only be a few seconds apart in time, and this results in a limitation on the possible changes in flow characteristics that might take place during longer sampling periods.

SUMMARY

This study has shown the technique used to compare favorably in many ways with more traditional techniques. Problems of data extraction have been eased if not totally eliminated.

A comprehensive check has shown the level of accuracy to be suitable for traffic studies, and an analysis of the results has shown that in many cases they agree with established theories. Deviations from these theories have occurred only where the particular theory itself is in doubt.

Several types of surveys—e.g., origin-destination studies—would, however, be difficult to undertake, and volume studies present problems. The photographs provide a permanent record of traffic conditions at that time and can be referred to later as and if required. The technique can be undertaken by unskilled or semiskilled personnel, and an accurate analysis is quickly obtained.

If some method could be found to eliminate the necessity of maintaining a strict vehicle order and thereby allow the data obtained from a coordinate reader to be read directly into the computer without any need for editing, the method could have many applications and could effectively replace some traditional ground-survey techniques. Even if one allows for this drawback, however, the photographic technique is a feasible one and represents a definite alternative to conventional ground methods.

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Measurement of the Performance of Signalized Intersections

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A survey technique for the measurement of the performance of signalized intersections is described. The technique is simple to perform in the field and produces the following types of information: (a) vehicle delay and its variability, (b) pedestrian delay and its variability, (c) vehicle flow rate, (d) total number of effective vehicle stops, and (e) a complete record of signal phasing and timing. Details are given for implementation of the technique as a conventional field survey, an "instant analysis" field survey, or a simulation model subprogram. The use of the survey technique in the evaluation of schemes for bus priority signalization is also discussed.

Although there has long been an interest in the performance level of intersections, especially signalized intersections, this interest has been heightened in recent years by the necessity to ensure that the existing transportation system operates at peak efficiency. This concentration on the performance of existing systems has been labeled transportation system management (TSM) and covers a wide variety of techniques. One of the major TSM techniques is managment of the system so as to give priority to high-occupancy vehicles. Examples of such priority techniques are priority lanes and bus priority signal systems. Such priority systems give preferential treatment to high-occupancy buses, usually at the expense of low-occupancy automobiles. However, before such a scheme is implemented or continued beyond a demonstration period, an assessment should be made of the relative impacts on various types of vehicles. In the case of bus priority signals, this assessment involves a survey of intersection operating conditions and performance levels.

The measurement of the level of performance of an intersection has been an area of concern in traffic planning almost since the birth of the profession. One can trace the attempts of traffic engineers to grapple with this problem through the works of several authors (1-6). In this evolution of techniques of performance measurement there have been two major variables: (a) the definition of criteria for level of performance and (b) the physical technique for obtaining such a measurement.

Indirect measurements of performance level that have been used include load factor (7), intersection flow ratio (8), and degree of saturation (9). Direct measurements of performance level include vehicle delay (however defined) and proportion of vehicles stopped. Reilly and others (6) describe the various definitions of delay and conclude that the most appropriate definition to use is that of approach delay, which includes not only the delay incurred by a vehicle while actually stopped but also the delay incurred while the vehicle is decelerating and accelerating as a result of the intersection operation. Their definition of the proportion of vehicles stopped is, as the name implies, the number of vehicles that come to a complete halt (no matter how many times) divided by the total number of vehicles crossing the stopline. They also classify the survey techniques into four types: point sample, path tracing, input-output, and modeling. They conclude that the point-sample method is the most desirable.

This paper addresses the question of devising a survey method that is particularly suited to the measurement of appropriate performance levels at a bus-priority-signalized intersection.

EVALUATION OF BUS PRIORITY SYSTEMS

The implementation of bus priority systems may be seen as an attempt to achieve either or both of the following objectives:

1. To improve the person-carrying capacity of a section of roadway and
2. To improve the level of service offered by buses in comparison with automobiles so as to induce a change in mode use along the route.

Either of these objectives may result in a reduced level of service for private automobiles in order to improve the level of service of buses.

The purpose of an evaluation study is to ensure that the degradation in the level of service offered to automobiles does not exceed the improvement in the level of service offered to buses (at least not beyond an acceptable level determined by policy makers). On what basis, then, should this evaluation be performed?

A previous study (10) has proposed an evaluation framework within which bus priority systems may be evaluated. This evaluation framework, shown in Figure 1, considers various evaluation methodologies as lying within a three-dimensional space. This space, with dimensions termed breadth, width, and depth, defines the complexity and completeness of the evaluation procedure. Breadth refers to the number of groups in the community included in the analysis. For bus priority systems, appropriate groups might include bus passengers, automobile drivers and passengers, pedestrians, and nonusers of the facility. Width refers to the geographic area over which the evaluation extends and, for bus priority studies, might consist of an intersection, a link, a route, or a network. Depth refers to the number of factors considered in the evaluation. Factors suggested as appropriate for bus priority studies include travel time delay, travel time variability, operating costs, energy consumption, pollution emissions, safety, mode choice, and distributional impacts.

Obviously, the extent of the evaluation will vary from location to location. Its degree of sophistication should be commensurate with the anticipated magnitude of the costs and benefits of the priority system. But it will be shown that, by using the survey technique described in this paper, a reasonably sophisticated analysis can be performed without vast expenditures on data collection or analysis. Specifically, this paper describes a technique that can be used to obtain data for the evaluation of an intersection signalized for bus priority. This evaluation will be broad enough to include bus passengers, automobile passengers, pedestrians, and nonusers; wide enough to encompass all approaches to a single intersection, from which the results may be used as input to route and network studies; and deep enough to include travel time delay, travel time variability, operating costs, energy consumption, and pollution emissions.

The survey method yields five distinct characteristics on each approach: average delay per vehicle, standard deviation of delay per vehicle, average number of stops per vehicle (as distinct from the proportion of vehicles that stop), flow rate, and sequence and timing of traffic signal indications on each approach. The survey technique uses, in the words of Reilly and others (6), a point-sample method. The time between sampling points, however, is not constant but is synchronized with the changing of signal aspects on each approach. This has the advantage of enabling the signal phasing to be obtained in the same survey while at the same time reducing the workload on survey personnel, who then normally have to record queue length only once per cycle (i.e., about once every 90 s) instead of once every 13 or 15 s as required by the method of Reilly and others. As will be seen later, the survey is also simpler in that only stationary queues are counted and not queues that are being shortened at the front by vehicles that move off after a green signal is shown.

