Techniques To Assess Delay and Queue Length Consequences of Bus Preemption

BILL ALAN CISCO AND SNEHAMAY KHASNABIS

Two deterministic methods for assessing delay and queue length consequences of bus preemption at signalized intersections are presented. The procedures are adapted from queueing theory and address three types of preemption strategies: green extension, red truncation, and red interruption. Method 1 macroscopically simulates groups of vehicles at the intersection using regular signal timing and timing under preempted conditions. Method 2 uses microscopic simulation in which each vehicle is treated individually and traffic flow patterns are evaluated for the regular signal timing and timing under preemption condition. Both methods are applied to three intersections in Ann Arbor, Michigan, representing different volume levels at the cross street. Data on vehicle arrival, service, queue lengths, and delays were compiled from videotapes made at the intersections during the spring of 1994. The algorithms developed were used to assess changes in queue lengths and delays resulting from the revised signal timing. The two methods appear to be viable tools for evaluating traffic flow consequences of preemption. The case studies indicate some variations in the results between the three strategies tested, between the two methods used, and between the intersections representing different volume levels. Method 2 (microscopic) is preferred for lighter volume levels, and Method 1 (macroscopic) should be used for higher volume levels. Further research is recommended to validate the proposed methods.

Preemption is a method of providing preferential treatment to buses at signalized intersections. Because the number of passengers boarding and unboarding at bus stops varies, predicting the exact arrival time of buses at intersections is difficult. A preemption strategy, if properly designed, can ensure continuous green phases to buses at successive intersections.

The technology uses instrumented buses, detectors, sensors, and a real-time traffic control system that can detect an approaching bus, predict its exact arrival time at the intersection, and communicate the information to the signal control system. The advent of intelligent transportation systems (ITSs) has made preemption a more viable tool for providing priority to buses than any time in the past. A description of available technologies for signal preemption and system logic is available in the literature (*1–3*).

Three categories of preemption strategies include green extension, red truncation, and red interruption. During green extension the green phase on the bus street is prolonged by a fixed amount of time. Red truncation allows premature termination of the red phase on the bus street. In red interruption, a short green phase, not contiguous with the adjacent green, is injected within the red phase along the bus street. In all the cases, the result is an increase in green time along the bus street allowing the bus to cross the intersection (*4*).

Experience with signal preemption in the United States and in Europe, although limited, suggests that signal preemption is a viable tool and, if properly implemented, may result in significant operational improvements along bus routes, including reduced delays and queue lengths, and increased throughput. However it also may adversely affect the traffic operation along the cross street by increasing delays and queue lengths and reducing throughput. Unfortunately no technique is available that can be used to assess the possible consequences of preemption. Without such an assessment tool, the only way to evaluate a preemption strategy is to actually implement the program and conduct a before-and-after study. Such an approach is not considered viable because of difficulties associated with conducting such field experiments under controlled conditions.

Two deterministic methods are presented to assess some of the operational consequences of bus preemption at isolated signalized intersections. Both methods are adapted from queueing theory and are designed to assess the three types of preemption strategies mentioned earlier (green extension, red truncation, and red interruption). Initial results of the application of the two methods on one intersection were reported at the March 1995 ITS National Conference in Washington, D.C. (*5*). A more complete description of the application of the two methods on three intersections is presented in the following sections.

The intersections selected are on Washtenaw Avenue (Route 4 on the Ann Arbor Transportation Authority System) in Ann Arbor, located in southeast Michigan approximately 50 mi west of Detroit. This street is a major transit corridor connecting the central business district (CBD) of a small town (Ypsilanti) with the western end of the city of Ann Arbor using a transfer point at the Ann Arbor CBD. The case study applications were based on actual vehicular arrival and service patterns at the intersection. The three intersections represent light, medium, and heavy traffic volumes on the cross street.

METHODOLOGY

The approach used to assess the operational consequences of preemption is adapted from queueing principles used in undersaturated situations (*6–8*). It was assumed that at each cycle the number of arrivals is less than the capacity of the approach, resulting in no overflow of vehicles from one cycle to the next. Thus, all vehicles queued during a given red phase cleared the intersection before the end of the green phase. Actual vehicular arrival, service data, and queue lengths were recorded on videotape for all approaches during the peak period of 5 p.m. to 6 p.m. These records were analyzed to determine the following:

- Vehicle arrival patterns at the intersection during the red and green phases;
- Vehicle service or processing patterns through the intersection during the first part of the green phase, until the queue was totally discharged; and

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Wayne State University, Detroit, Mich. 48202.

- Simultaneous vehicle arrival and service patterns after the queue was completely discharged during the later part of the green phase.

The information obtained was then used to simulate the possible traffic flow (in both bus and cross street directions) if signal preemption of a specified amount (10 sec) was granted to the bus street, following each of the three strategies separately.

