Evaluation of the Operating Cost Consequences of Signal Preemption as an IVHS Strategy

SNEHAMAY KHASNABIS, GANGULA V. REDDY, AND SYED KHURSHIDUL HODA

Signal preemption is a preferential treatment technique to ensure continuous green phases to buses at successive signalized intersections on urban arterials. Although it has been used in Europe with some success, a number of factors have thus far prevented its widespread application in the United States. With development of intelligent vehicle highway systems concepts, there is a growing belief among transit experts about the emergence of signal preemption as a tool for alleviating urban congestion problems. No quick-response tool is available to the transit operator to evaluate the operating cost consequences of signal preemption. A computer simulation model (PREEMPT) is presented to depict the operating cost and ridership consequences of signal preemption. Although no actual preemption device was installed, the model attempts to emulate travel over an urban bus corridor. An elasticity-based demand algorithm built into the model is designed to incorporate the possible effects of improved quality of service and fare changes on operating cost. The model output appears to be reasonable; however, model validation is needed before it can be applied in actual studies.

Delay to buses at signalized intersections on urban arterials makes up a significant fraction of bus trip time. Unlike automobiles, buses cannot be platooned through controlled intersections because of a large variance in the distribution of travel time between different runs. Random variations in the number of passengers boarding and unboarding at bus stops and the resulting differences in the loading and unloading times make the prediction of the exact arrival times of buses at intersections very difficult.

Preemption strategies are designed to provide priority to transit buses over passenger cars. They are preferential treatment devices for buses to ensure continuous green phases at successive signalized intersections on urban arterials, thereby reducing travel time and improving overall speed. The technology includes instrumented buses, transmitters, loop detectors, and a real time control system for estimating arrival times at the intersection and for triggering signal preemption.

If an approaching bus needs and qualifies for preferential treatment, preemption action is initiated. This is accomplished in the form of "green extension" (prolongation of the bus street green phase), "red truncation" (termination of the bus street red phase prematurely), or "red interruption" (injection of a short green phase not continuous with the adjacent green phase). The system logic must recognize that not all buses in need of preemption may qualify for such preferential treatment because of the maximum specified limit of preemption. Thus, when a bus needs preemption but the amount of preemption needed to clear the intersection exceeds the specified maximum, preemption cannot be granted.

In the mid-1970s, experiments were conducted with mixed success in a number of U.S. cities to test various methods of minimizing bus delays at intersections (*1*,*2*). Although specialized signal controls are used widely in Europe today, a number of factors have thus far prevented their widespread applications in the United States. These include the absence of a reliable technology to monitor the arrival of buses (particularly when bus stops are located immediately before the intersection) and to trigger preemption, lack of standards to determine warrants, and inability of the system to prevent inordinate delays to motorists traveling along the cross street. With advances in technology and increased application of intelligent vehicle highway systems (IVHS) concepts, there is growing belief among transit experts about the reemergence of bus preemption as a tool for alleviating urban congestion problems. Under the newly adopted advanced public transportation system program by the federal government, signal preemption is considered a major tool to be tested under the IVHS program in the United States (*3*).

European experience suggests that signal preemption is a viable technology and, if implemented properly, can result in significant reductions in bus delays without greatly affecting cross street traffic. Signals can be actuated by radio, inductive loops on the pavement, or by a combination thereof (*4*). In the past, standard loops reacted to the presence of any vehicle, making the system incapable of distinguishing buses from passenger cars. However, the technique of automatic vehicle classification (AVC) enables the identification of transit vehicles by in-pavement equipment, without the need for an on-vehicle detection system. This feature makes buses distinguishable from other vehicles and candidates for preferential treatment.

Automatic vehicle identification (AVI) technology is considered by many experts as a viable alternative to AVC. The technology consists of a communication link between an onboard transponder and a roadside reader unit. A vehicle identification number (VIN) included in the transponder is decoded whenever the vehicle passes a reader location. The application of AVI technology can be found in the Philips

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S. Khasnabis and S. K. Hoda, Wayne State University; Detroit, Mich. 48202. G. V. Reddy, Florida Department of Transportation, Fort Lauderdale, Fla. 33317.

