ever, ranks high because of its good safety record and excellent mobility rating.

3. The urban area rated high most consistently in terms of street and highway performance is Fresno, which ranks fifth in accessibility and twelfth in both safety and mobility and therefore has the second highest score in the composite index.
4. Grand Rapids, most nearly typical of the urban areas analyzed, scores 102.6 in accessibility, 97.2 in mobility, and 98.9 in safety and has a composite score of 106.5.
5. No single urbanized area ranks consistently low in all the indexes.
6. Columbus, highest scoring in the safety index, has an injury rate of less than half the arithmetic mean of the 52 selected urbanized areas, indicating a street and highway system that was designed and is being operated with strong emphasis on safe movement of motor vehicles and pedestrians.
7. St. Petersburg, which has an accessibility score of 195.7 and is the leader of that index, has almost twice the road kilometers per square kilometer of land of the average urbanized area and an accessibility score four times that of the lowest ranked city, Montgomery. The St. Petersburg urbanized area is apparently highly compact; most of its urbanized area is fully developed and well served by streets and highways. The Montgomery urbanized area apparently contains much underdeveloped land not well served by roads.

Since all urbanized areas are not included, the resulting indexes of highway service cannot be interpreted as national rankings. No doubt other urbanized areas have highway service characteristics both superior and inferior to those of the cities selected.

NEEDED RESEARCH

Traffic volume and roadway capacity data, as reported in the 1974 National Transportation Study, were used to assess mobility. However, average speed data segregated by various functional classes of urban road would more directly indicate vehicle mobility. Unfortunately, such data are not as yet universally available, and volume-to-capacity ratios are used instead.

Further study might show that other features of road performance in addition to accessibility, mobility, and safety might prove to be useful in analyzing urban road performance. An engineering appraisal of road surface might be included in further study because of the importance of road surface to travel comfort and to vehicle maintenance cost. But again such data are not generally available.

More study is required to translate performance measures into standards against which urban street and highway performance can be compared. Lacking standards for accessibility, mobility, and safety, we relied on the arithmetic mean for the selected cities as a basis for judging the comparative road performance. Further research might define, for example, an optimum road density as a benchmark for accessibility.

The question of weighting the performance measures is raised because the relative importance of the measures used in the analysis is unknown. For instance, the importance of mobility relative to accessibility is not clear. Lacking such information this analysis gave equal weight to each measure. Further research might reveal that accessibility, for example, is a relatively minor consideration, and safety and mobility are the primary measures of urban road performance. Particularly useful in this regard would be factor-analysis techniques applied to existing data.

CONCLUSIONS

This analysis of urban highway performance confirms the assumption that there are differences in quality of highway service in urbanized areas and that methods can be devised to assess urban road performance. However, lack of adequate data is a serious impediment to use of any method in comparing or monitoring urban road performance.

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Methodology for Evaluating Bus-Actuated, Signal-Preemption Systems

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The objective of this research was to model the impact of bus-actuated, signal-preemption systems on delay experienced by buses at signalized intersections and to develop a methodology to evaluate these systems by location. The model developed is green-extension strategy that quantifies the effect of the system on bus and other traffic at intersections depending on the characteristics of the intersections. Based on random arrivals, equations quantify the travel-time savings and losses experienced. Then, the cost of the preemption system is developed, and a revenue-cost ratio for any location is developed. The application of this revenue-cost methodology to a local bus route resulted in a 14:1 revenue-cost ratio. Transportation planners who reviewed this result and methodology expressed the desire to emphasize the ability of this system to reduce bus running times enough to remove at least one bus from the route. This criterion was applied and a bus was removed in the test cor-

ridor. Another result of this review was the initiation of field checks to test the assumption of random bus arrivals. Although these checks are not complete, the preliminary results suggest that under most circumstances the random-bus-arrival assumption is valid. Furthermore, in the cases that are being identified by these field checks as not having a uniform distribution, the distribution may either lessen or enhance the feasibility of a signal-preemption installation. From these results we concluded that the methodology and the priority technique are both sound.

