bus stops. The first bus stop (bus stop number 43) is a timed bus stop, which makes it possible to record the exact departure time of buses from this bus stop.

Observations were carried out during morning peak periods (7:30-9:00 a.m.) to consider bus waiting times at each bus stop and bus travel times between each two successive bus stops. Three different observations were carried out for each bus departure time from the first bus stop on different weekdays. Subsequent simulation results were obtained from the model under the same conditions as were observed, and the results were compared with observed data in Tables 1-4.

This comparison shows that the observed and simulated data are quite close to each other and that the model is adequate to represent their vehicle behaviors according to the purpose of the study.

The model is able to predict the effects on all vehicles of bus-priority measures at intersections. In addition to the usual form of bus-priority measures at traffic-signal-controlled intersections, the model also has the ability to predict the effects of bus-priority measures at priority junctions. Figure 2 shows the simulated variation of average delay to buses and other vehicles at a priority junction when the priority bus lane terminated 20 m from the "give way" line. The mean gap accepted was input as 5 s for left-turning vehicles and 6 s for right-turning vehicles. Equal flows were assumed in both directions on the major road and the simulation was carried out with 30, 50, and 70 percent of left-turning vehicles (left-hand rule of the road).

A section of bus route 1 along the ring road was selected for study in order to assess the usefulness of the program in estimating the effect of a bus-only lane on bus and passenger travel times. The part of the route chosen was located between bus stops 46 and 53 (as shown in Figure 3). It had a length of approximately 2 km and included three signalized intersections and eight bus stops. A curb-side bus-priority scheme was introduced along this section of the ring road. The priority lane terminated 40 m from the signal stop lines.

Reductions in bus-passenger journey times between bus stops 46 and 53 due to the introduction of the priority scheme for the three cases of 30, 60, and 90 buses/h in each direction are shown in Figure 4. Frequently when bus-priority schemes are introduced travel time is increased for nonbus vehicles. Figure 5 shows the increase in delay at the three signalized intersections along the priority route after the introduction of the bus-priority scheme.

We believe that the model has demonstrated its ability to simulate the effects of bus-priority schemes on travel time and delay. We intend to continue the work and evaluate future priority schemes.

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Evaluation of Active Bus-Priority Signals

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This paper describes the development and application of a methodology for the evaluation of an active bus-priority signal system. Results from a demonstration project show the impact of a bus-priority scheme on intersection delay and delay variability. Two new measures, perceived delay and budgeted delay, are introduced and are shown to have important implications in the evaluation of bus priority and other transportation system management schemes. We conclude that active bus priority is justified under a wider range of conditions than has hitherto been considered to be the case.

In recent years, a number of interrelated factors have combined forces to change the direction and emphasis of transportation planning. The days of seemingly unlimited expansion of the transportation system are gone. In its place are the tasks of maintenance and management of the existing transportation system. Although some may consider that these tasks are not as exciting as the previous growth phase, they are nevertheless equally, or perhaps more, demanding of initiative and intellectual effort.

The factors that have brought about this change are basically fourfold:

1. The increasing awareness of the magnitude of private transportation as a consumer of liquid fossil fuels,
2. The role of transport vehicles as mobile pollution sources,
3. The economic recession that affected most Western countries in the first half of this decade and has caused spiralling inflation rates and increasing unemployment to be the dominant domestic concerns of many governments, and
4. The emergence of citizen participation as a feasible and necessary planning technique.

For these reasons, and possibly others, this reversal in planning directions has taken place. One important consequence has been the emergence of transportation system management (TSM) as a planning philosophy in its own right. As described by Patricelli (1), TSM is "preeminently a process for planning and operating" whose key objective is the conservation "of fiscal resources, of energy, of environmental quality, and of the urban quality of life".

TSM has been defined to include a large number of project types; however, one category of particular interest is the use of traffic management techniques to give priority to high-occupancy vehicles (HOV). The types of priority technique may include the reservation of lanes on freeways or arterial roads, the granting of priority access at freeway on-ramps, or the granting of priority, by one means or another, at signalized intersections. This paper will concentrate on the final category and, in fact, will consider only one particular type of intersection priority. However, many of the issues raised could be applied equally well to other priority techniques.

BUS-PRIORITY SIGNAL SYSTEMS

Two essentially different techniques are available to grant priority to buses at traffic signals. These techniques may be classified as passive or active detection and granting of priority. Passive priority systems are characterized by the fact that the flow of buses need not be recorded at a particular instant in order to grant priority. Rather, the intensity of bus movements (or, more generally, HOV movements) is deduced from long-term measurements of traffic flows. These traffic flows, when expressed in terms of person movements, then form the basis of signal design.

The essence of active priority systems is that the passage of an individual bus is detected and priority is awarded to the bus as a result of this detection. Such detection may be accomplished by means of an ordinary loop detector if the bus is in a special bus right-of-way (such as a bus-only lane or a bus street) or by means of a unique transponder-interrogator communication link if the bus is moving in mixed traffic. Once the passage of a bus has been detected, priority treatment can be given in several different ways.