Vetag system in the Netherlands for mixed-mode operation; the EVADE system developed by Mullard for emergency vehicles in Northampton, United Kingdom; and the Vehicle Identification and Priority System used for express bus routes between The Hague and Delft in the Netherlands (*5–7*).

The use of license plate scanners developed originally for toll collection has gained some prominence in recent times as a means of selective vehicle identification (*7*). A comparison of license plates read by the system with a set of preferred vehicle records will enable the system to detect the "preferred" vehicles, thus triggering preemption. Unlike AVI or AVC technology, license plate scanners can be used without any on-board equipment, resulting in cost savings. It is not known whether these savings may be offset by the high cost of license plate readers.

Clearly, appropriate technology is available today to implement signal preemption strategies, at least for route level deployment. Unfortunately, no quick-response tool is available to the transit operator that can be used to evaluate the operating cost consequences of signal preemption. For example, increased travel speed may result in reduction of fleet size. It is not known how this reduction might result in reduced operating cost. Similarly, will improved quality of service help the operator gain a larger market share? If so, how might this affect fare box revenue and fleet size? These issues are addressed in the paper.

The purpose of this paper is to present a quick-response tool for analyzing the operating cost consequences of route level preemption. This tool is only for sketch planning purposes and is designed to provide the user with broad information on changes in fleet size, travel time, revenue, and operating cost as a consequence of changes in travel speed attributable to signal preemption. The study methodology does not use preemption development and implicitly assumes that the emerging IVHS technology will enable the deployment of an efficient preemption system. In an earlier paper the authors reported on their initial efforts on this topic (*8*).

METHODOLOGY

A simulation model, PREEMPT, was developed in C language. It can analyze the travel demand, fare box revenue, and operating costs consequences of signal preemption. The software consists of three separate entities that are appropriately linked to provide desired results (Figure 1): (*a*) fleet size, headway, and cycle time; (*b*) operating cost and revenue; and (*c*) elasticity-based demand function.

The model includes a procedure for estimating the number of stops that a bus is likely to skip following a probabilistic approach.

Definitions

The following definitions should be noted:

- Cycle time is the total round-trip time for a vehicle, that is, the interval between two consecutive passes of the same vehicle traveling in the same direction by a fixed point.
- Maximum loading section (MLS) is the line section between two terminal points on which the maximum passenger load occurs.
- Fleet size is the total number of vehicles required to meet the hourly passenger demand at the MLS.

Fleet Size, Headway, and Cycle Time

$$Nv \geq (Dp \times C)/(Vc \times 60) \qquad (1)$$

$$H = C/Nv \qquad (2)$$

$$C = Td + Ts + Tc \qquad (3)$$

where

Nv = number of buses required (fleet size),
Dp = hourly passenger demand at the MLS,
C = cycle time (min),
Td = driving time (min),
Ts = boarding/unboarding time (min),
Tc = layover time (min) (between 2.5 and 5.5 min),
H = headway (min), and
Vc = bus capacity (number of passengers).

Furthermore, driving time, *Td*, is calculated as follows:

$$Td = (60D)/V_{\max} + \{n(V_{\max}/2)\,(5{,}280/36{,}000)\,[(a + b)/60ab]\} \qquad (4)$$

where

D = distance between two terminal points (mi),
$V_{\max}$ = maximum velocity (mph),
n = number of stops at which the bus has to stop (a bus need not stop at all the stops),
a = acceleration rate (ft/sec^2), and
b = deceleration rate (ft/sec^2).

Equation 1 shows that for a given demand *Dp* and bus size *Vc*, the fleet size can be minimized by reducing the cycle time *C*. Furthermore, cycle time, being the total of driving time (*Td*), boarding/unboarding time (*Ts*), and layover time (*Tc*), can be minimized by reducing any of the three components or any combination thereof.