Within the analytic framework of queueing discipline, two methodologies were developed. In Method 1, macroscopic simulation was used to represent the flow of a group of vehicles by fixed arrival rates, service rates, and simultaneous arrival and service rates. The rates were determined from repeated observations of the traffic flow and from queueing patterns recorded at the site.

Method 2 is based on microscopic simulation, in which actual traffic flow patterns (arrival, service, and simultaneous arrival and service) over a three consecutive-cycle period were examined for each vehicle individually. Traffic flow consequences on all approaches were assessed based on the "superimposed" conditions of green extension, red truncation, and red interruption.

Method 1

Method 1 uses average rates of arrivals, services, and concurrent arrival-services, with the revised signal timings (resulting from preemption) "superimposed" on a time-rate diagram to assess traffic flow consequences. The amber phase was assumed to be essentially a part of the green phase. The approach used for green extension is explained in the next section. The following notations were used:

λ = vehicle arrival rate (vehicles/second) starting at t_1 and ending at t_2;
μ = vehicle service rate (vehicles/second) starting at t_3 (beginning of the green phase) and ending at t_4, when the queue is totally discharged;
k = simultaneous arrival-service rate (vehicles/second) beginning at t_4 (after the queue is discharged) and ending at t_5;
c = cycle length (seconds);
r = red phase (seconds);
g = green phase (seconds), so that
$c = r + g$ (ignoring amber phase);
t_1 = time of arrival of the first vehicle during the red phase;
t_2 = time of arrival of the last vehicle during the red phase;
t_3 = end of the red phase when the first vehicle in the queue starts moving;
t_4 = time when last vehicle in the queue clears the intersection, denoting the beginning of the simultaneous arrival-service process; and
t_5 = time when the last vehicle in the simultaneous arrival-service mode clears the intersection.

(Note: all t_i values are measured in seconds from the start of the red phase along the bus street.)

For Bus Street (Figure 1)

The number of vehicles arriving for service during time period $(t_2 - t_1)$ is $\lambda_b(t_2 - t_1)$ and the number of vehicles serviced during

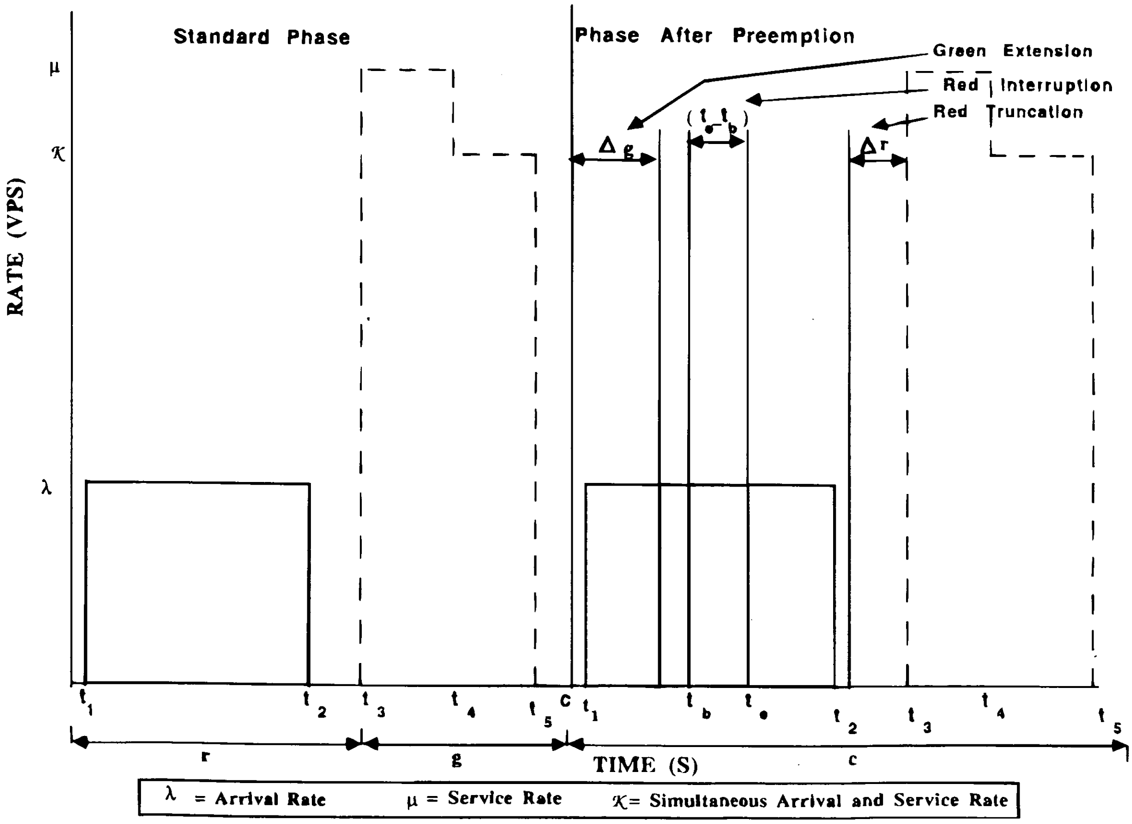

FIGURE 1 Arrival-service rate diagram (bus street).

time period $(t_4 - t_3)$ is $\mu_b(t_4 - t_3)$, until the queue is completely discharged.