SURVEY THEORY

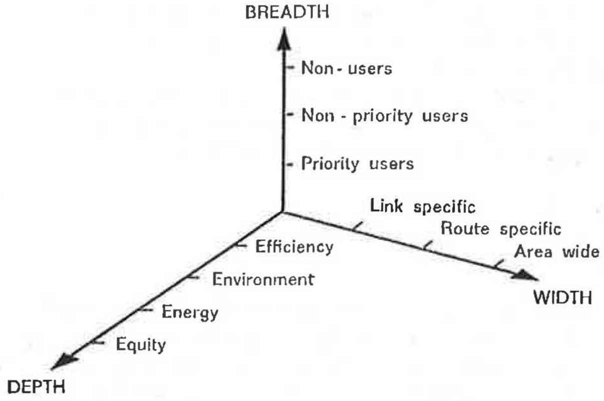
The starting point for the development of the survey theory is the idealized concept of intersection behavior used by May (11) and Sagi and Campbell (4). Unlike May, however, who considered arrival and departure rates to be constant over time, this survey method allows arrival and departure rates to vary from cycle to cycle and only assumes that, within each cycle, arrival and departure rates are linear. The assumption of linear arrival rates within each cycle may be questioned when significant upstream bunching occurs (4, 5). However, as long as the bunch arrivals are not synchronized with the phasing of the traffic signals, this bunching effect should even out over many cycles. One would not expect synchronized bunches along a route of isolated intersections that have vehicle-actuated signalization (this survey method was originally designed for such intersections).

Consider, then, the passage of a vehicle through a signalized intersection, as shown in Figure 2. Vehicle A arrives during the green period and proceeds through undelayed. Vehicle B arrives during the red period, decelerates, and comes to a complete stop. When the signal turns green, vehicle B accelerates to cruising speed and leaves the intersection area. Vehicle C arrives during the red (or green) phase and, finding a vehicle stopped ahead, slows down in preparation for a complete halt. However, the vehicle in front moves off before vehicle C reaches it, and so vehicle C accelerates back to cruising speed without coming to a complete halt.

In calculating delay, it has been shown (12) that, by considering vehicles with infinite acceleration and deceleration rates (i.e., squaring off the trajectory diagrams), the approach delay is equal to the length of the horizontal sections of the trajectories, as shown in Figure 3. This delay includes both the time that a vehicle is stopped, if at all, and the time lost in acceleration and deceleration maneuvers.

Consider now the trajectory diagram associated with one cycle of a set of traffic signals where the input and output flow rates, in that cycle, are constant. Figure 4 shows how the flow in this cycle can be represented by a family of trajectory lines made up of inclined and horizontal sections. The delay to each vehicle is represented by the horizontal section of each trajectory, and the total delay to all vehicles is the summation of the lengths of the horizontal lines. If one considers the flow to be continuous rather than discrete, the total delay can be represented by the area of the triangle that envelops the horizontal lines.

Figure 1. Framework of evaluation for bus priority systems.



To calculate this area, one must specify the location of the triangle apexes in time and space. Points A and B are easily specified. Both are located at the stopline or the front of the queue. Point A denotes the start of the red period, and point B denotes the start of the effective green time. The location of point C is a little less definite. Conceptually, it represents the time and queue position at which arriving vehicles are no longer influenced by the previous red phase. In practice, however, it is not simple to determine whether or not an arriving vehicle was delayed by the previous red phase. One must determine not simply whether the vehicle stopped but whether the vehicle slowed down at all because of the previous red phase. This calls for a degree of judgment that is not usually found in relatively inexperienced observers. What is needed is a rela-

Figure 2. Typical trajectory diagrams for the passage of three vehicles through a signalized intersection.

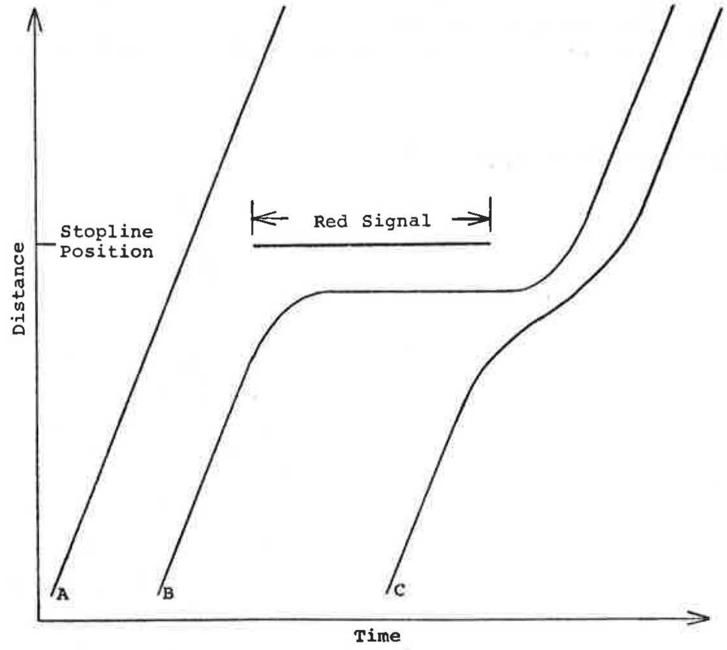
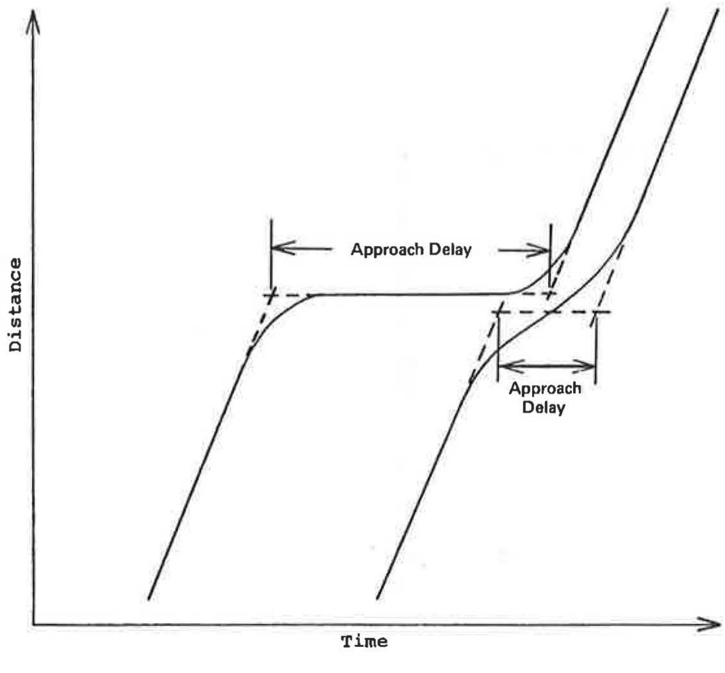


Figure 3. Approach delay calculated from idealized trajectory diagrams.



tively simple measurement that can be related to the position of point C.