Signal preemption is designed to reduce driving time between two terminals points, thus resulting in a reduction in cycle time, fleet size, and operating cost. Reduced travel time is likely to make the transit system more attractive, thus generating more ridership and higher revenue. PREEMPT can estimate driving times on the basis of (assumed) higher speeds and can recalculate the reduced fleet size and reduced operating costs directly attributable to signal preemption. An elasticity-based demand function that can assess the effect of varying travel times and fare changes attributable to signal preemption is incorporated in the model.

Probability of Skipping a Stop

At the beginning, an assumption must be made on the number of stops of a bus along the route. A bus will typically skip a

TABLE 3 Operating and Fiscal Data for Base Condition and Various Preemption Scenarios, Variable Demand–Variable Fare

Peak Off-Pk. (P, O)	Max. Speed (KM/H)	Fleet Size (No.)	Cycle Time (Min.)	Head-way (Sec.)	Annual O. Cost $(Mill)	Annual Revenue $(Mill)	% Deficit	Avg. Speed (KM/H)	EDDPH (No.)	Deficit $(Mill)	% Red. in Def.	% Inc. in Sp.
P	40.50	29	33.83	70.00	5.207	4.590	11.860	28.72	2500	0.617	Base	Cond.
O	40.50	14	32.67	140.00				29.76				
P	44.55	23	32.58	85.00	4.344	4.500	-3.58	29.82	2101	-0.156	125.284	8.310
O	44.55	12	29.00	145.00				33.52				
P	48.60	22	31.17	85.00	4.152	4.555	-9.72	31.19	2127	-0.403	165.316	13.767
O	48.60	11	27.50	150.00				35.35				
P	52.65	22	33.00	80.00	4.206	4.553	-8.27	33.13	2126	-0.347	156.240	19.169
O	52.65	11	26.58	145.00				36.56				
P	56.70	21	29.75	85.00	3.961	4.502	-13.65	32.68	2102	-0.541	187.682	20.222
O	56.70	10	25.83	155.00				37.63				
P	60.75	21	28.00	80.00	4.013	4.698	-17.07	34.72	2194	-0.685	211.021	25.845
O	60.75	10	25.00	150.00				38.88				
P	64.80	20	26.67	80.00	3.937	4.570	-16.07	36.45	2134	-0.633	202.593	31.108
O	64.80	10	24.17	145.00				40.22				

EDDPH - Expected demand during peak hour
% Red. in Def. - % Reduction in deficit over base condition
% Inc. in sp. - % Increase in speed over base condition

is the same as Table 2 (corresponding to 60 cents fare), and the remaining rows are for increased fare. Compared with Table 2, increasing speed results in decreasing demand, because of the adverse effect of increased fare on demand.

Figure 2 shows a set of three curves representing a relationship between percentage increase in speed and percentage reduction in deficit. Both of these are computed over the base case (i.e., for the maximum speed of 25 mph). These curves show, for each of the three cases analyzed, the percentage reduction in deficit can be expected as a consequence of increase in speed resulting from signal preemption.

Since the study did not use any actual preemption deployment, the validity of the curves cannot be assessed. The study, however, presents a procedure for quantifying the benefits of preemption. Similar curves can be developed for varying values of elasticity.

The results presented above are to be interpreted only as trends. There are a number of crucial assumptions that may