Further, since the queue is totally discharged,

$\lambda_b(t_2 - t_1) = \mu_b(t_4 - t_3)$ (Note: the subscript "b" represents the bus street) and $Q_m = \lambda_b(t_2 - t_1)$ where Q_m is maximum queue length (in number of vehicles) and $t_4 - t_1$ is time duration of the queue.

The number of vehicles processed during simultaneous arrival and service is $k_b(t_5 - t_4)$. If Δg is the amount of green extension (seconds), then $\Delta g - t_1$ is the amount of green time effectively utilized by arriving vehicles so that the traffic consequences of Δg seconds of green extension per cycle can be derived as

$$\lambda_b(\Delta g - t_1) = \text{savings in the maximum queue length in number of vehicles} \qquad (1)$$

$$\lambda_b(\Delta g - t_1) \times (t_3 - \Delta g) = \text{savings in delay in vehicle seconds} \qquad (2)$$

For Cross Street (Figure 2)

The traffic consequences of Δg seconds of green extension for the bus street on the cross street are as follows:

$$\text{Increased delay to cross street} = \mu_c\,[(t_4 - t_3)\,\Delta r + (t_5 - t_4)\Delta r] = \mu_c\Delta r(t_5 - t_3) \qquad (3)$$

(Note: the subscript "c" represents the cross street)

where Δr is additional red time along the cross street due to preemption (for all practical purposes, $\Delta r = \Delta g$, identified with the bus street).

Further, if the time needed for all the vehicles to clear the intersection (both those queued as well as those arriving during the green phase) exceeds the net green time (i.e., the original green time minus the lost time due to preemption) by an amount Δt, then additional delay and increase in queue length can be computed with Equations 4 and 5. In these equations, Δt_m is that portion of Δt comprising service events, and Δt_k is that portion of Δt comprising simultaneous arrival and service events. Additional delay and queue length can be computed as follows:

$$\text{Additional delay} = (\mu_c\Delta t_\mu + k_c\Delta t_k)\,(c-g) \qquad (4)$$

$$\text{Increase in queue length} = \mu_c\Delta t_\mu + k_c\Delta t_k = \text{loss in throughput} \qquad (5)$$

Similar algorithms for estimating delay and queue length consequences for red truncation and red interruption were developed separately for the bus street and cross street; these are not included in the text. However, results for all the three strategies are presented.

Method 2

Method 2 uses microscopic simulation, in which arrival and service rates are found by regression from the individual vehicle data points for three consecutive cycles, with the revised signal timings (resulting from preemption) altering the original signal timing for the first of the three consecutive cycles to assess traffic flow consequences. The amber phase was assumed to be part of the green phase.

The base condition data containing the arrival and service times of individual vehicles are used to find average arrival and service