Delay of buses at controlled intersections constitutes 10 to 20 percent of the average bus trip time (1). Bus-actuated, signal-preemption systems minimize or eliminate bus delays at intersections by temporarily altering the traffic signal phase so that an approaching bus receives a green phase when it arrives. The development of signal actuation by buses was prompted by the difficulty of adjusting standard fixed-time signal controllers to platoon buses through a series of controlled intersections because bus travel time through the same route segment varies from run to run. This variance is caused mainly by variations in the number of passengers boarding and alighting and the time that each passenger takes.

Figure 1 (2) shows the difference in the normal movements of a platoon of traffic and a bus. Because of this mismatch between signal-timing characteristics and bus-operating characteristics, experiments have been conducted to test a variety of methods for minimizing bus delays at signalized intersections. Through the Urban Traffic Control System-Bus Priority System (UTCS-BPS), U.S. experiments in Washington, D.C., Miami, and Louisville have concentrated on the development of hardware and software for area control of a series of interconnected intersections (3, 4, 5, 6, 7, 8). In Europe the emphasis has been on understanding the impact of controlling isolated intersections (9).

In most of these experiments bus-actuated, signal-preemption systems proved to be feasible and, in fact, to provide significant time savings to the bus user and transit operator. Moreover, time savings can generally be gained without seriously affecting cross-street traffic. The reduction in mean travel time for buses produces a more attractive service and enables the same level of service to be provided with fewer buses; thus revenue is increased but cost is reduced. However, to date little work has been done on generalizing the results of these experiments, and design guides and warrants for bus-actuated, signal-preemption systems have not been developed. [The exception is a report by Ludwick (10).]

The purpose of this research, therefore, was to examine the operating conditions under which a signal-preemption system can be operated and to construct equations that describe the costs and benefits to buses and other traffic. These equations were then used to develop a method by which the economic desirability of installing a bus-actuated, signal-preemption system at any particular location could be evaluated. This paper summarizes the results of a literature search on this topic, describes planning guidelines for use of the technique, and describes the development of the methodology.

CHARACTERISTICS OF A BUS-ACTUATED, SIGNAL-PREEMPTION SYSTEM

System Components and Operating Characteristics

A bus-actuated, signal-preemption system allows the bus driver to communicate with signal controllers and "instruct" them to alter the phase of the signal so that the bus has a green phase available when it arrives at the intersection. The system must contain three basic components: an identification scheme, a communication link, and a logic unit incorporated into the controller's operations. The identification scheme most commonly used involves a radio transmitter carried aboard the bus; however, magnetic and optical detection schemes are also possible. The bus-carried radio transmitter emits an ultrahigh frequency (UHF) signal or uses a near-field transmission that is picked up by a loop antenna buried in the roadbed. The cost of these transmitters ranges from $30 to $50/bus. The estimated cost of on-site equipment is $50 for an antenna and $100 for a receiver. The cost of a single approach that uses two antennas and one receiver is $400, plus modifications to the signal control and installation costs of approximately $200. If an intersection contains more than one bus approach, the cost of modification to the controller could probably be shared. OPTICOM, a system developed by the 3M Company, uses an optical transmitter with a receiver that is mounted on the traffic signal standard, which eliminates some construction costs. However, emitter (sender) units cost more for this equipment.

Hardware technology, however, is advancing; thus the cost of signal-preemption systems is being reduced while effectiveness is being increased. An example is the Passive Bus Detector/Intersection Priority System (PBD/IPS) that was developed by the Federal Highway Administration (FHWA) (11). The PBD/IPS uses an inductive loop detector and transducer that identify various vehicles by a unique magnetic signature and thus eliminates the need for bus-carried equipment.

The communication link connects the identification scheme with either a centralized computer or a localized logic unit. Carrying the message that a bus is approaching and other related messages to a centralized logic unit, such as a computer, requires a complex network and a sharp increase in equipment and installation costs. Thus, an important factor in the choice of systems is the cost of such an extensive communication network.

