one spare unit is not as dramatic. The efficiency of the provision of n spare units can be defined as one minus the ratio of the number of idle buses if n spare units are provided to that if no spare units are provided at all. The results are shown in Figure 11.

With further analysis, one can extract more information from Figure 12. If the service rate is increased, which reduces the value of α, greater benefits can be achieved by providing the same number of spare units.

SUMMARY AND CONCLUSIONS

The main purpose of this study was to provide an analytical basis for a bus maintenance shop. The bus maintenance procedure is primarily based on the mileages of the buses and the life mileages of major parts on each bus. This procedure becomes complicated as the variety of bus types increases and when the number of parts taken into consideration grows. To make the formal analysis possible, a generalized model was constructed. This model consisted of submodels of the inspection shop and the repair shop and a cost minimization submodel. The cost optimization model was not presented because no data were available to validate and demonstrate it. The validity of others was established through the comparison between observed data and that produced by the model. Information made available by DMT was used as the observed data base.

Queuing theory plays a key role in the analysis of the inspection shop and the repair shop. The inspection shop is treated as many single queues with a Poisson arrival rate and constant service, or assignment, rate. The inspection period had the most sensitive effect on the breakdown rate of parts that are inspected on a routine basis. The repair shop had many single channel queues with Poisson-distributed input and Erlang-distributed service time. There is more variety to the input into the repair shop than in the inspection shop, and it contains different channel types. Some spare units for each part are also provided in the repair shop. The relationship among these various factors is examined, and it was found that most of the characteristics of each part were determined by curve fitting to the life-mileage curve, which can be determined by curve fitting to the actual data.

Figure 9. Maintenance mileage related to broken-down rate.

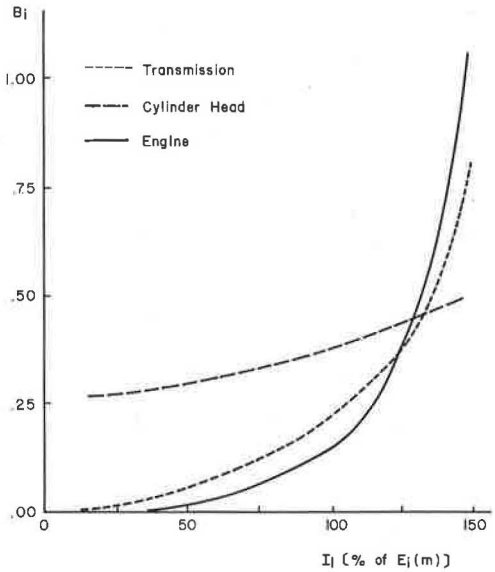


Figure 10. Maintenance mileage related to arrival rate.

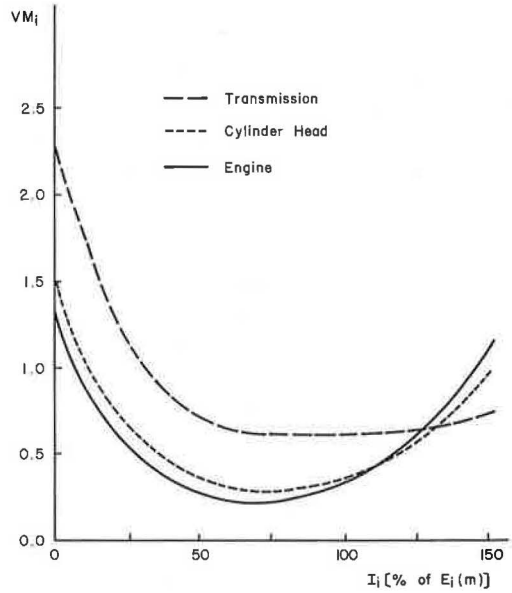


Figure 11. Efficiency of providing spare units (TG = transmission governor, T = transmission, C = compressor, R = radiator, and E = engine).

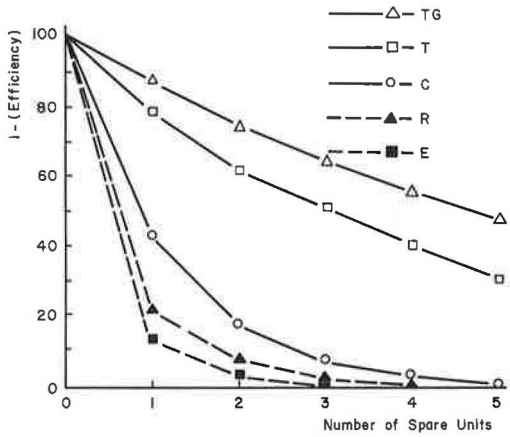
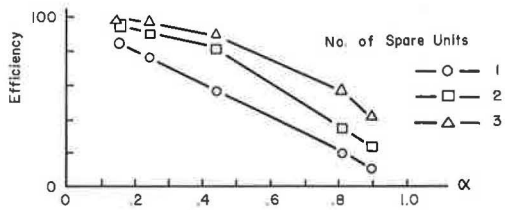


Figure 12. Effect of value of α on efficiency (compressor).



Although the model is quite simple, it provides much insight into the problems and complexities of a maintenance shop. If a computer simulation were applied, the model could be modified to become even more realistic.

ACKNOWLEDGMENT

The research presented in this paper is part of a project sponsored by the Urban Mass Transportation Administration. The results and views expressed are those of the authors and not necessarily those of the sponsoring agency. The assistance of Sharon Tomich in the data collection and preliminary analysis is gratefully acknowledged.

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