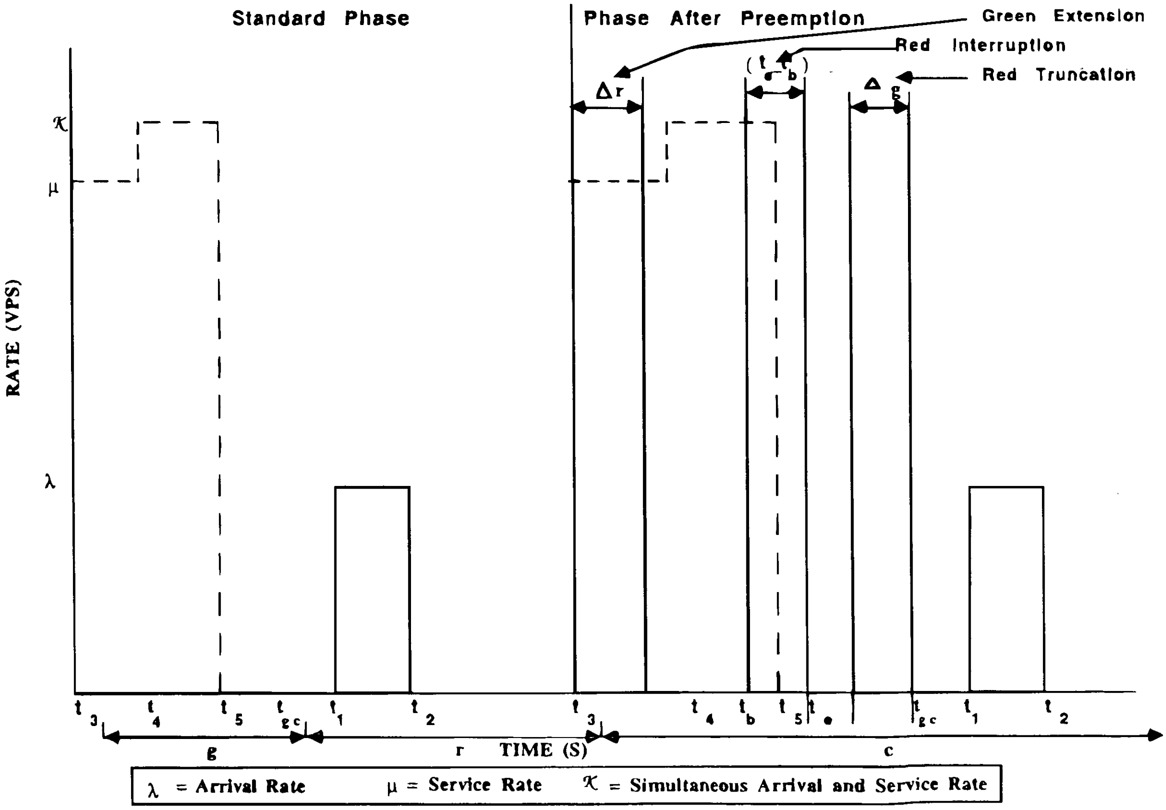

FIGURE 2 Arrival-service rate diagram (cross street).

rates by regression for all three cumulative cycles. These three values for arrival and service rates, as well as the number of vehicles that arrived during each cycle and the effective red times of each cycle, are then averaged. These values are then used to find the maximum queue, Q_m, the time duration of the queue, t_q, the average individual delay, and the total delay, TD, from the following equations:

Maximum queue, $Q_m = \lambda r$ (6)

where λ is the average of the arrival rates found by regression for the three cycles.

Time duration of the queue, $t_q = \mu r / (\mu - \lambda)$ (7)

where μ is the average of the service rates found by regression for the three cycles and r is the average of the effective red times for the three cycles.

Average individual delay, $d_a = (r\, t_q) / 2c$ (8)

where c is the average cycle length of the three cycles.

Total delay, $TD = d_a N$

where N is the average number of vehicles arriving in the three consecutive cycles.

The effect of a 10-sec green extension is found by analyzing the individual vehicular data for the second of the three cycles to determine the number of vehicles that arrive within the first 10 sec of this cycle, as these vehicles would now be processed during the first cycle due to the green extension. New values of λ and r are found, and the total delay is calculated as in the base condition using these new values. The change in the total delay is then the effect of the green extension. Essentially the same technique is used for the bus street and for the cross street, with the basic provision that a gain in Δg seconds of green time along the bus street would imply a loss of Δg seconds along the cross street.

RESULTS

Results of the application of the two methods on the three candidate intersections are presented in this section. The three intersections are designated as follows:

Volume Level on Cross St.	*Intersection*	*Description*	*Cycle Length (sec)*
Low	1	Washtenaw with Manchester/Sheridan	70
Medium	2	Washtenaw with Forest/Observatory	70
High	3	Washtenaw with Golfside	70

Compilation of Arrival and Service Rates

In Table 1, the t_i values for Intersection 1 are presented based on 10 cycles of observations. Table 1 shows that for the bus street through lane, the first vehicle arrived 10.3 sec after the start of the red phase. The last vehicle in the queue arrived at 23.4 sec. The first vehicle in the queue started moving at the beginning of the green phase at 26 sec and the last queued vehicle cleared the intersection at 42.1 sec. Between 42.1 and 64.9 sec, simultaneous arrivals and services occurred during the green phase. No arrivals were recorded between 64.1 sec and the end of the cycle at 70 sec.

TABLE 1 Values of t_i (seconds) for the Intersection of Washtenaw-Manchester/Sheridan

Approach (1)	Lane (2)	t_i - values (3)				
		t_1	t_2	t_3	t_4	t_5
Washtenaw EB (Bus Street)	Thru 1	10.3	23.4	26.0	42.1	64.9
	Thru 2	10.8	23.9	26.0	43.0	64.4
	Right	17.9	20.4	26.0	43.6	52.5
	Left	x	x	26.0	61.8	63.5
Washtenaw WB (Bus Street)	Thru 1	9.7	25.2	26.0	41.7	57.3
	Thru 2	9.2	15.9	26.0	38.6	58.5
	Thru 3/Right	5.0	22.2	26.0	41.4	57.4
	Left	10.8	11.7	26.0	52.9	x
Manchester (Cross Street)	Thru/Right	46.3	54.3	0.0	10.5	10.8
	Left	41.3	41.9	0.0	2.6	x
Sheridan (Cross Street)	Thru/Right	39.9	54.3	0.0	5.5	x
	Left	35.3	49.6	0.0	5.8	x

Table 2 gives the average rates of arrival (λ), service (μ), and simultaneous arrival-service (k) compiled from the observation of 10 consecutive cycles. Expressed in vehicles per second, these rates are computed for each lane from average time intervals between successive arrivals and service. Similar information for the other two intersections was also derived from the data collected.