The logic unit receives a stimulus from the detectors, after which the unit implements a preemption action, subject to any constraints incorporated within its algorithm. The most sophisticated logic unit possible is a computer, which could collect information from several sources and make a split-second decision on the granting of a preemption. The simplest logic unit would be mechanical and would properly plan the configuration of the system to control the preemption. Whichever method is used, the logic unit then produces a command that is carried to the relay logic interfaced with the standard traffic-signal controller and alters the cycle phase.

Signal Modifications

A preemption can be performed by extending the green phase, truncating the red phase, or interrupting the red phase. Red truncation and red interruption were found to be less effective and more difficult to implement. Therefore, these modifications were not considered further in this analysis.

Green extension, which was analyzed, consists of the elongation of the green phase when an approaching bus has been detected and the system has determined that the arrival time of the bus is within a period immediately following the start of the red phase and some maximum extension length. If the bus arrival were detected after the start of the red phase, then the extension would not be contiguous to the preceding green phase, and thus the

Figure 1. Time-distance difference between normal movements of traffic platoon and bus.

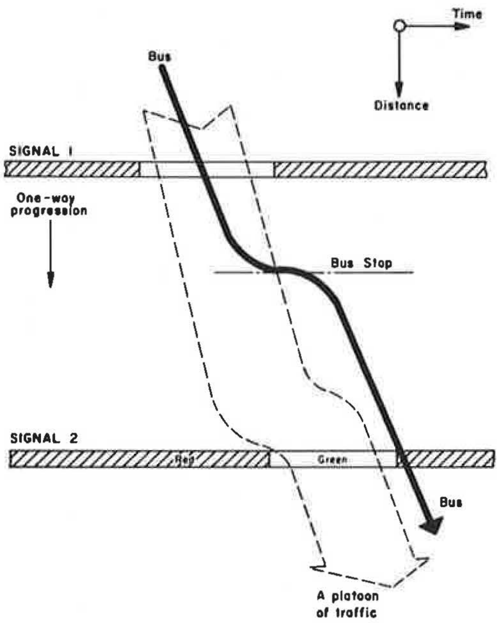
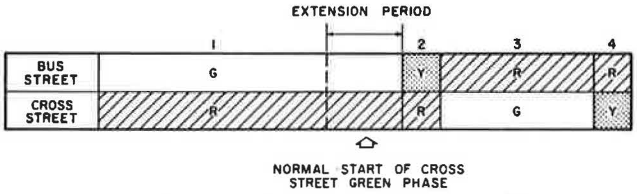


Figure 2. Signal modification to delay red phase and extend green phase.



green extension would not be possible. When the bus is expected to arrive within the period immediately following the phase change, then the red phase is delayed and the green phase is extended until the bus has entered the intersection or the maximum extension period has been reached (Figure 2).

System Logic Processes

The signal modification previously described is implemented by predetermined logic incorporated into the components of the system. These components determine whether an approaching bus needs a signal preemption to avoid stopping at an intersection and whether a bus is eligible to receive the particular signal modification the preemption system has available. The components must determine three events:

1. When a bus is detected;
2. When a bus is expected to arrive at the intersection (thus, whether it will probably need a priority); and
3. Whether the bus-arrival time allows the bus to be eligible for a particular signal modification.

Although complicated, the process can be accomplished by using simple mechanical components if the system is configured correctly.

When a bus is detected, bus-arrival time at the intersection is assumed to be equal to the detection time plus the average travel time from the detector to the intersection. Then, if the arrival is expected at a time when priority is possible, the signal modification is put into effect. For this signal modification to occur, however, the travel time between the detector and the intersection must also be greater than or equal to the maximum length of the preemption period. This time factor is necessary to ensure the use of the full preemption period. For example, a bus that is expected to arrive at 10 s after the start of the red phase will not get a preemption from a 10-s green-extension strategy if this bus is detected only 6 s before its arrival at the intersection because the red phase will have begun 4 s before its arrival. Thus, the bus must be detected 10 s before its arrival at the intersection for the system logic to determine whether the phase change should be delayed.