One measurement that is relatively easy to obtain is the length of the queue at the time when the green phase begins (shown by BE in Figure 4). An associated measurement is the time at which a vehicle at the end of this queue crosses the stopline after it moves off in the green period (assuming an undersaturated cycle), as shown by point D in Figure 4. These values are sufficient to perform this survey and are summarized in Figure 5. The four values recorded are the time at the start of the red period, the time at the start of the green period, the queue length at the start of the green period, and the time at which a vehicle at the end of this queue crosses the stopline.

From these measurements, the position of C may be estimated graphically as follows (Figure 5). Join points A and E and continue the projection beyond E. From E, construct a horizontal line that represents this stopped vehicle. To represent a vehicle moving at cruise speed, construct an inclined line from D to intersect the horizontal line through E at F. Point F represents the time at which the last vehicle in the queue at time B starts to move off. From B, draw a line through F to intersect AE at C. Point C is defined as before and represents the third corner of the delay triangle.

The vertical distance from point C to the stopline (i.e., the length of queue affected by the red signal) can be expressed mathematically as follows:

$$Q_T = Q_G\,[1/(1 - a \times m)] \qquad (1)$$

where

Q_T = total queue length affected by the red signal,
Q_G = queue length at the start of the green period,
a = average arrival rate at the end of the queue, and
m = average move-off time at the head of the queue.

$$a = Q_G/AB \qquad (2)$$

$$m = (BD - kQ_G)/Q_G \qquad (3)$$

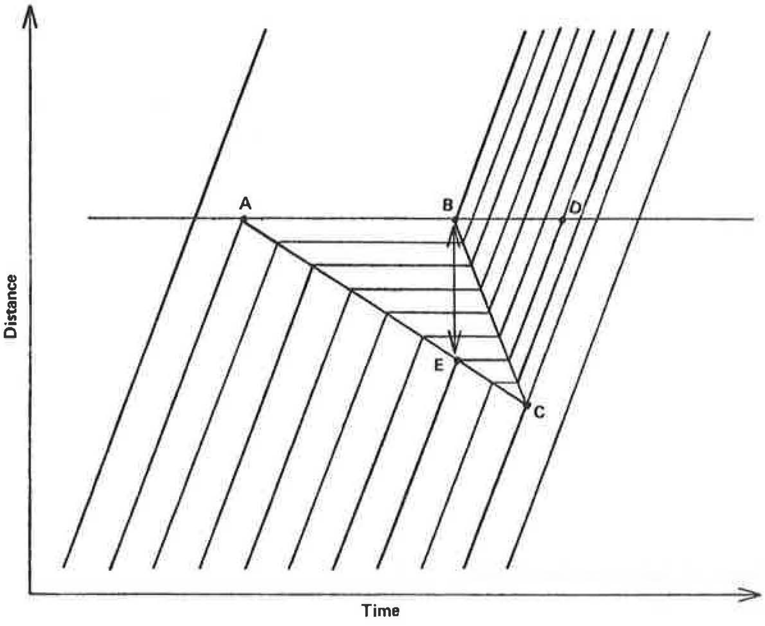


Figure 4. Trajectory diagram for one cycle of traffic signals.

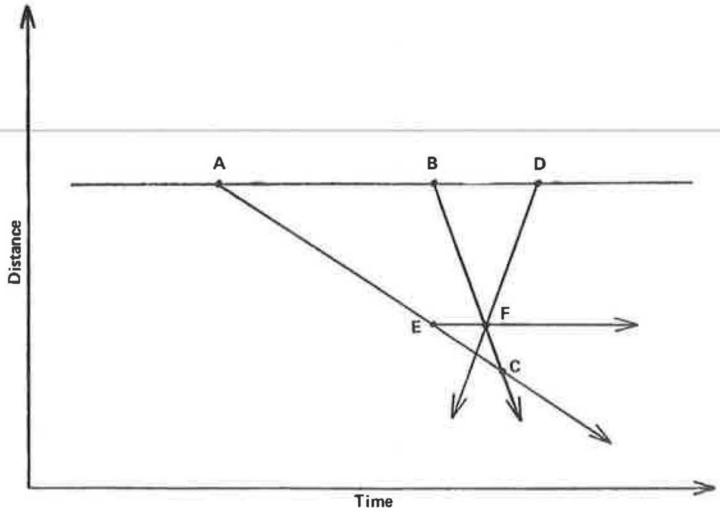


Figure 5. Summary of survey measurements.

where AB, BD = times as shown in Figure 5 and k = time to travel one vehicle spacing at cruise speed. Thus,

$$Q_T = Q_G \{1/[1 - (BD - kQ_G)/AB]\} \qquad (4)$$

Given this estimate of Q_T in terms of the values measured in the survey, it can be seen from Figure 5 that the delay experienced by each vehicle varies from AB (the effective red period) for the first vehicle in the queue to zero for the Q_Tth vehicle in the queue. This can be redrawn to show vehicle delay as a function of vehicle arrival order (see Figure 6). The total delay for this cycle is then given as the area of this triangle:

$$\Sigma d = (1/2) \times AB \times Q_T \qquad (5)$$

where d = individual vehicle delay.

An important indicator of level of performance for a bus priority intersection is the variability in delay experienced by various vehicle streams. It is possible, by using the data collected in this survey of queue length, to calculate the variance in travel delay.

Consider the delay diagram shown in Figure 6. The variance in delay within each cycle may be calculated by

$$\sigma^2 = (\Sigma d^2/n) - (\Sigma d/n)^2 \qquad (6)$$

where d = individual delay and n = vehicle flow ($n \approx n - 1$).

It has already been shown that Σd is the area under the curve in Figure 6. Similarly, Σd^2 is the area under the curve in Figure 7, which shows d^2 as a function of vehicle arrival order. Thus,

$$\Sigma d^2 = (1/3) \times (AB)^2 \times Q_T \qquad (7)$$

The flow within each cycle may be determined as a function of the measured variables by

$$n = (Q_G \times AD)/(AB - kQ_G) \qquad (8)$$

This equation expands the number of vehicles that arrive at the end of the queue during the red period to give the number of vehicles that cross the stopline during the cycle.