Traffic Operational Consequences

Intersection 1 A low volume

Tables 3, 4, and 5 show the operational consequences of the three preemption strategies for a 10-sec interval for the low-volume intersection using the models presented earlier. The negative signs represent reductions and the positive signs represent increases. Table 3 shows that the use of Method 1 will result in an increase of 31 vehi-

TABLE 2 Average Arrival and Service Rates (vehicles/second) for All Lanes at the Washtenaw-Manchester/Sheridan Intersection

Approach (1)	Lane (2)	Arrival Rate (λ) (3)	Service Rate (μ) (4)	Simultaneous Arrival/Service Rate (k) (5)
Washtenaw EB	Thru 1	0.53	0.51	0.46
	Thru 2	0.56	0.48	0.49
	Right	0.64	0.37	0.37
	Left	x	0.03	0.14
Washtenaw WB	Thru 1	0.22	0.38	0.24
	Thru 2	0.28	0.24	0.18
	Thru 3 & Right	0.30	0.41	0.19
	Left	0.74	1.0	x
Manchester	Thru & Right	0.11	0.32	0.67
	Left	0.50	0.29	x
Sheridan	Thru & Right	0.17	0.31	x
	Left	0.16	0.13	x

TABLE 3 Traffic Operational Consequences of Green Extension(10 sec) on the Intersection 1(Low-volume) for Every Cycle Preempted

Approach	Lane	ΔDelay (veh-sec)		ΔQueue (veh)	
		Method 1	Method 2	Method 1	Method 2
Washtenaw EB (Bus Street)	Thru 1	0	-35	0	-0.9
	Thru 2	0	-43	0	-1.1
	Right	0	0	0	0
	Left	0	0	0	0
Washtenaw WB (Bus Street)	Thru 1	-1	-13	-0.1	-0.5
	Thru 2	-4	0	-0.2	0
	Thru 3/Right	-24	-5	-1.5	-0.3
	Left	0	0	0	0
Total - Washtenaw		-29	-96	-1.8	-2.8
Manchester (Cross Street)	Thru/Right	35	14	0	0.7
	Left	8	0.6	0	0.6
Sheridan (Cross Street)	Thru/Right	9	2.7	0	0.4
	Left	8	0	0	0
Total - Manchester/Sheridan		60	17.3	0	1.7
Total - Intersection		31	-78.7	-1.8	-1.1

cle-sec of delay and a reduction of 1.8 vehicles of queue length for the intersection as a whole for every cycle preempted by 10 sec of green extension. Corresponding figures for each approach are also presented in Table 3. Method 2 predicts reductions in delay of 78.7 vehicle-sec and in queue length by 1.1 sec. The following observations may be made:

- Table 4 shows that with Method 1, for every cycle preempted by a 10-sec red truncation, 662 vehicle-sec of savings in delay and 13.2 vehicles of queue length savings will result. All of these savings will result from the bus street with no adverse effect on the cross street. Predictions by Method 2 are considerably smaller, with reductions in delay and in queue length of 100.5 vehicle-sec and 6.1 vehicles, respectively.
- Table 5 shows that as a result of 10 sec of red interruption, 925 vehicle-sec of delay and 15.6 vehicles of queue length will be saved per cycle preempted, as predicted by Method 1. A minimal adverse effect will be observed on the cross street (10 vehicle-sec). With Method 2, savings in delay are considerably lower.

Intersection 2: Medium Volume

Tables 6, 7, and 8 show the operational consequences of the three preemption strategies on Intersection 2 (medium volume). These three tables may be interpreted in the same manner as Tables 3, 4, and 5. The differences in the model output predicted by Method 1 versus Method 2 appear to have decreased some-

TABLE 4 Traffic Operational Consequences of Red Truncation(10 sec) on the Intersection 1(Low-volume) for Every Cycle Preempted

Approach	Lane	ΔDelay (veh-sec)		ΔQueue (veh)	
		Method 1	Method 2	Method 1	Method 2
Washtenaw EB (Bus Street)	Thru 1	-82	-37	-3.9	-1.0
	Thru 2	-82	-43	-3.8	-1.1
	Right	-65	0	-1.6	0
	Left	-11	0	0	0
Washtenaw WB (Bus Street)	Thru 1	-60	-14	-2.0	-0.4
	Thru 2	-30	-1.5	0	-3.4
	Thru 3/Right	-63	-5.0	-1.9	-0.2
	Left	-269	0	0	0
Total - Washtenaw		-662	-100.5	-13.2	-6.1
Manchester (Cross Street)	Thru/Right	0	0	0	0
	Left	0	0	0	0
Sheridan (Cross Street)	Thru/Right	0	0	0	0
	Left	0	0	0	0
Total - Manchester/Sheridan		0	0	0	0
Total - Intersection		-662	-100.5	-13.2	-6.1