Operational Limitations

The maintenance of pedestrian safety affects the operation of any signal-preemption system. If pedestrians cross with vehicle flow, pedestrians must be stopped from entering the intersection and pedestrians already crossing must clear the intersection before the end of the green phase. This usually is performed by flashing DON'T WALK or DON'T START signals. The length of pedestrian clearance time depends on the geometrics of the intersection. The standard speed for pedestrian movement used by traffic engineers is 1.22 m/s (4 ft/s). Thus, the time necessary for clearance (y) is

$$y = (\text{distance } x/1.22 \text{ m/s}) \qquad (1)$$

As a result, the distance a pedestrian must travel to cross the bus-street width determines the limit to which the preemption can encroach on the normal green time of the cross street.

Another constraint that must be dealt with in the design of a signal-preemption system is adequate clearance time for cross-street traffic. In essence, the designer of the system must balance two conflicting objectives: expedite bus travel and at the same time not unduly delay cross-street traffic. Thus the designer must constrain the preemption period based on minimum green time necessary for vehicle clearance if that preemption period is longer than pedestrian clearance time. If the existing green time for the cross street exceeds the longer of the two minimum clearance times, the excess amount is slack time. This slack time is the portion of cycle length not necessary to maintain cross-street traffic flow and pedestrian safety and can be shifted, when needed, to the green phase on the bus street to avoid delay.

COSTS AND REVENUES OF SIGNAL-PREEMPTION SYSTEMS

To develop a warrant for bus-actuated, signal-preemption systems, we had to perform the following:

1. Obtain cost data for necessary equipment;
2. Assign values to time savings associated with signal preemption;
3. Devise equations that describe the effects of signal preemption on traffic conditions; and
4. Devise equations that describe the relation between system costs, return per preemption, and frequency of bus use of preemption system.

The warrant was then applied by calculating revenue-cost ratios for installation of preemption equipment at candidate intersections.

The methodology understates the return from the system because generalizing the results of preemption installation is not possible with respect to attracting new riders. The modal split for a given corridor is the result of the relative attractiveness of all modes and the characteristics of the trip makers, not the absolute performance of the preemption installation. Thus, although signal preemption would increase bus ridership and system revenue, these benefits are not counted in this methodology.

Automobile operating costs were not considered because those costs are not primarily dependent on time as are bus operating costs. Also, the equations do not consider failures of the system, e.g., failure of a bus to make use of a granted preemption because of chance delay between detection and arrival at the intersection. We felt the occurrence of delays resulting from some uncontrollable traffic or passenger conflict would be rare, and thus the frequency of such occurrences can only be determined through experimentation with the preemption strategy and the methodology.

Bus-Operating Savings

For each preemption used, the travel time experienced by the bus that actuated the preemption is reduced. The time saved is equal to the red time not experienced by the bus that was granted the preemption.

Since only eligible buses can be granted a preemption, time saved is dependent on the arrival time of the eligible bus and the length of the red phase that is not experienced. If over a long period of time buses arrive randomly at the intersection, the bus arrivals will range from the last second of the normal green (when extension is first actuated) to the last second of the extended green. Therefore, the average time of arrival is one-half the length of the green extension. This conclusion also assumes that some prior decision has to be made to detect the presence of an upstream bus that will arrive sometime during the 10-s extension.

Hence, the time saved by a bus entering an extended green phase is the full length of the red phase missed minus the average time of arrival, which is one-half the extension period. This time is converted into its cost equivalent by a dollar value per minute of bus-operating time as shown below:

$$\begin{aligned} \mathrm{Bs} = {} & \{[\text{cross-street green time} - (\text{max extension length}/2)]/60\ \text{s/min}\} \\ & \times \text{value of operating time} \end{aligned} \tag{2}$$

where Bs = bus-operating savings.

Bus-Passenger Savings

For each preemption used the time saved by the bus is passed on to the passengers it carries because they also do not experience a red phase. These passengers perceive this time saved at some monetary value. Assuming an average perceived value of time, we can calculate a bus passenger's savings, which is multiplied by the number of passengers on the bus to determine total value of passenger time saved.

$$\begin{aligned} \mathrm{BPs} = {} & \{[\text{cross-street green time} - (\text{max extension length}/2)]/60\ \text{s/min}\} \\ & \times \text{perceived value of travel time} \\ & \times \text{average number of passengers per bus} \end{aligned} \tag{3}$$

where BPs = bus-passenger savings.