To obtain statistics over a number of cycles, one simply sums, over all cycles, the values of Σd, Σd^2, and n obtained from each cycle and, at the end of the desired period, calculates values as follows:

Total delay = $\Sigma(\Sigma d)$.
Total flow = Σn.
Average delay = $\Sigma(\Sigma d)/\Sigma n$.
Variance in delay = $[\Sigma(\Sigma d^2)/\Sigma n)] - [\Sigma(\Sigma d)/\Sigma n]^2$.

Another statistic of particular interest, especially in considerations of energy or pollution, is the total number of vehicle stops. Intuitively, one might consider that the total number of vehicle stops is simply ΣQ_T. However, although in our model the assumption of infinite acceleration and deceleration rates makes no difference to the calculation of delay, such an assumption does affect calculation of the actual number of stops. It must be remembered that, in real life, not every vehicle that is delayed is brought to a complete halt (as shown by vehicle C in Figure 2). Thus, a correction must be made to ΣQ_T to account for those vehicles that do not come to a complete halt.

It is easily shown that, with a cruising speed of V m/s and an acceleration-deceleration rate of a m/s^2, vehicles that have delays less than V/a seconds do not experience complete halts. In fact, the change in speed is linear between zero when delay is zero and V when delay is V/a.

In calculating energy consumption and pollution emissions it has been shown (13,14) that they are related to intersection conditions by a common formula,

$$E = \alpha D + \beta s \qquad (9)$$

where

E = energy consumed (or emissions),
D = delay,
S = number of stops, and
α, β = conversion coefficients.

Number of stops S is considered to be complete stops from an initial speed. Figures 8 (15) and 9 (14) show the effect of initial speed on the energy consumed and the pollutants emitted. In each case, it can be seen that the relation is approximately linear. Thus, the energy consumed or the pollutants emitted are roughly proportional to the change in vehicle speed irrespective of the initial speed. Thus, vehicles that have delays less than V/a seconds will have energy consumption and pollution characteristics that correspond to their changes in speed. These vehicles can thus be considered fractions of a complete stop with respect to energy and pollution.

The effect of these incomplete stops is to reduce the calculated number of stops, as given by Q_T, according to the number of vehicle stops with delays less than V/a. With a triangular delay diagram (Figure 6), the reduction in the number of stops will be determined solely as a function of the maximum delay. The reduction coefficients do not depend on the number of vehicles delayed but only on the maximum delay in each cycle.

It can be shown that, provided the maximum delay per cycle is greater than V/a ($\approx$10 s), the equation for the stop-number reduction coefficient C is

$$C = [AB - (V/2a)]/AB \qquad (10)$$

where

AB = maximum delay in cycle,
V = cruising velocity, and
a = acceleration-deceleration rate.

For typical conditions, the reduction coefficient will be in the range 0.85 to 0.95. Thus, the final statistic of interest may be expressed as

$$\text{Number of stops} = \Sigma\left(\{Q_T \times [AB - (V/2a)]\}/AB\right) \qquad (11)$$

So far, the analysis has assumed that all vehicles that form a queue are cleared across the stopline before the next red phase starts. But this is not the situation in heavy flow conditions, where vehicles may be forced to stop at least twice before clearing the lights. For the case of oversaturated cycles, a more general form of Figure 6 is shown in Figure 10, and a more general form of Figure 7 is shown in Figure 11.

By use of arguments similar to those used in the undersaturated situation, the following general equations may be derived:

Figure 6. Delay versus vehicle arrival order.

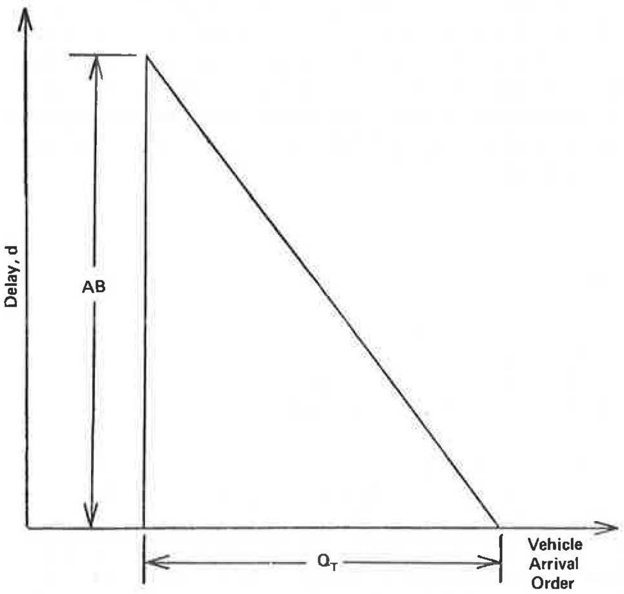


Figure 7. Square of delay versus vehicle arrival order.

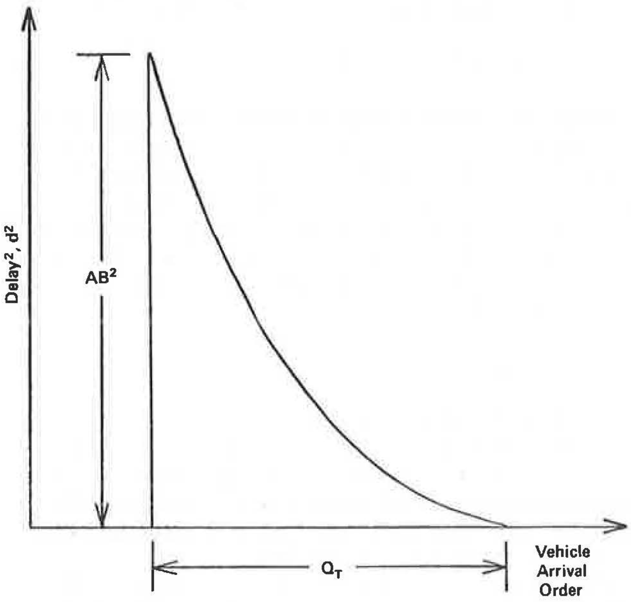
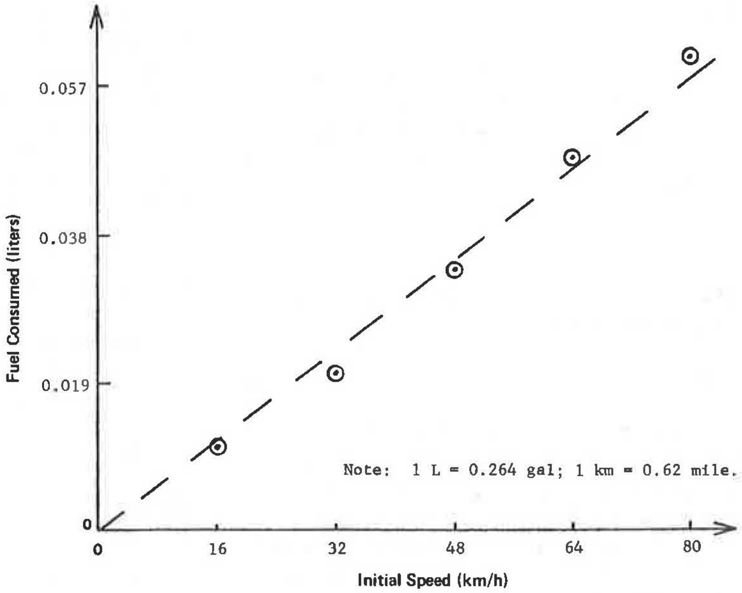
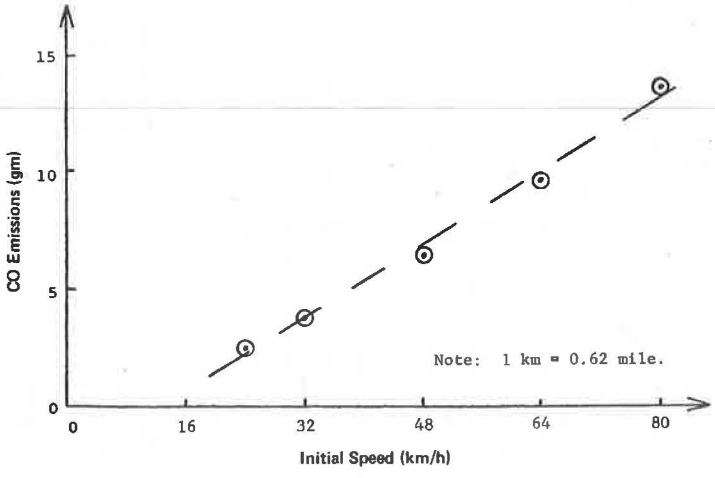