The two principal methods of active bus priority are phase extension and recall. If a bus arrives at a detector on the approach to a signalized intersection and that approach is currently being shown a green signal, by the time the bus reaches the stop line the signal may have changed to red. In such a situation, it would be desirable to extend the green period by a small amount of time to enable the bus to pass through the intersection in that phase. The effect of this phase extension is to reduce the bus delay from that of the total red time on that approach to no delay. This type of priority treatment also has negligible effects on other road users.

When a bus arrives at an approach detector and that approach is being shown a red signal, a different strategy is employed. In this case the bus phase may be restarted earlier than normal in one of two ways. The hurry-call strategy involves giving minimum time to all other demanded phases in sequence, starting with the phase currently being served. The skip-phase strategy involves giving minimum time to the phase currently being served and then skipping directly to the bus phase. This obviously results in lower delays for the bus than would be the case with the hurry-call strategy (except, of course, when there are only two phases per cycle, in which case the two strategies are equivalent). The minimum time for each phase is taken as equal to the minimum green time of each phase, providing, of course, that pedestrians are also given adequate clearance time.

After the award of a bus-priority phase, control may then be returned in one of three ways:

1. Control may always be returned to a particular phase if, for example, for safety reasons one particular phase must always follow the bus phase;
2. Control may be returned to the phase that was interrupted; or
3. Control may be returned to the first skipped phase.

The choice of strategy after awarding priority will, in most cases, depend on the circumstances that prevail at the particular intersection in question.

Irrespective of which phase control is returned to, it may be desirable, especially in peak periods, to compensate the nonbus phases for time lost while awarding priority to the bus phase. This may be done by adding the time lost by each phase to the maximum green time in the next cycle. However, if another bus arrives in this cycle and is awarded priority, then the nonbus phases will again lose time, which will have to be added on in the next cycle. If this is allowed to continue, then the nonbus phases will simply accumulate a large amount of green time that is never repaid. Hence, effective compensation involves not only the repayment of lost green time but also the refusal of priority demands for buses that arrive in the next cycle following the award of a priority phase. In this way, the original green time balance is preserved over a period of two cycles.

The above description of bus-priority signal systems is necessarily brief and serves only to place in context the priority scheme that is the subject of evaluation in this paper.

BELL STREET DEMONSTRATION PROJECT

In November 1977, the Road Safety and Traffic Authority, in conjunction with the Melbourne Metropolitan Tramways Board (MMTB), installed the first active bus-priority system at traffic signals in Victoria, Australia, at the intersection of Bell Street and Oriel Road in Heidelberg.

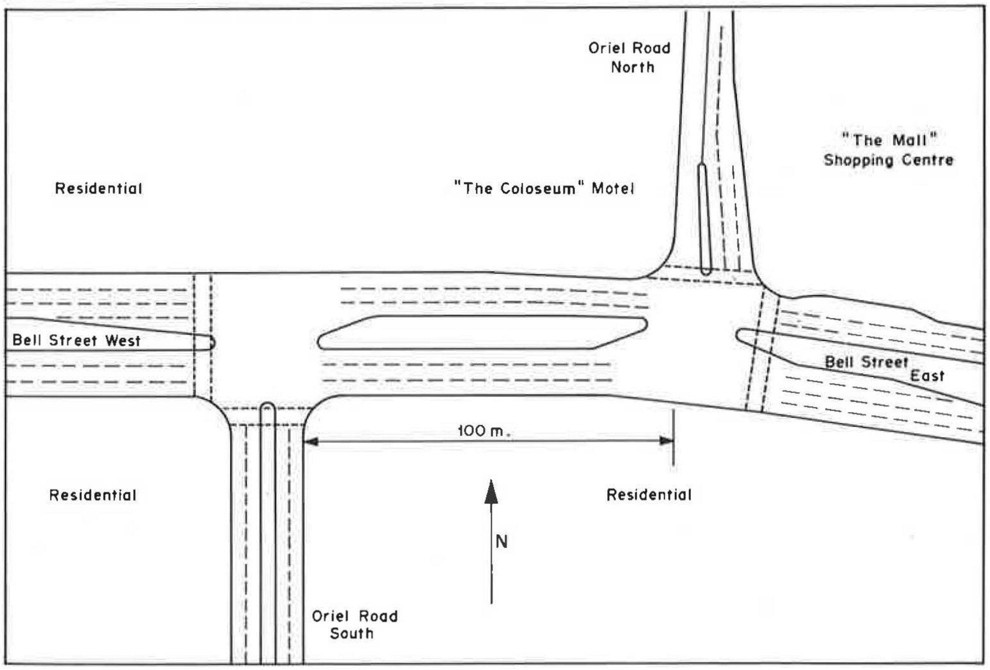
The intersection is located approximately 11 km northeast of the Melbourne central business district (CBD), in a predominantly residential area. Bell Street is an important east-west circumferential route that links residential and industrial areas and is the most important nonradial arterial route in this part of Melbourne. Oriel Road is a comparatively minor north-south subarterial route, so far as general traffic is concerned, but it carries a substantial flow of buses. The intersection is of a staggered twin-tee configuration, as shown in Figure 1. (Note that traffic in Australia drives on the left-hand side of the road.) The intersection was originally controlled by stop signs on Oriel Road, which caused considerable delays to buses on Oriel Road. As a result of these delays, the decision was made to install traffic signals at the intersection and, subsequently, to install bus-priority signals on a demonstration project basis. Monash University was engaged to develop and apply an evaluation methodology to assess the impact of the priority signals (2).