Automobile-Passenger Losses

To determine automobile-passenger loss ($\mathrm{AP_L}$) experienced during a preemption action, we assumed that the total queue of cross-street traffic would be delayed. This assumption is conservative because only with perfect progression and operation at capacity would the entire platoon of cross-street traffic be stopped and delayed. Under any other conditions only a portion of the queue would be delayed the full length of the extension.

The queue length (in passengers) is determined by the volume of cross-street traffic and the average occupancy per automobile. The perceived value of travel time of automobile passengers (including driver) is equal to the earlier value for bus-passenger travel time. The number of vehicles delayed for an additional cycle by the preemption action is determined by the minimum green time and the associated failure rate. The level chosen for this methodology was a 10 percent failure rate for the peak period, usually 3 h, which approximates a 30 percent peak-hour failure rate (12). If we assume that this failure rate will cause an average increase in the failure rate of 10 percent, then this additional delay must be accounted for in the equation because 1 out of every 10 cross-street vehicles present during a preemption will be delayed the maximum extension period and will be unable to successfully clear the intersection during the cross-street green phase and will thus experience further delay. This assumption is also conservative because failures will probably be limited to hours within the peak periods, yet the method assumes failures due to preemption actions will occur throughout the total operating period. The resulting equation is as follows:

$$\begin{aligned} \mathrm{AP_L} = {} & [(\text{max extension length}/2)/60\ \text{s/min}] \\ & + (0.1)\ \{[(\text{max extension length}/2) \\ & + \text{cross-street red}]/60\ \text{s/min}\} \\ & \times \text{preceived value of travel time} \\ & \times \text{number of passengers per automobile} \\ & \times \text{average number of cross-street vehicles per cycle} \end{aligned} \tag{4}$$

Automobile-Passenger Savings

To determine how many automobile passengers will gain time by an extended green phase, we assumed that additional volume can be anticipated beyond the platoon of automobiles that would have normally cleared the intersection in a perfectly progressed system. This additional volume might be generated by previous preemption actions, by automobiles entering the link from side streets, or by failures at upstream intersections. In a less than perfectly progressed system, there is potential for late arrivals that would benefit from an extension. Travel time savings of automobile passengers equal to the length of the bus-street red phase minus one-half of the green extension period would result if these late arrivals or additional volumes appeared. However, these occurrences are difficult to predict and are not general conditions.

Automobile passengers who have saved travel time would still be behind the normal traffic platoon and would have difficulty maintaining their savings unless the bus continues to travel with the extended platoon and to preempt signals. If the bus leaves the traffic flow to make a service stop and successive signalized intersections are progressively timed, then there is a high probability that the savings to the automobile passenger will be lost at the next intersection. Because of the uncertainty of maintaining the savings and the efforts to present conservative estimates for bus-actuated signal preemption, the possibility of automobile-passenger savings (APs) was not considered in the revenue-cost analysis. Thus, the revenue per preemption (R/P) used of a green-extension preemption scheme of bus priority is

$$\mathrm{R/P} = \mathrm{Bs} + \mathrm{BPs} - \mathrm{AP_L} \tag{5}$$

Total Preemptions Used

Once the return per preemption is determined by using the preceding equations, the next task is to estimate the total number of preemptions granted during the life span of the equipment (P/LS). This estimate is a function of bus frequency, cycle length, extension length, and total life span of equipment and is calculated by the following equation:

$$\text{P/LS} = \text{extension length/cycle length} \times \text{weekday bus volume} \times \text{number of equivalent weekdays per year} \times \text{number of years per life span} \quad (6)$$

The major assumption in the computation of the total preemptions used per life span is that the proportion of preemptions granted equals the length of the maximum extension period during the total cycle length. Also, we assumed that all preemptions granted are used. The goal of the dual detection scheme is to minimize unused granted preemptions and thus give validity to this assumption.