Figure 8. Fuel consumed by vehicles coming to a complete halt from various initial speeds.



Note: 1 L = 0.264 gal; 1 km = 0.62 mile.

Figure 9. CO emitted by vehicles coming to a complete halt from various initial speeds.



Note: 1 km = 0.62 mile.

Figure 10. General diagram of delay versus vehicle arrival order.

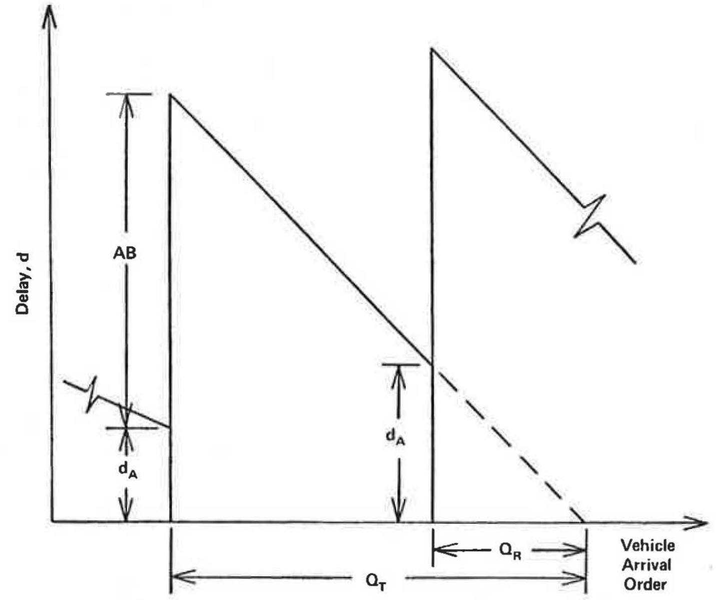
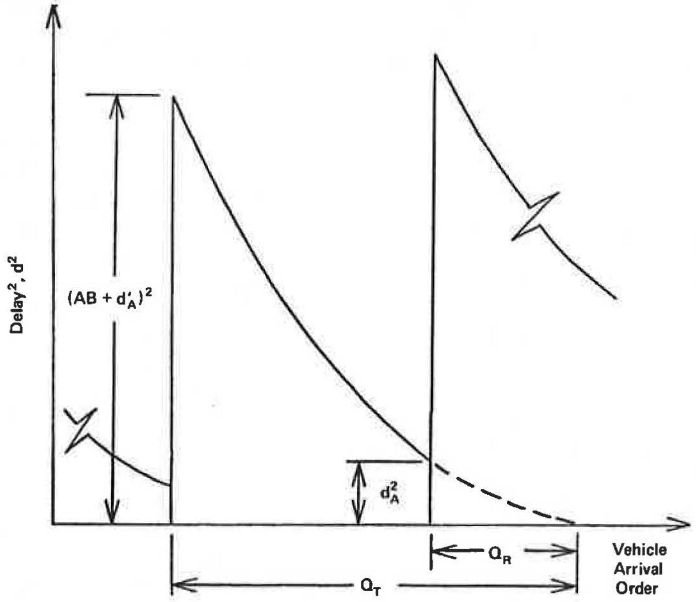


Figure 11. General diagram of square of delay versus vehicle arrival order.



$$Q_T = Q_G \left[1/\left(1 - \{ [(Q_G - Q_R')(BD - k(Q_G - Q_F)] / AB \times Q_G \}\right)\right] \quad (12)$$

where Q_F = number in the queue ahead of, and including, the last vehicle in the queue at the start of the green when a new queue forms at the end of the green and Q_R' = total number in the queue held over from the previous cycle.

It should be realized that in an oversaturated cycle the last vehicle in the queue at the start of the green may not reach the stopline before the light turns red. In this case, the recording technique is modified so that, instead of recording the time at which this vehicle crosses the stopline, it records the number of vehicles in front of, and including, this vehicle that are stopped by the red light. So, of the two variables defined above, Q_F is recorded and Q_R' is calculated from measured variables as

$$Q_R = \begin{cases} Q_T - (1/k)[D - (Q_T - Q_R')/(Q_G - Q_R') \times AB] & \text{if } Q_R > 0 \\ 0 \quad \text{if } Q_R < 0 \end{cases} \quad (13)$$

where Q_R = total number in the queue held over until the next cycle and D = time at which the signal turned red at the end of the green. In the first oversaturated cycle, Q_R' will be zero, and thus the recursive nature of the above equation is broken.

It can be seen in Figure 10 that the maximum delay to the first vehicle in the queue is made up of two components: (a) the delay caused by the red period of the present cycle and (b) the delay carried over from the previous cycle (d_A'). The additional delay d_A that is carried over to the next cycle is given by

$$d_A = (Q_R/Q_T)(AB + d_A') \quad (14)$$

Again, the recursive nature of this equation is broken in the first oversaturated cycle.