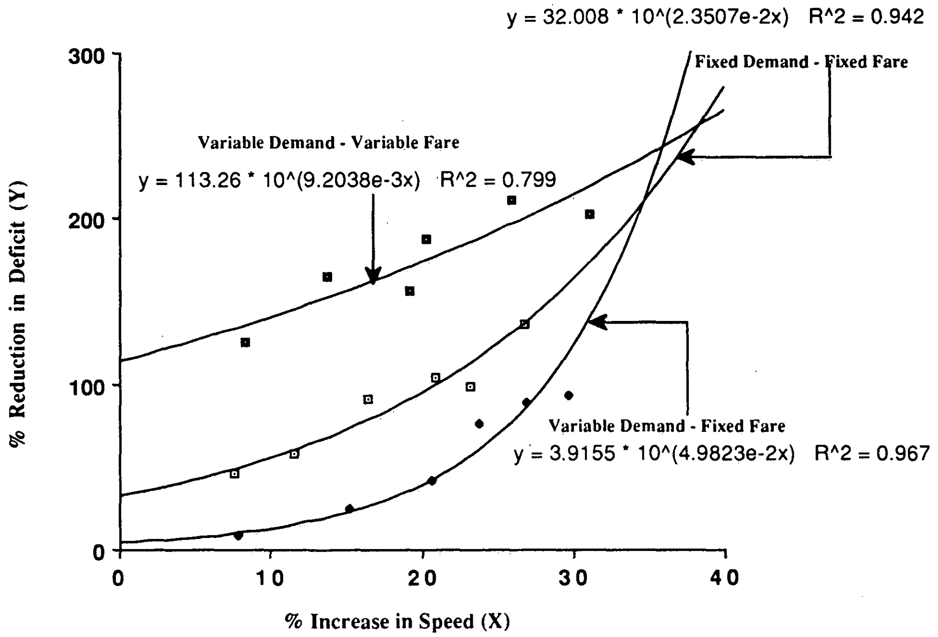

FIGURE 2 Relationship between changes in speed and operating deficit under different demand-fare conditions.

TABLE 1 Operating and Fiscal Data for Base Condition and Various Preemption Scenarios, Fixed Demand–Fixed Fare

Peak Off-Pk. (P, O)	Max. Speed (KM/H)	Fleet Size (No.)	Cycle Time (Min.)	Head-way (Sec.)	Annual O. Cost $(Mill)	Annual Revenue $(Mill)	% Deficit	Avg. Speed (KM/H)	EDDPH (No.)	Deficit $(Mill)	% Red. in Def.	% Inc. in Sp.
P	40.50	29	33.83	70.00	5.180	4.590	11.380	28.72	2500	0.59	Base	Cond.
O	40.50	14	33.83	145.00				28.72				
P	44.55	27	31.50	70.00	4.911	4.590	6.54	30.86	2500	0.32	45.760	7.586
O	44.55	13	31.42	145.00				30.94				
P	48.60	26	30.33	70.00	4.837	4.590	5.11	32.04	2500	0.247	58.136	11.562
O	48.60	13	30.33	140.00				32.04				
P	52.65	25	29.17	70.00	4.643	4.590	1.14	33.32	2500	0.053	91.017	16.356
O	52.65	12	29.00	145.00				33.51				
P	56.70	24	28.00	70.00	4.569	4.590	-0.46	34.71	2500	-0.021	103.559	20.869
O	56.70	12	28.00	140.00				34.71				
P	60.75	24	28.00	70.00	4.599	4.590	0.19	34.71	2500	0.009	98.47	23.096
O	60.75	12	27.00	135.00				36.00				
P	64.80	23	26.83	70.00	4.375	4.590	-4.92	36.22	2500	-0.215	136.44	26.706
O	64.80	11	26.58	145.00				36.56				

EDDPH - Expected demand during peak hour
% Red. in Def. - % Reduction in deficit over base condition
% Inc. in sp. - % Increase in speed over base condition

TABLE 2 Operating and Fiscal Data for Base Condition and Various Preemption Scenarios, Variable Demand–Fixed Fare