Computation of Revenue-Cost Ratios

When all of the cost and revenue components of a signal-preemption system are known, the next step is to determine the revenue-cost ratio for the system and thus its feasibility. Because actuators can be used to operate several installations on a route or corridor, the revenue-cost ratio (R/C) equation takes the following form:

$$\text{R/C} = (\text{revenue per preemption used} \times \text{number of preemptions used per life span})/[\text{on-site equipment costs} + (\text{actuator cost/number of sites using these actuators}) + \text{engineering and maintenance costs}] \quad (7)$$

This revenue-cost ratio is then used to determine the economic desirability of the installation of a preemption system at any particular location. If the revenue-cost ratio is greater than one, the installation is justified. The equation implies that, although preemption equipment must be justified on the basis of the revenue-cost ratio at the candidate intersection, the optimal configuration is to convert as many intersections as possible on a single corridor. Thus, the expense of installing actuators on buses is amortized by the largest possible number of intersections, and the unit cost per intersection is reduced as much as possible. Moreover, a passive detection or identification scheme, which uses some mechanism other than bus-mounted transmitters, would eliminate the actuator cost entirely and further improve the revenue-cost ratio.

APPLICATION OF THE METHODOLOGY

The methodology described was used to evaluate the economic desirability of installing a bus-actuated, signal-preemption system in a street corridor in Milwaukee that was outside of the central business district and had a high bus frequency. The selection of this study area, containing 11 signalized intersections, from 122 similar sites was based on the following:

1. The intersections had to be situated on one local bus route;
2. The corridor had to be intersected by only three arterials so that only a minimum of cross-street traffic existed;
3. The route had to consist of a pair of one-way arterials; and
4. Only one intersection could contain a cross-street bus flow other than that resulting from route branching.

The objective of this methodology is to screen and warrant individual intersections for installation of bus-actuated, signal-preemption systems. This methodology is an iterative process that is data intensive. The adequacy of the revenue-cost ratio for determining system feasibility depends on the level of detail obtained, which is a policy decision.

The first step of the process, screening of intersections, is more general and uses as criteria bus frequency and major conflicts (or lack of conflicts) with pedestrian or cross-street bus flow. Sufficient bus frequency is considered to be 10 or more buses/h.

Signalized intersections in the CBD were not considered because of conflicts with pedestrian movement. Other intersections were dropped from consideration because of sufficient probability that gains received by through buses would be canceled by cross-street bus flow. An arbitrary limit to the combined bus frequency was chosen as sufficient cause to drop an intersection from consideration. If a minimum of two buses, one from each major bus-flow direction, would arrive at the intersection within a period of less than five cycle lengths, then the probability that these two buses will arrive within the same cycle and in such a manner as to conflict with the movement of the other was considered to be too great. Thus, 3 out of 5 intersections containing some sort of cross-street bus flow were not considered candidate intersections. The number of potential intersections was then reduced from 11 to 8 and the approaches from 20 to 11.

In the second step, the slack time at each signal was calculated from the pedestrian and cross-street traffic clearance required at each intersection being examined. Sufficient slack time was available for at least a 10-s green extension in 19 out of the 20 approaches examined. The approach that did not have slack time was part of the intersection containing five legs; therefore, 10 of the 11 approaches qualified under both criteria.

In the third step, a preliminary revenue-cost analysis was performed on candidate intersections. An estimated average return per preemption was determined from the equations derived in the preceding section. The data necessary to compute these equations include the cycle length, signal split, traffic volumes, and average loadings. In addition, assumptions must be made regarding the bus-operating cost and the passenger's perceived value of travel time. Knowledge of the slack time available determines which preemption length is possible and therefore what proportion of the total number of buses in the primary direction will receive a preemption. The total number of buses is easily obtainable from bus schedules. This information is adequate to estimate the average daily return for a candidate intersection. The cost was determined in the following manner.