The total delay in this cycle is given by

$$\Sigma d = (1/2)(AB + d'_A + d_A)(Q_T - Q_R) \qquad (15)$$

It can be seen in Figure 11 that

$$\begin{aligned}\Sigma d^2 &= (1/3)[(AB + d'_A)^2 - d_A^2](Q_T - Q_R) + d_A^2(Q_T - Q_R)\\ &= (1/3)[(AB + d'_A)^2 + 2(d_A^2)](Q_T - Q_R) \qquad (16)\end{aligned}$$

Referring back to Figure 10, the flow in each cycle can be expressed as

$$n = \{(Q_G - Q'_R)/[AB + k(Q_G - Q'_R)]\} \times BD + Q'_R \qquad (17)$$

The number of effective stops in each cycle is given by

$$\begin{aligned}S = &\left(Q_T \times \{AB + d'_A - (1/2)[(V/a) - d_A]\}\right)\\ &\div (AB + d'_A) \quad (V/a) - d_A \geqslant 0 \qquad (18)\end{aligned}$$

Again, after the desired number of cycles, the final statistics may be collected by use of the calculations that follow Equation 8.

This survey method also enables calculation of the delay to pedestrians who use the intersection. The first step is to determine in which phase, or phases, pedestrian movements can occur. Assume for the moment that pedestrians on one crossing can only cross during phase A. Then, any pedestrian who arrives during phase A may cross without delay. Any pedestrian, however, who arrives during any of the other phases must wait for phase A before crossing. Pedestrian delay as a function of time of arrival is shown in Figure 12.

Assuming that pedestrians arrive randomly during the entire cycle, the average delay to pedestrians can be found by using logic similar to that used in the analysis of vehicle delay and in Figure 6. Similarly, by using the signal timings recorded in the survey as the basic input, the variability in pedestrian delay can be found by analogy with Figure 7. Delay to various pedestrian groups can be found simply by determining the phase in which they can cross and structuring the analysis program to suit. No extra data need be recorded to obtain pedestrian delay; it is simply a matter of a different analysis. It should be noted that, although the equations developed appear to be rather involved, the traffic surveyor need not be concerned with their complexities. It is a relatively simple matter to write a computer program to perform these calculations with very straightforward and easily collected input data. In fact, the analysis can be performed, if desired, on a handheld, programmable calculator, and the data can be entered directly in the field. This technique yields an instant analysis of the data.

As in most survey procedures, there is a trade-off between accuracy, complexity of analysis, complexity of data collection, and survey cost. This method has been developed with the objective of obtaining a relatively low-cost survey technique that is easily implemented in the field. At the same time, the results should be of particular relevance to bus priority intersections. In this respect, the measurement of variability in delay was considered to be an essential feature of the technique. It should be noted, however, that this survey does not give details of bus operations and that a separate survey is necessary to obtain that information. This survey gives information on the effect of bus priority on other traffic that uses the intersection.

FIELD TECHNIQUE

As mentioned earlier, one of the prime considerations in the design of this survey was that it should be easily implemented in the field. To this end, only four items of data are recorded in any one cycle on each approach to the intersection. An example of the survey form used in the field is shown in Figure 13. At the start of the green phase, the time is recorded in column A, and the queue length of stopped vehicles at that time is recorded in column B. A stopped vehicle was originally defined as one that had locked its wheels. In practice, however, it was found that many vehicles were effectively stopped although still "creeping". Some judgment is required of the observer here, and it may be advisable to have observers on different approaches observe several situations together and agree on a mutual definition before the survey begins.

A mental note is made of the last vehicle in the queue and, when the queue moves off, the progress of this vehicle is noted. At this stage, a point of clarification is needed. If one is observing a single lane of traffic, the above routine is straightforward. But if one is observing two or more lanes, how is the last vehicle in the queue defined? Is it the last vehicle in the longest queue or not? Ideally, if there are Q vehicles observed in the queue, then the end of the queue crosses the stopline when the Q th vehicle crosses the stopline independent of whether or not that particular vehicle was in the actual queue or not. Since it is sometimes difficult to count vehicles that cross the stopline, a simpler technique is used. In this, a representative end-of-queue vehicle is defined and its progress is noted. For two lanes of traffic, a vehicle in the longer queue is selected that is halfway between the ends of the long and short queues. This should then approximate the Q th vehicle in the queue. For more than two lanes, a vehicle is selected that represents the weighted average of the end of the queues. Observers report little difficulty in making this selection over three lanes.

If this representative end-of-queue vehicle crosses the stopline before the signal changes back to red, the time at which it crosses the stopline is recorded in column C. The time at which the signal changes back to red is recorded in column D (Column E is, in this case, left blank).

If this representative vehicle does not cross the stopline before the lights change to red, the time at which the lights change to red is recorded in column D and the number of vehicles in front of, and including, this vehicle when the new queue forms is recorded in column E (Column C is, in this case, left blank). This process is repeated for every cycle in the survey period.

Personnel requirements for this survey are minimal. It was found that one relatively inexperienced observer could record data on an approach to an intersection where there are low to medium rates of flow. But when the rate of flow exceeded approximately 1000 vehicles/h on an approach, it was found to be desirable to assign an assistant to count vehicles in the queue. Data were recorded directly on the field sheet shown in Figure 13. Survey equipment consisted of a watch with a second hand, survey forms, and pencils.

For instant analysis of field data, it is possible to dispense with the field sheets and input data directly to a handheld, programmable calculator. The calculator already has the analysis program stored in memory, and data for each cycle are entered directly by way of the keyboard. At the end of each cycle—that is, during the red period—the

Figure 12. Pedestrian delay versus time of pedestrian arrival.