Following operation of the signals in a conventional, nonpriority manner for approximately two months, bus priority VETAG equipment was installed. The VETAG system is composed of

1. A vehicle-borne semipassive transponder,
2. A loop antenna buried in the road surface, and
3. An interrogator, which is connected to the loop.

Low-power interrogation signals are constantly radiated through the loop by the interrogator. As a bus passes over a loop on either approach in Oriel Road, the transponder is activated by the interrogation signals

Figure 1. Bell Street-Oriel Road site details.



and transmits a vehicle identification code to the interrogator via the loop detector. This code is then decoded by the decoder and, if valid, is passed to the intersection controller as a priority demand.

The response of the controller to a priority demand is one of extension or skip-phase recall, as described earlier. Extension of the phase is granted by allowing a set time interval after detection to enable the bus to cross the stop line. Compliance with this minimum set time interval may necessitate exceeding the maximum green time. The time interval is adjustable and is currently set at 10 s, in accordance with the distance from the stop line to the bus detector. Compensation is provided to Bell Street through traffic by means of two-cycle balancing of green time allocation, as described earlier.

EFFECT ON TRAVEL TIME AND TRAVEL TIME VARIABILITY

The impacts of bus-priority schemes on travel time (or delay) and travel time variability have traditionally been the factors considered in most detail. The present study also considered a number of other factors; however, the results for travel time and travel time variability are presented here because these factors continue to be important evaluation factors. Also, the results offer some point of comparison with previous studies. The method of using these factors is radically different in this study and deserves consideration in itself, free from the extraneous influence of other factors.

The objectives of this evaluation are twofold: (a) to ensure that buses do, in fact, obtain a significant advantage after installation of the signals and (b) to ensure that the net benefit after installation of the priority signals is, in view of the limited scope for mode switching, nonnegative.

Bus Delay Changes

Data for the calculation of bus delays were obtained by means of a travel time survey in which the time at which a bus passed a point upstream and downstream of the intersection was recorded (among other things). After allowing for synchronization errors, a comparison of these two times revealed the travel time for that particular bus to pass through the intersection. Subtraction of a free travel time gave an estimate of the delay incurred by that bus. The mean and standard deviation of delay were then calculated for each survey period. The number of buses in each period and the average passenger occupancy were also calculated from recorded information.

Table 1 shows the results obtained from surveys conducted on two days in December 1977: one when the priority signals on Oriel Road were switched on and one when the conventional signals were switched on. The passenger flow is given in terms of the number of buses multiplied by the average bus occupancy during that period. The results are given for two bus groups; the MMTB buses, which were fitted with transponders, and buses from the Ivanhoe Bus Company, which also ran along Oriel Road but were not fitted with transponders and hence acted as a control group.

Several features of the table deserve comment. First, note that the average bus occupancy levels are very low. At most, they correspond to a 25 percent load factor. This is consistent, however, with the position of the intersection, close to the outer extremities of the bus routes that pass through the intersection. These low bus-loading figures make it difficult, on the basis of net benefit, to justify bus-priority measures at such an intersection. Second, the introduction of the priority signals appears to have the desired effect of reducing both mean delay and standard deviation of delay for transponder-equipped buses. On the other hand, the effect on nonpriority buses appears rather variable.

More complete statistical testing of the changes in means and variances confirms this initial impression. Four out of the 12 priority bus flows experienced significant reductions in variance of delay at the 5 percent level, but none of the nonpriority bus flows experienced such reductions. Similarly, 4 out of 12

Table 1. Bus flow summary.