Peak Off-Pk. (P, O)	Max. Speed (KM/H)	Fleet Size (No.)	Cycle Time (Min.)	Head-way (Sec.)	Annual O. Cost $(Mill)	Annual Revenue $(Mill)	% Deficit	Avg. Speed (KM/H)	EDDPH (No.)	Deficit $(Mill)	% Red. in Def.	% Inc. in Sp.
P	40.50	29	33.83	70.00	5.207	4.590	11.860	28.72	2500	0.617	Base	Cond.
O	40.50	14	32.67	140.00				29.76				
P	44.55	28	32.67	70.00	5.202	4.637	10.86	29.76	2526	0.565	8.427	7.867
O	44.55	14	29.17	125.00				33.32				
P	48.60	28	30.33	65.00	5.431	4.968	8.53	32.04	2706	0.463	24.959	15.230
O	48.60	15	27.50	110.00				35.35				
P	52.65	29	29.00	60.00	5.630	5.269	6.41	33.52	2870	0.361	41.49	20.637
O	52.65	15	26.25	105.00				37.03				
P	56.70	29	29.00	60.00	5.684	5.537	2.59	33.52	3016	0.147	76.175	23.795
O	56.70	15	25.00	100.00				38.88				
P	60.75	30	27.50	55.00	5.843	5.777	1.12	35.35	3147	0.066	89.303	26.925
O	60.75	15	25.00	100.00				38.88				
P	64.80	30	27.50	55.00	6.033	5.990	0.71	35.35	3263	0.043	93.031	29.695
O	64.80	16	24.00	90.00				40.50				

EDDPH - Expected demand during peak hour
% Red. in Def. - % Reduction in deficit over base condition
% Inc. in sp. - % Increase in speed over base condition

where

Dp = demand,
K = constant,
T = travel time,
p = cost of travel (fare),
y_1 = time elasticity of demand (assumed to be -1.60), and
y_2 = cost elasticity of demand (assumed to be -0.70).

Experience has shown that travel demand varies inversely both with travel time and cost; however, transit demand is more sensitive to travel time than to travel cost. Thus y_1 and y_2 are negative, and the numerical value of y_1 is higher than y_2.

The demand model must be properly calibrated through estimation of the parameter K in Equation 6. The user is prompted to enter the weighted average fare, fare elasticity, and travel time elasticity. The model uses the cycle time computed by the program as a measure of travel time. As the user revisits the program to determine the effect of signal preemption, it will estimate new demand using the constant K along with revised values of travel time and fare. PREEMPT can simulate transit operation under the following three scenarios over and above the base condition:

- Static, for the same demand with different maximum speed, which is assumed to be the result of preemption (fixed demand–fixed fare);
- Dynamic-1, for revised demand resulting from reduced cycle time (consequences of preemption), with an assumed travel time elasticity (variable demand–fixed fare); and
- Dynamic-2, for revised demand resulting from reduced cycle time (result of preemption) and revised fare, with assumed elasticities of travel time and price (variable demands–variable fare).

Operating Cost and Revenue

The cost of the operating services is derived by the fully allocated cost (FAC) method, a technique increasingly applied by transit agencies in which all the cost elements are apportioned into different variables. The FAC model developed for large buses for the regional transit agency in southeast Michigan was used to compile operating cost data (*10*).

$$\mathrm{FAC} = \$1.025X + \$21{,}03Y + \$80{,}516Z \qquad (7)$$

where

FAC = annual fully allocated cost,
X = annual total vehicle miles,
Y = annual total vehicle hours, and
Z = number of buses required to provide peak service.

PREEMPT can develop fare box revenue estimates, given ridership data by fare zones and corresponding fares. This requires information on transit ridership by fare zones. An alternative simplistic technique for computing fare box revenue is also incorporated in the model.

RESULTS

PREEMPT was used to compute operating and fiscal data for three possible scenarios described earlier, for a range of maximum speed values from 25 to 40 mph in increments of 2.5 mph.

The revenue model is based on a fare zone system that requires zonal demand interchange data. For the hypothetical example analyzed in this paper, such zonal data were not available. A simplistic assumption of a constant fare was used, which may have resulted in somewhat unrealistic fare box revenue in the example case. The assumed elasticity values of -1.60 and -0.70 for y_1 and y_2 represent typical values found in the literature.