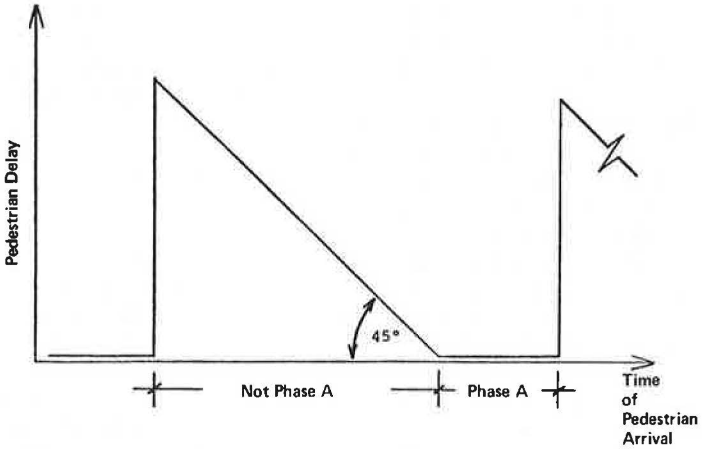
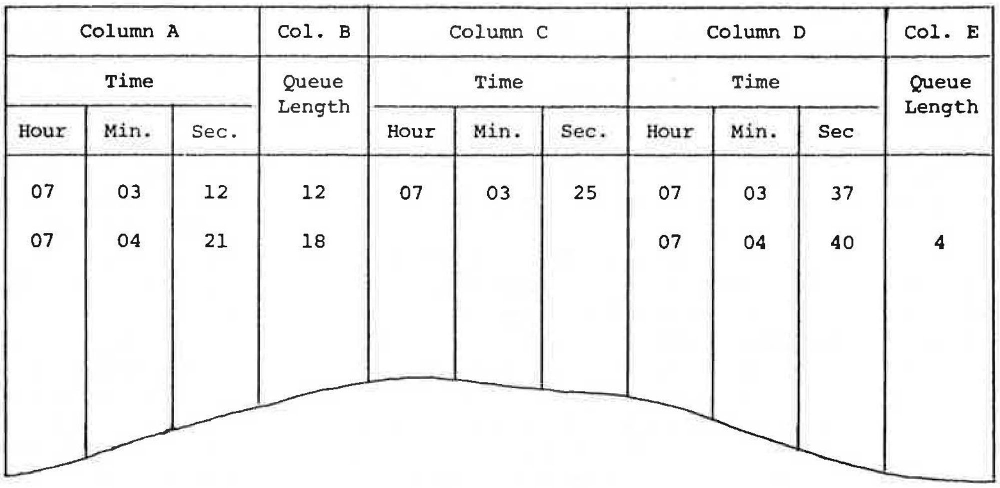


Figure 13. Example of form used in survey of queue length.



Column A			Col. B	Column C			Column D			Col. E
Time			Queue Length	Time			Time			Queue Length
Hour	Min.	Sec.		Hour	Min.	Sec.	Hour	Min.	Sec	
07	03	12	12	07	03	25	07	03	37	
07	04	21	18				07	04	40	4

analysis program is run to calculate values of Σd, Σd^2, etc., for that cycle and add them to the running total of these values. This program takes only a matter of seconds and can easily be run during the red period. Data for the next cycle are then entered as events occur and the process is repeated. At the end of the survey period, another subprogram is run to calculate the final statistics, and the analyst obtains the results in a matter of seconds after the data collection is finished.

This technique is not recommended for general, large-scale use for two reasons:

1. The data are not retrievable, and errors in data entry are not correctable. When many inexperienced observers are recording the data, such errors are inevitable.
2. The cost of equipping a complete survey team with programmable calculators is, at this time, considerable.

Future advances in programmable calculator technology will undoubtedly solve both of these problems. That is, a permanent record on input data will be possible on some form of disc or tape, and the cost of the calculators will inevitably decrease.

For the present, however, this method is recommended only for the use of the experienced professional or researcher. It enables such a person to perform instant checks on the operation of an intersection (perhaps under different control strategies). By performing 15-min sample surveys on each approach to an intersection, a general idea of intersection performance can be obtained in little more than an hour. Instead of a simple, general observation of intersection performance, a complete statistical analysis can be performed on the spot with little extra effort.

Such a technique can be used in preparation for a major survey when initial estimates of results are needed in the survey design. It can also be used when a quick decision by policy makers is needed to respond to the complaints of road users. In using the technique, one person can be dispatched to the site to obtain data and results on which an informed decision can be made. Another use—and the one that was the central objective of the overall development of this method—is the evaluation of the performance of an intersection where various configurations of bus priority signaling have been introduced. In general, the use of this method is limited only by the imagination of the user.

CONCLUSIONS

The evaluation of bus priority signals at an isolated intersection requires the use of a survey technique to measure the effects of the priority signals on other users of the intersection. The method developed and described in this paper is a low-cost, low-manpower effort that gives results that are equal, or superior, to other comparable survey methods. The survey results include vehicle flow, average and total delay, variance in vehicle delay, effective total number of stops, average pedestrian delay and variance in pedestrian delay, and a complete record of intersection signal timings.

The survey method involves recording only four variables per cycle: the start of the red period, the start of the green period, the queue length at the start of the green, and either the time at which the last vehicle in this queue crosses the stopline or the number of vehicles in this queue that are held over to the next cycle. The method is designed so that data can be recorded in the field on survey forms that are then brought back to the office for analysis or data can be keyed in directly to a programmable calculator for instant analysis in the field. The first method is recommended for large-scale surveys and the second for preliminary surveys or spot checks on intersection performance.

Although the method described here was originally developed for the evaluation of an intersection signalized for bus priority (16), the survey technique is general and can also be used for other intersections. It is recommended, however, that it not be used at intersections where the arrival of vehicles is synchronized with the timing of signals (such as at intersections along a route of coordinated signals). In that situation, a survey method similar to that of Reilly and others (6), in which the observation of queue length is done at regular intervals unrelated to signal timing, is recommended.

As a further precaution regarding the interpretation of the results of the analysis, it should be noted that, as a result of a traffic management scheme at an intersection, the delay to nonpriority vehicles at that intersection may increase. But it should not automatically be inferred from this result that, overall, nonpriority vehicles are disbenefited. The increase in delay at one intersection may be more than compensated for by a decrease in delay downstream of the intersection. It is necessary to consider at least the route effects of such TSM schemes, and it may sometimes be advisable to consider the network effects.

Gathering data in the field on route and network effects, however, may be an involved process, even when a relatively simple survey procedure, such as the one described in this paper, is used. It may be necessary to resort to simulation of the system in order to investigate these effects. To this end, I have developed an intersection simulation model to investigate the effects of various strategies of bus priority signalization. To demonstrate the generality of the survey technique described in this paper, exactly the same logic is used in the collection and analysis of data from the simulation model. Thus, a one-to-one correspondence exists between the simulation data and the field data used in validation of the model.

The survey method described here is simple, inexpensive, and flexible and generates a large array of output results from relatively few input variables. It can be used as a data collection system for the analysis of data in the office, as an instant analyzer of data in the field, or as a submodel of an intersection simulation model.