			Without Priority			With Priority				
Time Period	Bus Flow	Direction	Passenger Flow	Average Delay (s)	Standard Deviation (s)	Passenger Flow	Average Delay (s)	Standard Deviation (s)	Variance Reduction (%)	Mean Reduction (%)
7:15-8:15 a.m.	MMTB	Northbound	13 × 6.5	52.38	27.37	12 × 5.8	30.42	10.98	5[a]	5[a]
		Southbound	19 × 9.3	68.74	36.48	18 × 10.6	31.89	28.56	5	5[a]
	Ivanhoe	Northbound	4 × 8.1	37.25	37.70	4 × 7.5	50.50	29.72	5	50
		Southbound	5 × 7.8	91.60	9.69	5 × 12.3	38.40	35.60	5	5[a]
8:15-9:15 a.m.	MMTB	Northbound	12 × 8.1	41.25	22.97	11 × 7.3	31.45	17.55	5	50[a]
		Southbound	10 × 14.5	56.30	24.16	8 × 16.5	39.88	25.32	5	20[a]
	Ivanhoe	Northbound	4 × 7.8	37.75	15.63	4 × 4.7	30.25	27.68	5	50
		Southbound	3 × 9.0	45.33	13.61	1 × 3.0	22.00	-	-	50[a]
11:00 a.m.-12:00 n.	MMTB	Northbound	9 × 11.2	46.67	33.94	8 × 10.4	35.38	19.14	5	50[a]
		Southbound	8 × 10.0	44.13	29.24	8 × 9.4	22.00	9.80	5[a]	10[a]
	Ivanhoe	Northbound	3 × 4.3	58.67	40.87	3 × 6.7	40.00	16.52	5	50
		Southbound	3 × 5.5	36.67	27.93	3 × 3.5	28.33	32.81	5	50
1:30-2:30 p.m.	MMTB	Northbound	8 × 9.1	62.13	17.88	8 × 9.6	31.75	15.23	5	5[a]
		Southbound	8 × 7.6	35.50	18.80	8 × 7.9	24.50	13.47	5	20[a]
	Ivanhoe	Northbound	3 × 5.3	49.67	29.40	4 × 1.7	58.25	26.83	5	50
		Southbound	3 × 2.7	43.67	22.03	3 × 1.8	35.33	31.88	5	50
3.15-4.45 p.m.	MMTB	Northbound	11 × 11.6	79.55	26.49	10 × 9.1	50.20	22.77	5	5[a]
		Southbound	10 × 7.9	39.30	34.27	10 × 11.5	24.00	9.68	5[a]	20[a]
	Ivanhoe	Northbound	5 × 4.9	103.60	43.41	4 × 5.1	47.20	24.48	5	10[a]
		Southbound	4 × 9.7	10.50	12.45	5 × 2.9	38.50	34.46	5	50
4:45-5:45 p.m.	MMTB	Northbound	15 × 11.2	111.47	117.86	19 × 12.4	64.32	40.47	5[a]	20[a]
		Southbound	9 × 10.0	25.33	26.60	11 × 8.9	26.36	18.91	5	50
	Ivanhoe	Northbound	4 × 5.9	82.00	44.23	4 × 5.7	59.00	40.92	5	50
		Southbound	4 × 6.9	26.75	27.63	4 × 5.0	21.50	17.82	5	50

[a] Significant.

priority bus flows experienced significant reductions in mean delay at the 5 percent level and another 5 priority bus flows were found to have significant reductions in mean delay at the 20 percent significance level. None of the nonpriority bus flows experienced reductions in mean delay at the 5 percent level and only two experienced significant reductions at the 20 percent level.

In view of these results, it seems reasonable to conclude that priority bus flows experienced significant reductions in both mean delay and variance of delay, but nonpriority bus flows experienced no such reductions. Hence, the priority system is capable of giving differential priority to vehicles on an approach to the intersection.

Nonpriority Vehicle Delay Changes

The granting of priority within the context of a positive net benefit is a little more complex to analyze. To do this, information is needed on the delay suffered by nonpriority vehicles at the intersection. These data were obtained by conducting surveys on the same two days as the bus survey, by use of a survey technique described by Richardson (3). The survey method is based on the measurement of queue length on each approach at various times within a signal cycle. The results of these surveys are shown in Table 2 for one of the survey periods. Similar tables exist for the other five survey periods (2) but, for brevity, are not included here. An explanation of the terms used in Table 2 is given below.

Vehicle flow—vehicular flow as measured in survey (vehicles/h).
Passenger flow—passenger flow using average automobile occupancy of 1:30 as measured at site for automobiles, and using observed average bus occupancies for buses.
Total vehicle stops—total number of effective vehicle stops.
Average number of stops—total vehicle stops divided by vehicular flow.
Average delay—average delay per vehicle (or person) on each approach (s).
SD delay—standard deviation of delay for vehicles on each approach (s).
Average + SD—sum of average delay and standard deviation of delay, which is defined in this paper as budgeted delay (s).
Δ Average number of stops—change in the average number of stops per vehicle between the without priority case and the with priority case.
Δ Average delay—change in the average delay per person.
Δ (Average + SD)—change in the budgeted delay per person.
$(\Delta \text{ Average})^2$—square of the change in the average delay per person, which accounts for the perceived value of this change.
$[\Delta \text{ (Average + SD)}]^2$—square of the change in budgeted delay per person, which reflects the change in perceived, budgeted delay.
Δ Total stops—total change in the number of effective stops obtained by multiplying the change in the average number of stops per vehicle by the vehicular flow.
Flow × ΔA—total change in delay obtained by multiplying the change in delay per person by the passenger flow (s).
Flow × Δ(A + S)—total change in budgeted delay obtained by multiplying the change in the budgeted delay per person by the passenger flow (s).
Flow × $(\Delta A)^2$—total change in perceived delay (s^2).
Flow × $[\Delta(A + S)]^2$—total change in perceived, budgeted delay (s^2).