TABLE 5 Traffic Operational Consequences of Red Interruption(10 sec) on the Intersection 1(Low-volume) for Every Cycle Preempted

Approach	Lane	ΔDelay (veh-sec)		ΔQueue (veh)	
		Method 1	Method 2	Method 1	Method 2
Washtenaw EB (Bus Street)	Thru 1	-123	-67	-4.1	-1.3
	Thru 2	-120	-46	-4.0	-1.2
	Right	-95	0	-0.1	0
	Left	-13	0	0	0
Washtenaw WB (Bus Street)	Thru 1	-90	-33.0	-1.8	-1.1
	Thru 2	-49	-3.1	-1.9	-9.2
	Thru 3/Right	-96	0	-3.0	0
	Left	-349	-5.8	-0.7	-0.1
Total - Washtenaw		-935	-155	-15.6	-12.9
Manchester (Cross Street)	Thru/Right	10	0	0	0
	Left	0	0	0	0
Sheridan (Cross Street)	Thru/Right	0	0	0	0
	Left	0	0	0	0
Total - Manchester/Sheridan		10	0	0	0
Total - Intersection		-925	-155	-15.6	-12.9

what for the red interruption and red truncation strategies, compared with the low-volume intersection presented in the previous section.

Intersection 3: High Volume

Tables 9, 10, and 11 give the traffic operational consequences predicted by the two methods on the high-volume intersection. The differences in the operational consequences predicted by the two methods appear to have decreased somewhat compared with the medium volume level intersection, particularly for the green extension and red truncation strategies than for the red interruption strategy.

Delay In Person-Seconds

The delay results presented in this study are expressed in vehicle-seconds, where each vehicle is the basic unit of measurement. However, the overriding impetus for preemption is the fact that a bus generally carries many more passengers than a car. Preemption is viewed as a means to increase the throughput of persons rather than vehicles. To account for this, the delay data were converted from vehicle-seconds to person-seconds using the following assumptions:

- Preemption is triggered only if at least one of the approaching vehicles is a bus,
- No more than one bus benefits from the preemption,

TABLE 6 Traffic Operational Consequences of Green Extension(10 sec) on the Intersection 2(Medium-volume) for Every Cycle Preempted

Approach	Lane	ΔDelay(veh-sec)		ΔQueue (veh)	
		Method 1	Method 2	Method 1	Method 2
Washtenaw EB (Bus Street)	Thru	0	-14	0	0
	Thru/Right	-9.3	-53	-0.4	-0.7
	Left	0	0	0	0
Washtenaw WB (Bus Street)	Thru	0	-31	0	-0.8
	Thru/Right	0	0	0	0
	Left	0	0	0	0
Total - Washtenaw		-9.3	-98	-0.4	-1.5
Observatory (Cross Street)	Thru	0	0	0	0
	Thru/Right	0	0	0	0
	Left	183	6	2.9	0.6
Forest (Cross Street)	Thru	0	0	0	0
	Thru/Right	0	0	0	0
	Left	103	0	1.6	0
Total - Forest/Obsevatory		286	6	4.5	0.6
Total - Intersection		277	-92	4.1	-0.9

TABLE 7 Traffic Operational Consequences of Red Truncation(10 sec) on the Intersection 2(Medium-volume) for Every Cycle Preempted

Approach	Lane	ΔDelay (veh-sec)		ΔQueue (veh)	
		Method 1	Method 2	Method 1	Method 2
Washtenaw EB (Bus Street)	Thru	-47	-38	0	-0.6
	Thru/Right	-56	-38	0	-0.5
	Left	-8	0	0	0
Washtenaw WB (Bus Street)	Thru	-43	0	0	0
	Thru/Right	-33	-15	0	-0.4
	Left	0	0	0	0
Total - Washtenaw		-187	-91	0	-1.5
Observatory (Cross Street)	Thru	0	6	0	0.2
	Thru/Right	0	4	0	0.6
	Left	0	0	0	0
Forest (Cross Street)	Thru	0	0	0	0
	Thru/Right	0	0	0	0
	Left	14	0	0.3	0
Total - Forest/Observatory		14	10	0.3	0.8
Total - Intersection		-173	-81	0.3	-0.7

- The candidate bus is traveling on the rightmost through lane on Washtenaw eastbound,
- Because of the unidirectional peak flow (p.m.) in the easterly direction, no bus on Washtenaw westbound benefits from preemption,
- Average automobile occupancy is 1.3 passengers/vehicle,
- Average bus occupancy is 20 persons/bus, and
- Bus stop location is at far side.