ACKNOWLEDGMENT

The work described in this paper was performed as part of a research contract for the Road Safety and Traffic Authority, Melbourne, Australia, to develop and apply an evaluation methodology for intersections with bus priority signalization. Their assistance and that of the Melbourne Metropolitan Tramways Board in the conduct of the study and the collection of the data are most appreciated. The advice and assistance of K.W. Ogden and W. Young of the Department of Civil Engineering, Monash University, are also greatly appreciated.

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Discussion

William R. Reilly, JHK and Associates, Tucson

Several comments should be made on the assumptions contained in Richardson's paper. First, the departure rates (e.g., discharge headways) of vehicles that are moving away from an intersection queue can vary considerably from the linear assumption. Where heavy pedestrian volumes are encountered with right turns, discharge headways in a right-hand lane can vary widely. The same phenomenon occurs in a left-hand lane where both left turns and through movements are allowed and where the left turns create nonlinear discharge headways for the lane.

A second situation, which is noted by Richardson and for which the assumption of linear arrivals and departures does not hold, is that of a synchronized signal system. Because platooning, or "bunching", will occur in such systems, a linear arrival pattern at a downstream signal is often not observed. Thus, the technique is not particularly applicable to lanes that exhibit platooning of either arrivals or departures.

Richardson has attempted to guide the user in conversion from a lane-by-lane survey to a total approach survey by defining a representative end-of-queue vehicle. This is a useful description since, in many cases, a measure of performance for the total approach rather than a lane-specific measure is desired.

A difficulty found in the work I performed with Gardner and Kell (6) was that, along intersection approaches that have long queues and major driveways, the number of vehicles that entered or exited the driveways could substantially alter the values for delay (by as much as 5 or 10 percent), depending on the survey technique used. Another phenomenon that does not appear to be accounted for in Richardson's method is the delay values for right-turn-on-red vehicles and the volume that crosses the stopline during a red interval.

It is these numerous "small" effects that are best captured by the more general survey technique described by my coauthors and me (6), which is based on original work by Berry and VanTil. Richardson has, however, set forth a logical and simple technique that, under certain traffic and geometric conditions, could require the use of fewer personnel than are required in the application of many other field methods.

The procedure my coauthors and I recommend for surveying delay and stops (6) does not include any measurement of signal intervals. For multi-phase-actuated equipment, this is a distinct advantage. In Richardson's method, a special technique and calculation would be required to estimate delay on an intersection approach that has "protected" or "protected-permissive" left-turn phasing. In the latter case, discharge headways in the protected and then the permissive situation are usually very different. The Federal Highway Administration work Gardner, Kell, and I described (6) concludes that, for typical field personnel, any field method that requires observation of signal phase times is less easily performed than a method that does not.

The paper by Richardson includes a section on pedestrian delay that suffers from using the same assumptions of linear (i.e., not platooned) arrivals and departures for vehicle flow. The impact of vehicle flow on pedestrians and their discharge patterns can be substantial. In addition, the actual behavior of pedestrians is often distinct from the behavior implied as a result of knowledge of signal timing and phasing. At busy intersections, it could be difficult to distinguish pedestrians who are queuing for a given crossing. Until a more explicit set of definitions and field procedures is available and the concept is validated by field data, the use of the method for studying pedestrian delay appears undesirable.

The inclusion of comments on air pollution and bus priority systems tends to distract from the central presentation of a field survey technique. It is suggested that a short user-oriented set of explicit instructions be set forth and that this include an example calculation. In this way, the reader (user) can better follow the technique. It would also be useful to check the model, and especially its assumption of linearity for arrivals and departures, against a set of field data at several intersections.

Author's Closure

The discussion by Reilly raises some important points about the survey method, especially in relation to the lack of field validation. Several issues he raises, however, require some clarification.

First, Reilly mentions the problems involved in the assumptions made for arrival and departure rates. It is true that an asssumption is made that departure rates are linear (or, more correctly, displaced linear to account for an initial start-up period). But it should also be noted that this linearity assumption can vary from cycle to cycle; that is, the assumed constant departure headway is obtained, in each cycle, by dividing the time taken to clear the queue (minus the start-up period) by the number of vehicles in the queue. Thus, if a significant interruption to departing vehicles occurs in any cycle, this is reflected in the higher than average departure headway. In this way, the departure rate accounts for such occurrences as pedestrians or opposing vehicles that may hinder the discharge process.

It is also true that linear arrival rates are assumed in each cycle (though with a variable average arrival rate in each cycle) and that the existence of synchronized platooning—that is, platoons synchronized with the signal phasing—will significantly deviate from this assumption. It should be noted, however, that the platoons must be synchronized with the signals before the survey method becomes inappropriate. Unsynchronized platoons will, on the average, have no significant effect on the survey results.

Reilly's comments on the measurement of pedestrian delay also need some clarification. He states that the method suffers here from use of the same assumptions of linearity for arrivals and departures. This, in fact, is not true. Pedestrian departures are instantaneous; that is, pedestrians leave the curb as soon as their light turns green. Pedestrian arrivals are assumed to be random rather than linear. Although it is realized that pedestrian arrivals may in fact be grouped, the assumption of randomness is satisfactory if it is assumed that pedestrian groups arrive randomly.

Reilly's comment about the actual behavior of pedestrians is of more significance. It is a well-documented fact that pedestrians do not always comply with the instructions given by signals. It has also been observed that pedestrian compliance with signals decreases as the signals cause greater delay to the pedestrians who are waiting to cross. Thus, if one calculates from the survey method that pedestrian delays are very high, it does not necessarily mean that the pedestrians are actually suffering this delay. Many will already have taken a chance and crossed the road before the light turned green. So pedestrian delay is really a combined measure of delay and risk. The greater the calculated delay is, the greater is the actual delay and risk. Either way, calculated delay is a useful measure of pedestrian signal performance.

Most of Reilly's remaining comments can be related to the purpose for which the survey method was developed. He states, "The inclusion of comments on air pollution and bus priority systems tends to distract from the central presentation. . . ." On the contrary, comments on bus priority are central to the presentation since the survey method was designed to pick up features of a bus priority intersection that could not be accounted for by other survey methods. The method was therefore designed specifically to measure (a) signal phasing and timing, which would be drastically modified by bus priority demands; (b) the variability of delay; and (c) stopped delay and effective stops, which could then be used to calculate energy consumption and air pollution emissions.

The three most important areas of further research that have emerged as a result of Reilly's comments and research conducted since the writing of this paper are the following:

1. Full field validation of the method by a comparison of field results with measures obtained from a filmed record of intersection operation,
2. Combination of Reilly's data collection method with the method of analysis presented in this paper, and
3. Development of theoretical and empirical interrelationships among various measures of intersection performance.