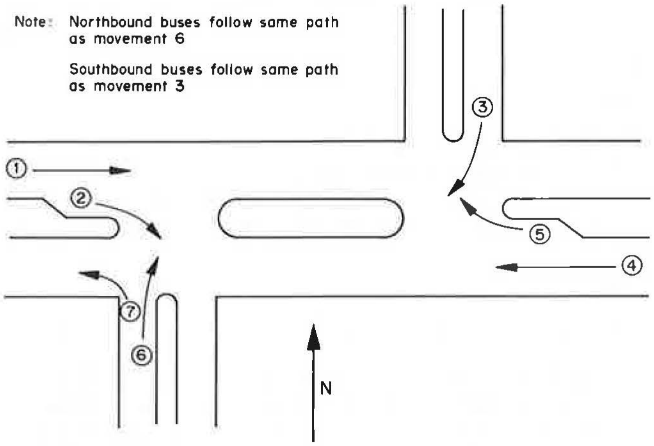
Results are presented individually for the seven distinct vehicle movements (as shown in Figure 2) and for the four bus movements along Oriel Road.

Flows that are in direct conflict with the priority bus movement (i.e., movements 1, 2, 4, and 5) may be ex-

Table 2. Summary of survey results for survey period 1.

Measure	Vehicle Group Movement—7:15-8:15 a.m.							Bus Group Movement—7:15-8:15 a.m.				
	1	2	3	4	5	6	7	MMTB Bus Northbound	MMTB Bus Southbound	Ivanhoe Bus Northbound	Ivanhoe Bus Southbound	Σ
Without priority												
Vehicle flow	794	54	583	1 980	13	149	216	13	19	4	5	
Passenger flow	1 032	70	758	2 574	17	194	281	84	177	33	39	
Total vehicle stops	424	52	544	1 040	13	124	156	12	23	4	9	
Average number of stops	0.53	0.96	0.93	0.53	1.00	0.83	0.72	0.92	1.21	1.00	1.60	
Average delay	20.77	64.91	47.43	22.50	50.69	42.54	32.39	52.38	68.74	37.25	91.60	
SD delay	25.35	52.79	40.21	28.13	34.66	36.52	32.37	27.37	36.48	37.70	9.69	
Average + SD	46.12	117.70	87.64	50.63	85.35	79.06	64.66	79.75	105.22	74.95	101.29	
With priority												
Vehicle flow	848	55	540	1 915	29	156	205	12	18	4	5	
Passenger flow	1 102	72	702	2 490	38	203	267	70	191	30	62	
Total vehicle stops	549	41	424	1 444	24	126	148	12	16	5	4	
Average number of stops	0.65	0.75	0.79	0.75	0.83	0.81	0.72	1.00	0.89	1.25	0.80	
Average delay	22.95	50.60	40.82	31.37	74.21	42.47	30.96	30.42	31.89	50.50	38.40	
SD delay	26.67	56.74	38.77	33.72	74.67	40.99	31.73	10.98	28.56	29.72	35.60	
Average + SD	49.62	107.34	79.59	65.09	148.88	83.46	62.69	41.40	60.45	80.22	74.00	
Comparison												
Vehicle flow	821	55	562	1 948	21	153	211	13	19	4	5	
Passenger flow	1 067	71	730	2 432	28	199	274	77	184	32	51	
ΔAverage number of stops	+0.12	-0.21	-0.14	+0.22	-0.17	-0.02	0	+0.08	-0.32	+0.25	-0.80	
ΔAverage delay	+2.18	-14.31	-6.61	+8.87	+23.62	-0.07	-1.33	-21.96	-36.85	+13.25	-53.20	
Δ(Average + SD)	+3.50	-10.36	-8.05	+14.46	+63. 53	+4.4	-1.97	-38.85	-44.77	+5.27	-27.29	
$(\Delta\text{Average})^2$	+4.8	-204.8	-43.7	+78.7	+557.9	0	-1.8	-482.2	-1 357.9	+175.6	-2 830.2	
$[\Delta(\text{Average + SD})]^2$	+12.3	-107.3	-64.8	+209.1	+4 036.0	+19.4	-3.9	-1 509.3	-2 044.4	+27.8	-744.7	
ΔTotal stops	+99	-12	-79	+429	-4	-3	0	+1	-6	+1	-4	+422
Flow × ΔA	+2 326	-1 016	-4 825	+21 572	+661	-14	-364	-1 690	-6 780	+424	-2 713	+7 581
Flow × Δ(A+S)	+3 735	-736	-5 877	+35 167	+1 779	+876	-540	-2 991	-8 238	+168	-1 392	+21 951
Flow × $(\Delta A)^2$	+5 122	-14 541	-31 901	+191 398	+15 621	0	-493	-37 114	-249 688	+5600	-144 330	-260 326
Flow × $[\Delta(A+S)]^2$	+13 124	-7 618	-47 304	+508 531	+113 008	+3860	-1086	-116 193	-368 736	+890	-37 980	-60 496

Figure 2. Intersection movement numbers.