1. Actuator cost was determined to be \$30/actuator and the number of actuators needed is determined by the specific characteristics of the bus route (7). The test route has approximately 50 vehicles in operation during peak periods; therefore, 50 actuators are required at a cost of \$1500.
2. On-site equipment cost was estimated from the previous experiments. The Louisville experiment projected the average cost per intersection (more than 26 intersections) to be \$500 (7). The Washington experiment estimated that the antenna would cost \$50 and the receiver would cost \$100. Using these estimates, we estimated that a single approach using two antennas and one receiver and requiring approximately \$200 worth of modification to the traffic control would cost approxi-

mately $400/approach. In cases in which intersections contain more than one approach, shared cost of signal modifications may be possible and total cost reduced. However, no such assumption was made in this analysis. Thus, for the test corridor, which contained 10 approaches to be equipped, a total cost for the on-site equipment was estimated to be $4000.

3. Equipment engineering and maintenance costs incurred during the assumed life span of the equipment were estimated to equal 100 percent of the total equipment cost. The test corridor has a $1500 actuator cost and a $4000 on-site equipment cost. A $5500 engineering and maintenance cost will be incurred during 10 years, and the total cost of the system during its use is the sum of the cost estimates for the actuators, on-site equipment, engineering, and maintenance, which is $11 000 or $1100/approach.

4. The revenue-cost ratio was then determined by using the methodology presented in this paper and time value of $15/bus-operating h and $1.25/h of traveler's time. The average daily return per approach ranged from $2.40 to $7.52, and the average daily return for the total system was $50.47. A break-even time of 218 equivalent weekdays was determined by dividing total cost per day by the total average daily return. The computed revenue-cost ratio for the entire system was 14:1, and individual intersections ranged between 4.5:1 and 19.8:1. Therefore, we concluded that the installation of a green-extension capability at the identified locations is not only feasible but also economically desirable.

As a result of these preliminary findings, a consortium of transportation planners from the community reviewed and commented on the methodology and the implementation potential of bus-actuated, signal-preemption systems. There was little argument as to the feasibility of signal preemption and the costs of installing such equipment. However, there was skepticism as to the feasibility of implementing this transportation improvement because the prime benefits are based on travel-time savings. Although the majority of transportation improvements are justified by time savings to the traveler, the planners felt that a more tangible benefit would have more influence on officials responsible for public expenditures. Therefore, the suggestion was given and followed that the installation of signal-preemption equipment be based primarily on the ability to reduce bus requirements.

The definition of reducing bus requirements was further limited to the ability to eliminate a bus from service and thus reduce labor cost without reducing the level of service offered. To eliminate a bus from service requires that the accumulation of average bus travel-time savings from all the intersections on a bus route (in both directions) be equal to or greater than the bus headway. The accumulated travel-time savings on two major routes in Milwaukee were estimated to be 5.9 and 6.9 min, large enough to eliminate a bus from peak-hour service.

Another result of this review was the questioning of the assumption of random bus arrivals. Preliminary field tests were conducted that generally support the assumption of a uniform distribution of arrivals especially in situations in which there is wide spacing between traffic signals or an intermittent passenger service stop or both. When the spacing is short and the bus movement is not interrupted by a passenger-service stop, buses tend to arrive predominantly during the green phase. These field checks were not conclusive. They indicated the need to further investigate the assumptions underlying this methodology and to validate the methodology by further experimentations with the application of bus-actuated signal preemption.

CONCLUSIONS AND RECOMMENDATIONS

Previous research on the bus-actuated, signal-preemption system has concentrated on proving the feasibility of a particular strategy. The feasibility was established by measuring whether a significant decrease in the bus-travel time and the number of stops made for traffic signals occurred in a demonstration or simulation test. This measurement then proved that under the conditions existing at the demonstration site the preemption system was effective. However, no generalizations have been drawn from these experiments, and planners have had no assurance that the system could be successfully installed in particular geographic locations.

In this paper bus-signal preemption is evaluated on an intersection-by-intersection basis and manually calculated, single-intersection results are provided. The methodology development and the results of the test application of the methodology have led to four significant conclusions:

1. By examining the operations of signal-preemption systems, we may derive general equations that describe the savings and losses from preemption;
2. Intersections can be equipped with a dual-detector, green-extension scheme without requiring areawide, computerized traffic control systems;
3. As a result of the modest equipment cost and the high efficiency of green extension, revenue-cost ratios as high as 20:1 are possible and even single location systems can be justified; and
4. Bus-actuated, signal-preemption systems can increase the economic efficiency of an intersection.