Revised Output for Red Interruption

Because the system is burdened with an additional amber phase for every red interruption granted, the authors decided that a correction should be made to the results of red interruption. Although the amber phase is considered part of the green phase, the correction is recommended to make up for a basic inconsistency in the assumption. In the cases of green extension and red truncation, the system is not subjected to the burden of an additional amber phase because the extension or truncation periods are contiguous to the regular green or red phase. This is not true for the red interruption strategy. For every interruption granted, an additional amber phase is required. Therefore the results were corrected by a factor of 0.65 (6.5 net green-sec out of a total of 10 sec, to provide for a 3.5-sec amber phase).

The delay and queue length data based on person-seconds and persons are shown in Table 12. It should be noted that for the green extension strategy, no bus qualified for preemption for the low-volume intersection. However, for the purpose of computing delay in person-seconds, an assumption was made that one bus (carrying 20 passengers) benefited from preemption. This assumption is justified because unless a bus preempts the signal, the increase in delay for the cross street would not materialize either.

TABLE 8 Traffic Operational Consequences of Red Interruption(10 sec) on the Intersection 2(Medium-volume) for Every Cycle Preempted

Approach	Lane	ΔDelay (veh-sec)		ΔQueue (veh)	
		Method 1	Method 2	Method 1	Method 2
Washtenaw EB (Bus Street)	Thru	-56	45	-2.0	-1.6
	Thru/Right	-64	-117	-2.3	-0.8
	Left	-10	0	-0.3	0
Washtenaw WB (Bus Street)	Thru	-49	0	-2.7	0
	Thru/Right	-37	-33	-1.6	-1.5
	Left	0	0	0	0
Total - Washtenaw		-216	-105	-8.9	-3.9
Observatory (Cross Street)	Thru	16	7	0	0.2
	Thru/Right	25	4	0	0.7
	Left	8	0	0	0
Forest (Cross Street)	Thru	18	0	0	0
	Thru/Right	0	0	0	0
	Left	0	0	0	0
Total - Forest/Observatory		67	11	0	0.9
Total - Intersection		-149	-94	-8.9	-3.0

TABLE 9 Traffic Operational Consequences of Green Extension(10 sec) on the Intersection 3(High-volume) for Every Cycle Preempted

Approach	Lane	ΔDelay (veh-sec)		ΔQueue (veh)	
		Method 1	Method 2	Method 1	Method 2
Washtenaw EB (Bus Street)	Thru	-87	-82	-1.6	-0.9
	Thru/Right	-48	-43	-0.9	-0.6
	Left	0	0	0	0
Washtenaw WB (Bus Street)	Thru	0	-34	0	-0.3
	Thru/Right	-46	-56	-0.8	-0.7
	Left	0	0	0	0
Total - Washtenaw		-181	-215	-3.3	-2.5
Golfside SB (Cross Street)	Thru	0	0	0	0
	Thru/Right	0	0	0	0
	Left	129	28	0.8	0.3
Golfside NB (Cross Street)	Thru	0	0	0	0
	Thru/Right	0	0	0	0
	Left	103	12	0.3	0.2
Total - Golfside		232	40	1.1	0.5
Total - Intersection		51	-175	-2.2	-2.0

TABLE 11 Traffic Operational Consequences of Red Interruption (10 sec) on the Intersection 3(High-volume) for Every Cycle Preempted

Approach	Lane	ΔDelay (veh-sec)		ΔQueue (veh)	
		Method 1	Method 2	Method 1	Method 2
Washtenaw EB (Bus Street)	Thru	-237	-267	-2.2	-2.6
	Thru/Right	-186	-183	-1.8	-2.4
	Left	0	0	0	0
Washtenaw WB (Bus Street)	Thru	-207	-100	-1.5	0.4
	Thru/Right	-223	-207	-1.9	-2.4
	Left	0	0	0	0
Total - Washtenaw		-843	-757	-7.4	-7.0
Golfside SB (Cross Street)	Thru	249	0	2.4	0
	Thru/Right	418	468	4.4	0.8
	Left	0	0	0	0
Golfside NB (Cross Street)	Thru	56	0	0.5	0
	Thru/Right	277	0	2.9	0
	Left	0	0	0	0
Total - Golfside		1000	468	10.2	0.8
Total - Intersection		157	-289	2.8	-6.2

Results of Method 1 versus Method 2

A review of the results presented in Table 12 indicates significant differences in the delay output derived by the two methods. However the differences are less significant when comparing the queue data. Also, differences in delay appear to be more significant in the case of the low-volume, undersaturated intersection. Method 2 generally appears to under-predict savings in delay compared with Method 1. Further research is necessary before these differences can be fully explained. Current literature suggests that macroscopic simulation (Method 1) is more effective under steady-state conditions than under random flow conditions. When vehicular arrival rates are high, any randomness in the individual arrivals around the mean becomes insignificant. In the present study (for the low-volume intersection in particular), arrival rates cannot be considered high. Thus, the assumption of uniform arrival rate by Method 1 (based on data collected for 10 cycles) can be questioned.