Note: Northbound buses follow same path as movement 6

Southbound buses follow same path as movement 3

Table 3. Effect of priority system on delay suffered by various traffic movements.

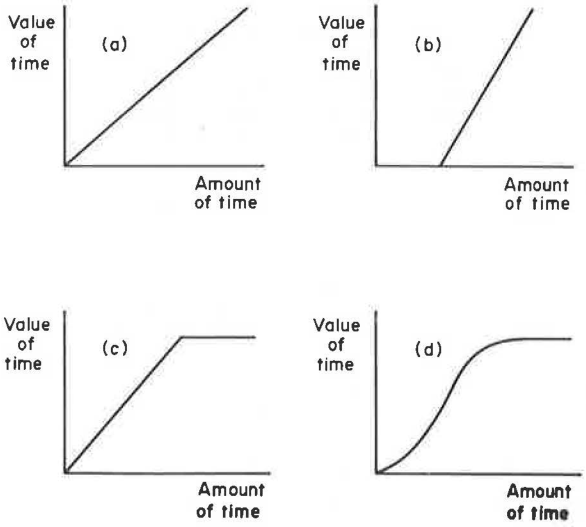
Movement	Increase Delay	Reduce Delay		Total
		Number	Percent	
Priority buses	1	11	91	12
Nonpriority buses	3	9	75	12
Complementary movements (3 and 6)	5	7	63	12
Movement 7	5	1	17	6
Conflicting movements (1, 2, 4, and 5)	18	6	25	24
Total	32	34	52	66

pected to suffer additional delay. Flows that run in the same phase as the priority bus movements might be expected to obtain a reduction in delay; however, this reduction in delay would be offset by the fact that, although some of the vehicles in these flows would obtain secondary priority, others would suffer the effects of the compensation cycles and hence suffer additional delay. Thus, while it might be expected that, overall, these movements would receive some priority, they would not receive the same degree of priority as the priority buses. This should apply both to the vehicular flows (movements 3 and 6) and the nonpriority bus flows. The remaining vehicular flow (movement 7) should lie somewhere between these extremes, since it shares a phase with a conflicting movement (movements 2 and 5) and hence will be adversely affected, but also shares the phase with the priority buses and hence might expect some benefit.

If the results of Table 2 (and the results for the other five time periods) are examined, the above speculation is largely borne out. Consider the effect of the priority scheme on the delay suffered by the 66 recorded movements at the intersection (11 traffic movements × 6 time periods). As shown in Table 3, the probability of obtaining a reduction in delay decreases as the degree of conflict with the priority bus movement increases. Hence, the measured effect of the bus-priority system appears to be logical, insofar as the direction of the change in delay is concerned.

Consider next the effect of the priority system on the magnitude of these changes in delay. Although the priority system has quite substantial effects on the delay suffered by priority buses (most changes in the range -10 to -40 s), the effect on the nonpriority vehicular flows was much less marked (generally in the range +1 to +10 s). In fact, statistical testing was unable to reveal any significant changes in delay for

Figure 3. Value of time and amount of time relationships.



nonpriority vehicles because of the effects of the relatively large variances in delay and the relatively small changes in mean delay. At this stage, it is tempting to conclude that a Pareto improvement has been achieved, since significant reductions in delay were obtained for buses without causing significant increases in delay for nonpriority vehicles. However, because of the very consistent pattern of changes revealed in Table 3, it seems unlikely that the observed changes in delay, although small, were due entirely to chance.

Hence, in determining the net benefit of the priority scheme (in terms of total delay changes), all changes in delay have been considered irrespective of whether or not they have been shown to be significant by statistical tests. The traditional method of obtaining net benefit is to multiply the average change in delay for each movement by the passenger flow in that movement and then to sum these passenger delay terms across all movements. The results, using this technique, for this study are given below.

Time Period	Total Change in Delay (s)
7:15-8:15 a.m.	+7 581
8:15-9:15 a.m.	−10 919
11:00 a.m.-12:00 n.	−1 458
1:30-2:30 p.m.	+8 743
3:45-4:45 p.m.	−3 739
4:45-5:45 p.m.	+36 529

It appears from this table that the effects are rather variable. In three of the periods delay has been reduced, but in the other three delay has been increased. Even when allowance is made for the extreme variability in results obtainable with field surveys, the priority scheme appears to have, if anything, slightly increased the total delay at the intersection over the course of a full day. This is because the relatively large decreases in delay that accrued to bus passengers have been more than offset by the small increases in delay suffered by the much larger number of automobile travelers.

Perceived Delay

The above argument has been based on the implicit assumption that small changes in delay should be weighted at the same value as large changes in delay. That is, the value of time (delay) savings is independent of the amount of time saved. There is, however, a growing body of literature in the travel demand field that questions this assumption [Thomas and Thompson (4), Hensher (5), and Gray and Bowen (6)]. Instead of assuming a constant value of time, they suggest that the value of time savings is itself a function of the amount of time saved. Thus the value of saving one unit of time is not half the value of saving two units of time. Similarly, the value of x people saving y units of time is not the same as one person saving x·y units of time.