The following areas seem most fruitful for the application of bus-actuated, signal-preemption systems.

1. Additional field checks and experiments should be conducted to test the assumptions presented in this report and thus verify or modify this methodology as warranted.
2. The methodology presented here should be expanded and modified to include the full range of preemption strategies. European experiments sometimes use manipulation of the cycle rather than alteration. Schemes such as compensating cycles or double green cycles are being tested and should be treated in subsequent methodologies.
3. Equipment involved in these preemption strategies should be further developed to lower the costs involved in their use. Further research and development in the technology of vehicle detection or identification, such as the federally funded Passive Bus Detector/Intersection Priority System, should be encouraged.
4. Research should be done to determine whether priority can be given to buses and emergency vehicles by using different preemption techniques for each but the same equipment.
5. The interaction of preemption systems with other bus-priority measures should be investigated.

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Estimation of Delay at Traffic-Actuated Signals

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Field measurement of delay at traffic signals is a costly and cumbersome process, and the use of analytical models to estimate delay is, therefore, of interest to the traffic engineer. A model originally developed by Webster has gained widespread use and acceptance in the estimation of delay at pretimed signals where signal timing remains constant from cycle to cycle. The original version of this model has been modified for application to traffic-actuated signals where signal timing is determined on the basis of vehicle presence information received from detectors in the roadway. This paper describes the modifications to Webster's model, which consist primarily of the substitution of values in the second (random arrival) term based on maximum cycle length rather than on optimal or average cycle lengths. The delay calculations that result from the modified version are compared with the values for pretimed operation based on the original model. Both versions of the model are compared with a simulation model and found to produce satisfactory approximations. Delay under traffic-actuated control is lower than delay under pretimed control. The difference depends on the degree of saturation of the approach lanes. The maximum difference is observed at 75 percent saturation. No difference is observed at very low saturation levels because very little delay accrues under these conditions. The difference also approaches zero at very high saturation levels because the actuated controller becomes constrained by the maximum interval timer to operate in a pretimed mode.

Delay is well recognized by the traffic engineer as a useful measure of effectiveness in a traffic-control system. Motorists view traffic delay with great disfavor, and economists agree that delay in movement of traffic is costly. Estimation of delay is, therefore, an important topic in the analysis of transportation systems.

Delay may be estimated either by field measurement or by analytical or simulation models. Although field measurement produces the most accurate results, the procedures are somewhat costly and time consuming. Furthermore, field measurement techniques cannot be applied to hypothetical situations such as proposed signal installations. Analytical approximations are, therefore, of interest to the traffic engineer.

The best recognized analytical treatment of delay estimation has been performed by Webster (1, 2). Webster demonstrates that satisfactory delay estimates may be obtained for any signalized approach when one is given the traffic volume, capacity, and signal timing (cycle length and effective green time) for that approach. The analytical process becomes, however, substantially more complicated when the signal timing varies with demand as in the case of traffic-actuated signals. A complex stochastic queuing model evolves from this analytical process, and this complex model is not adaptable to a practical solution because of the simplifying assumptions that must be made. The purpose of this paper, therefore, is to examine an analytical model that can be used to produce a useful approximation of delay at intersections where fixed signal timing does not exist. This examination is accomplished by refining Webster's model for pretimed control rather than by developing a separate, theoretical model. This refinement technique is further investigated by simulation to determine whether the techniques can be applied in a practical sense to estimate delay at vehicle-actuated signals.

WEBSTER'S PRETIMED DELAY MODEL

Webster demonstrates (1) that delay at pretimed signals may be approximated by the sum of two separate components.

1. The component due to uniform vehicle arrivals may be derived analytically in the form

$$D_1 = [C(1 - \lambda)^2]/[2(1 - x)] \qquad (1)$$

where

D_1 = delay per vehicle, seconds,
C = cycle length, seconds,
λ = proportion of green time given to the approach, and
x = degree of saturation of the approach, volume/capacity.