By contrast, Method 2 uses individual vehicular arrival data over a three-cycle period. Because of the randomness in arrivals at low volumes, microscopic simulation may be considered more effective for Intersection 1. A major disadvantage of the results obtained by Method 2 is that simulation was conducted over a three-cycle period, and data collected over such a limited period may not be representative of the majority of arrivals during peak hours of operation. Both methods have advantages and disadvantages, and a decision to use Method 1 or Method 2 should be made based on traffic conditions. Intuitively, microscopic simulation (Method 2) should work better under low-volume conditions because of the implicit assumption of constant arrival patterns under macroscopic simulation (Method 1). From the point of view of statistical reliability, for high-volume conditions (when arrival patterns are likely to be more homogeneous) Method 1 appears to be a better approach. However, all of these observations require validation through further research.

TABLE 10 Traffic Operational Consequences of Red Truncation (10 sec) on the Intersection 3(High-volume) for Every Cycle Preempted

Approach	Lane	ΔDelay(veh-sec)		ΔQueue (veh)	
		Method 1	Method 2	Method 1	Method 2
Washtenaw EB (Bus Street)	Thru	-114	-55	0	-0.5
	Thru/Right	-87	-40	0	-0.5
	Left	146	29	1.5	0.3
Washtenaw WB (Bus Street)	Thru	-99	-31	-1.1	-0.4
	Thru/Right	-118	-42	-0.2	-0.5
	Left	0	6	0	-0.5
Total - Washtenaw		-272	-133	0.2	-2.1
Golfside SB (Cross Street)	Thru	0	0	0	0
	Thru/Right	0	0	0	0
	Left	0	0	0	0
Golfside NB (Cross Street)	Thru	0	0	0	0
	Thru/Right	0	0	0	0
	Left	0	0	0	0
Total - Golfside		0	0	0	0
Total - Intersection		-272	-133	0.2	-2.1

TABLE 12 Traffic Operational Consequences Expressed at the Personal Level for Three Preemption Strategies

Strategy	Intersection	ΔDelay		ΔQueue Length	
		Method 1	Method 2	Method 1	Method 2
Green Extension	1	-280	-389	-22.3	-20.1
	2	-991	-1292	-22.9	-21.8
	3	-168	-628	-14.7	-21.0
Red Truncation	1	-1048	-318	-35.9	-26.6
	2	-541	-360	-19.7	-22.1
	3	-412	-292	-19.6	-20.3
Red Interruption Original	1	-1394	-356	-39.0	-35.5
	2	17	-563	-15.1	-26.8
	3	-381	-309	-30.3	-22.8
Red Interruption Corrected	1	-906	-234	-25.4	-23.1
	2	13	-366	-12.0	-17.4
	3	-248	-201	-19.7	-15.0

Comparative Results of the Three Strategies

It is difficult, if not impossible, to make any comparative evaluation of the three preemption strategies from the limited data developed in this study. The strategies' actual effectiveness depends on how many vehicles clear the intersection along the bus street behind the bus that triggers the preemption device, and how many vehicles are made to stop along the cross street. If vehicular arrivals are random (for low-volume conditions), a large sample size would be required to discern any trends. For uniform arrivals (because of homogeneity in arrival patterns), general conclusions may be derived with a smaller sample size.

CONCLUSIONS

The purpose of this study is to present a procedure for assessing delay and queue length consequences of bus preemption at signalized intersections. Two methods are presented that are adapted from queueing theory and that use a deterministic approach to simulate traffic flow at the intersection by superimposing a revised signal phasing on the regular signal phasing. Constant rates of arrivals, services, and simultaneous arrivals and services were used in the manual simulation of Method 1, and a regression analysis was performed on the data points to obtain arrival and service rates for Method 2. Separate procedures for green extension, red truncation, and red interruption were developed. The procedures developed were applied to three signalized intersections on a major bus corridor in Ann Arbor, Michigan, representing various volume levels. The conclusions of the study are:

1. The procedures developed appear viable, and the case studies presented indicate some variations in the results from the three strategies, as well as from the three intersections. Such variations are expected due to the inherent differences in the nature of the strategies as well as in the vehicular arrival patterns at the intersection.
2. The case studies appear to indicate more significant differences in the delay results for Method 1 and Method 2. However, differences in queue lengths as derived by the two methods for compatible strategies are less significant.
3. The validity of the assumption of constant arrival, service, and simultaneous arrival and service rates made by Method 1 can be questioned for the low-volume intersection. Under such circumstances, Method 2 appears to be more effective.
4. For higher volume levels, Method 1 may be more appropriate.
5. Further research is needed to validate the proposed methods.

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