This realization has important consequences for the evaluation of TSM schemes, especially bus-priority schemes. In these schemes large time savings to a small number of priority mode users are usually traded off against small time increases to a large number of nonpriority mode users. If large time changes are weighted more heavily (on the grounds that they are more easily perceived and usable), then the evaluation results will be more favorably inclined toward the consideration of large delay reductions or increases.

Various functional forms have been suggested for the relationship between value of time and the amount of time saved, some of which are shown in Figure 3. They include (a) a linear relationship, (b) a displaced linear relationship in which a minimum threshold amount of time saved (or lost) must be exceeded before time has any value, (c) a linear relationship with a maximum value of time, and (d) an ogive or sigmoid relationship (e.g., a probit curve) with a maximum value.

For illustration of the effects of assuming a variable value of time, and for simplicity of calculation, the linear relationship that has a maximum value of time that occurs for all time savings greater than 5 min will be adopted. Since all amounts of time saved or lost in this study are less than 5 min, this relationship reduces to a simple linear relationship. Thus,

$$v = v_m \times t/t_m \qquad (1)$$

where

v = value of time,
v_m = maximum value of time,
t = amount of time saved (or lost), and
t_m = minimum time for which v_m is assumed.

Hence,

$$TV(t) = (v_m \times t/t_m) \times t = (v_m/t_m)\, t^2 \qquad (2)$$

where TV(t) = total value of amount of time t. Thus, by using a linear relationship between value of time saved and amount of time saved, which gives greater weight to larger amounts of time saved or lost, the overall effect of the priority system can be estimated. This is done by considering the squared values of the amount of time saved or lost. These values are shown in Table 2 and are summarized for all periods below.

Time Period	Total Change in Delay (s^2)
7:15-8:15 a.m.	−260 326
8:15-9:15 a.m.	−98 479
11:00 a.m.-12:00 n.	−28 622
1:30-2:30 p.m.	−15 383
3:45-4:45 p.m.	−171 518
4:45-5:45 p.m.	+234 201

This table demonstrates that when larger changes in delay are given more weight, it is relatively easier

Table 4. Effect of priority system on variability in delay suffered by various traffic movements.

Movement	Increase Variability	Reduce Variability		Total
		Number	Percent	
Priority buses	1	11	91	12
Nonpriority buses	5	6	55	11*
Complementary movements (3 and 6)	8	4	33	12
Movement 7	4	2	33	6
Conflicting movements (1, 2, 4, and 5)	19	5	21	24
Total	37	28	43	65

*One nonpriority bus movement contained only one bus and therefore had no variability in delay.

to justify the bus-priority scheme. When unweighted delay changes are used in the evaluation, the results are generally inconclusive. However, when delay changes are weighted by the magnitude of the change, then the bus-priority scheme can be justified on the basis of the net perceived change in delay.

Delay Variability and Budgeted Delay

Recent research in behavioral travel demand theory [e.g., Stopher and Meyburg (7)] has indicated that many factors affect travel demand besides the traditional variables of time and cost of a trip. Such additional variables include comfort, convenience, and reliability. One of the prime determinants of reliability is the ability to arrive at one's destination on time. This can be related easily to the distribution of travel time for a trip.

Consider a journey to work where the employee is permitted to arrive at work late once per pay period. Further late arrivals will result in deductions being made from his or her pay. If the employee aims to meet this standard, once every two weeks he or she can be late (i.e., 1 day in 10 or 10 percent of the time). Thus he or she must schedule the trip such that the 90th percentile of travel time distribution will be equal to the time between leaving home and starting work. Hence, he or she must budget for this 90th percentile time rather than for the 50th percentile time (the median ≃ mean). If the employee were to allow simply for the mean time, he or she would be late approximately 50 percent of the time.

Hence in the comparison of alternative modes, a function of mean travel time and variability of travel time should be considered. Similarly, in the evaluation of the level of service provided by a mode, this budgeted time should be considered rather than the mean time since it is this budgeted time that is effectively spent in using the mode. By considering the budgeted time, it is possible to obtain an improvement in the level of service without decreasing the average travel time (or delay). Thus a bus-priority scheme that does not result in a significant reduction in mean delay for buses may still be worthwhile if a considerable reduction in delay variability is achieved. In fact, it is possible to have better service even when mean delay increases, provided that the reduction in variability of delay is of sufficient magnitude. Thus the consideration of budgeted rather than mean delay presents more opportunities for the justification of bus-priority schemes.

The exact definition of budgeted time is, however, difficult to specify. In this study, it is defined as being equal to the sum of the mean and the standard deviation of travel time (or delay). It corresponds to an upper percentile point of the delay distribution. For a normal distribution, it would represent the 84th percentile point. For other distributions, the exact percentile point would depend on the skewness and kurtosis of the distribution. Although other definitions of budgeted time are possible, this simple sum is used in this study for purposes of illustration and ease of calculation.