Input Data

The following input data were used for all three cases:

Item	*Value*
Distance between the two terminal points of the bus route (mi)	10
Peak-hour demand at MLS (passengers per hour)	2,500
Off-peak-hour demand at MLS (passengers per hour)	1,250
Average passengers boarding (passengers per stop)	3
Average passengers alighting (passengers per stop)	3
Acceleration rate (ft/sec^2)	4
Deceleration rate (ft/sec^2)	5
Average boarding time (seconds per passenger)	3
Average alighting time (seconds per passenger)	3
Assumed layover time (min)	5
Bus capacity (excluding standees)	40
Standing capacity (percent)	30
Total number of stops	25
Assumed percentage of stops (anywhere between 70 and 100)	90

Model Output

Table 1 gives the model output under the fixed demand–fixed fare condition. Table 1 indicates that increases in maximum speed result in increases in average speed and reductions in fleet size, cycle time, and operating costs. Since Table 1 is based on constant fare, the revenue remains unchanged. However, since operating cost goes down with increase in speed, there is a gradual reduction in deficit that is directly attributable to signal preemption.

Table 2 (variable demand–fixed fare) represents the situation in which reduced travel time (or improved quality of service resulting from preemption) results in increased travel demand brought about by the elasticity-based demand model. The increase in demand requires a larger fleet size, which results in higher operating cost. Since revenue remains unchanged, higher operating cost results in a larger deficit (compared with Table 1). This feature is somewhat misleading in that improved quality of service appears to contribute to larger deficit! However, the model, by virtue of the demand function, perhaps depicts a reality that increased demand may require larger fleet size and hence higher operating cost.

Table 3 is designed to address the issues raised in Table 2. In this case fare has been increased from 60 to 70 cents and demand is considered to be sensitive to both fare and travel time. To provide a fair comparison, the first row in Table 3