The effect of the priority scheme on variability in bus delay has already been discussed. Consider now the effect on nonpriority vehicular traffic. Table 4 shows the effect of the priority scheme on the variability in delay for the 66 recorded intersection traffic movements. As in Table 3, the probability of receiving favorable treatment from the priority scheme is inversely proportional to the degree of conflict with the priority bus movement. Again, however, statistical testing of the changes in variance revealed no significant changes for nonpriority traffic. Once again, however, all changes in variability are included in the calculation of net benefit.

As before, both weighted and unweighted delay changes are calculated, except in this case budgeted delay is used instead of mean delay. The results are given below for the six time periods.

Time Period	Budgeted Time Change (s)	Perceived Budgeted Time Change (s)
7:15-8:15 a.m.	+21 951	-60 496
8:15-9:15 a.m.	-13 958	-76 468
11:00 a.m.-12:00 n.	-7 679	-205 669
1:30-2:30 p.m.	+14 180	+42 487
3:45-4:45 p.m.	-4 892	-233 204
4:45-5:45 p.m.	+43 231	-1 183 688

This use of budgeted delay appears to have had little effect on the overall results. Hence, as before, the unweighted budgeted delay results show an even split of positive and negative net benefits; however, the weighted delay results again show a five-to-one balance in favor of the bus-priority system. Overall, the inclusion of variability changes does not have as great an effect on the outcome of this evaluation as does the use of a variable, or perceived, value of time.

CONCLUSION

The evaluation of TSM schemes is, and will continue to be, an important topic of discussion in transportation planning. The current emphasis on improving the efficiency of the existing transportation system demands that TSM schemes be implemented if they can be shown to be economically, socially, and environmentally efficient. In the consideration of one type of TSM project, bus-priority schemes, this paper has suggested that a number of refinements can be made to improve the evaluation process. Specifically, two new variables are introduced: perceived delay and budgeted delay. Perceived delay accounts for the psychological finding that the relationship between stimulus and response is rarely linear. In terms of travel time delay, this is equivalent to the statement that the value of time savings is a function of the amount of time saved. Hence, large changes in delay are weighted more heavily than small changes in delay. In the evaluation of bus-priority schemes, where the basic trade-off is between large time savings to a small number of priority mode users and small time increases to a much larger number of nonpriority mode users, this realization is of considerable significance. Application of this principle to a case-study evaluation shows, as expected, that the results of the evaluation can be influenced considerably by the adoption of perceived delay as the appropriate measurement of performance.

The second major development is the concept of budgeted delay. This variable accounts for the amount of time a traveler budgets for a trip. It is a function of the mean travel time for a trip and the variability of travel time for a trip and corresponds to an upper percentile point on the travel time distribution. Reductions in budgeted time are a more accurate measure of the benefit of a bus-priority scheme than reductions in mean time. Use of budgeted time in a case-study evaluation produced no significant difference to the results, although this is not likely to be a general finding.

Finally, and most importantly, many bus-priority schemes that have been evaluated on the basis of net reductions in mean travel time may have been incorrectly labeled as infeasible. Reevaluation of these schemes on the basis of perceived, budgeted time changes would probably result in many of them being relabeled as feasible TSM schemes that can contribute to the more efficient operation of the existing transportation infrastructure.

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Impact of Short-Term Service Changes on Urban Bus Transit Performance

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This paper examines the impact on a fixed route of small changes in three operational policy variables: frequency, number of bus stops, and fare. Analytical expressions are developed that trace the impact of each variable on various other system variables, which leads to an assessment of changes in selected measures of efficiency and effectiveness. The application of the methodology is demonstrated by a case study of a selected bus route in a medium-sized Indiana city. Three specific options are evaluated in terms of alternative frequency, number of stops, and fare policies. Since none of the options was actually implemented, the paper reports only on a theoretical analysis of the changes that might be expected under each option. The results indicate that significant improvements are possible in most of the efficiency and effectiveness measures under all three options examined. The technique does not require an extensive amount of data or calibration effort; instead it relies on information generally available from the records of a transit company and reasonable assumptions where necessary.

Much effort is currently being directed toward gaining a better understanding of urban transit performance. Under public ownership, transit systems are being subsidized heavily by federal, state, and local funds. These subsidies are necessary if transit companies are to continue to provide service to the public even when they cannot recover their operating costs from the farebox. Under these circumstances, if service improvements are evaluated solely on the basis of cost recovery, few projects, if any, would be implemented. Previous studies of short-term changes in service have concentrated on ridership, costs, and revenue impacts; little emphasis was given to their impact on accepted measures of performance.

This paper presents a methodology for relating short-term service changes to changes in selected measures of performance. Particular reference is made to bus transportation in medium-sized urban areas. Specifically, an examination is made of the effect of changes in three major operational policy variables along a fixed