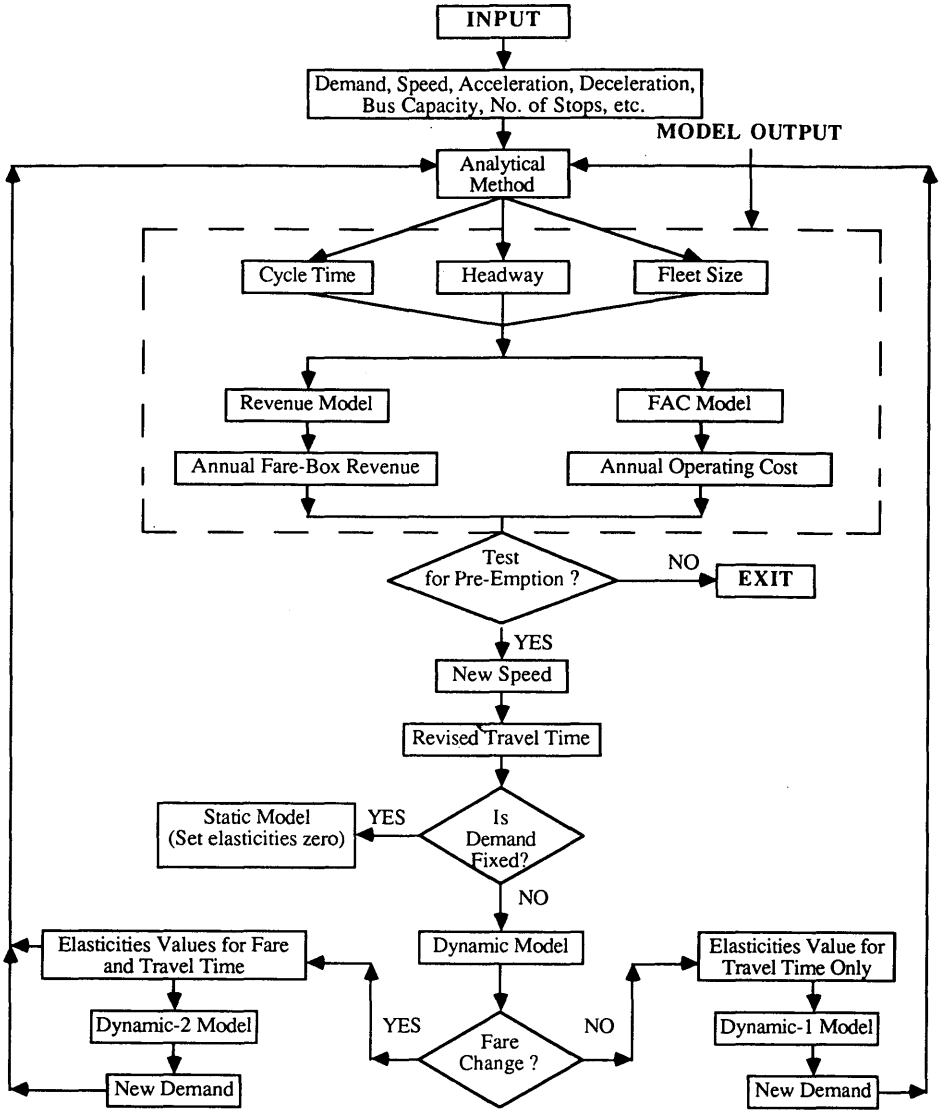

FIGURE 1 Flowchart for PREEMPT software.

stop if there is no boarding or unboarding. For simplicity, the likelihood of a stop being skipped is assumed to be a percentage of the total stops. Once the headway is calculated, the assumption can be checked using the Poisson distribution as follows, where H is headway (min), x' is average arrival rate at a stop (passengers per minute), and y' is average departure rate from a stop (passengers per minute):

$$\text{Probability of skipping a stop} = e^{-(x' + y')H} \tag{5}$$

A review of the preceding equations shows that to calculate H (Equation 2), the cycle time C must be calculated first. Cycle time, however, is a function of driving time Td, which is a function of n, the number of stops where a bus is likely to stop (Equation 4). But one must have a prior estimate of the number of stops likely to be skipped to estimate Td. However, as Equation 5 shows, to estimate the probability of a stop being skipped, the headway H must be known. Thus, a dilemma is presented here in that one requires preknowledge of H to calculate H!

This feature requires the initial assumption of the number of stops where a bus is likely to stop. One can check whether the assumed probability matches the actual probability of skipping stops computed on the basis of headway, passenger arrival rate, and departure rate. The PREEMPT software has a loop operation that facilitates the user in deciding whether (*a*) to check the assumption of stops and (*b*) to recalculate the operating factors in the event the assumed probability of skipping stops does not match the actual probability as calculated above.

Elasticity-Based Demand Function

In Equation 1 the demand Dp is assumed to be fixed under normal conditions. However, reduced travel times resulting from preemption may result in increased demand or larger market capture. Equation 6, which uses the concept of elasticity, was used to estimate the revised demand (*9*):

$$Dp = KT^{y_1}p^{y_2} \tag{6}$$

have an impact on the results. The trends observed in the data presented appear reasonable, indicating that the PREEMPT model is functional. However, further testing of the software and field validation will be needed before it can be applied.

CONCLUSIONS

The purpose of this paper is to demonstrate the use of a computer simulation model, PREEMPT, to depict the operating cost and ridership consequences of traffic signal preemption. Whereas no actual preemption mechanism was installed, the model PREEMPT attempts to emulate the travel time consequences of signal preemption over an urban bus corridor.

The model appears to depict some of the operating and fiscal consequences of signal preemption in a reasonable manner. It computes the operating consequences for given maximum speed values resulting from preemption. A probabilistic approach is incorporated into the model to recognize that a bus may skip certain stops along the route depending on boarding/unboarding demands. An elasticity-based demand algorithm built into the model is designed to incorporate the possible effects of improved quality of service (through preemption) and fare changes on travel demand. Operating cost and revenue consequences are estimated through a FAC model.

No effort was made to validate the model through the actual deployment of preemption hardware, nor was it possible to assess the adverse consequences of preemption for motorists traveling along the cross streets.

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