Measuring Delay by Sampling Queue Backup

Martin G. Buehler, Lake County Highway Department, Illinois
Thomas J. Hicks, Richard P. Browne Associates
Donald S. Berry, Northwestern University

The relation of sampling of queue backup and delay at signalized intersections was studied and evaluated for use as a level-of-service indicator for intersection performance. Time-lapse photography was used at four urban intersections controlled by pretimed signals to determine time-in-queue delay. At the same time, each field observer sampled the position of the rear of the queue in one lane at 10-s intervals. Other field methods of measuring delay were tested also. Regression analyses of resulting delay values by cycle yielded high correlations between queue backup delay from field sampling and time-in-queue delay from film analysis. Field sampling of queue backup was found to be much simpler to use in the field than field sampling of stopped time delay. Field sampling was confined primarily to three unsaturated approaches that had few left-turning vehicles. Further study is needed to validate and refine field procedures under a wider range of conditions.

This report summarizes results of studies of methods for field measurement of delay at signalized intersections (1). The purpose of the study was to identify and validate a method that traffic engineers can use in the field to measure intersection performance. The method should be simple enough for widespread use in obtaining delay; updated data are particularly needed to revise the chapter on signalized intersections of the Highway Capacity Manual (HCM) (2).

Figure 1 illustrates the three types of delay at approaches to signalized intersections that have been identified in previous research and are discussed below.

1. Travel-time delay (TTD) is the difference between the time a vehicle passes a point downstream of the intersection where it has regained normal speed and the time it would have passed that point had it been able to continue at its approach speed.
2. Stopped-time delay (STD) is the time a vehicle is substantially standing still while waiting in line in the approach to a signalized intersection (3).
3. Time-in-queue delay (TIQD) is the difference between the time a vehicle joins the rear of a queue and the time the vehicle clears the intersection (4). Other authors have used different terms, specifically, queue delay (5), aggregate delay (2), and system delay (6).

Methods for field measurement of delay that have been studied previously include

1. The Berry-Van Til method, in which stopped-time delay is periodically sampled (2, 3, 7, 11),
2. The Sagi-Campbell method for determining TIQD, in which queue lengths are observed at specified times in each cycle (8),
3. The delay meter method, in which vehicles are input as they stop and output as they enter the intersection and the meter accumulates the TIQD (2, 3, 10),
4. The volume density method for determining TTD, in which observers count the number of vehicles occupying the section of the approach under study at successive time intervals such as 15 s (9), and
5. The time-lapse photography method that is used primarily to validate other field methods that utilize observers (2, 3, 5, 11).

To investigate the current use of delay as an indicator of signalized intersection performance, a questionnaire was sent to 78 traffic engineers with experience in delay measurement. The questionnaire attempted to determine which types of delay are thought to be most useful as indicators of intersection performance, which types of delay are considered the easiest to measure in the field, and which types of field methods for measuring delay are being used most often. Questions regarding field techniques also were asked to facilitate selection of standards for data collection in the field.

Forty traffic engineers or 51 percent of the sample responded. Tabulated replies to questions relating to delays considered "most useful" and "easiest to measure" are shown in Table 1. Each respondent indicated first preference as Rank 1, second preference as Rank 2, and third preference as Rank 3.

Weighted totals of the most useful indicators show that TTD is ranked first and STD second. Weighted totals of the easiest-to-measure indicator reveal that average length of queue ranks first, STD ranks second,

Publication of this paper sponsored by Committee on Highway Capacity and Quality of Service.

and load factor ranks third.

The field method reported as most frequently used was measurement of STD. Method TTD was reported the second most frequently used. Most (26 of the 39 who responded to the question) measured intersection delay over the entire approach width rather than by separate lanes. In reporting on criteria for when a vehicle was considered delayed, 11 of 28 used a locked-wheel criterion, but 17 others reported that vehicles are considered delayed when speeds are below 3.2, 4.8, or 8.0 km/h (2, 3, or 5 mph).

RELATIONSHIPS OF INDIVIDUAL VEHICLE DELAY TYPES

Three types of vehicle delay—TTD, STD, and TIQD—are obviously interrelated, as shown in Figure 1. Equations were developed for computing the differences in delay, assuming that each delayed vehicle decelerates to a stop at a uniform rate and then accelerates to its departure speed at a uniform rate of acceleration (1).

The equations reveal that TTD always exceeds STD by the amount of time spent accelerating and decelerating and that the difference is greater for higher initial speeds. In contrast, TTD is greater than TIQD only when the vehicle stops close to the stop line, but the reverse is true when the vehicle stops farther from the stop line. The results suggest that average TIQD can be expected to be closer to average TTD than average STD is.

METHODS USED

A base method for obtaining delay in each lane was applied by using time-lapse photography. During filming observers used at least two different manual methods for field measurement of delay. Results of manual methods were then compared with results from the base method by use of regression analysis on delays as calculated per cycle.

Base Method

TIQD was selected as the base method for the following reasons.

1. TIQD for each vehicle can be measured quickly and accurately by using time-lapse photography.
2. TIQD approximates TTD, which is more difficult to measure accurately even with time-lapse photography because of different approach speeds and varying speed change rates of different vehicles.
3. TIQD appears to approximate the individual driver's concept of delay, since TIQD covers the time utilized from the stop until the driver is sure of clearing the intersection.

As many as three cameras were used simultaneously from different camera positions to identify queue positions accurately. Film speed was 1 frame/s except for one series where the speed was 5 frames/s. Time was estimated to the nearest 0.5 s for a film speed of 1 frame/s. These film speeds were considered to be adequate, since a vehicle at 4.8 km/h (3 mph) travels only 1.3 m/s (4.4 ft/s).

Manual Methods

Observers used two field methods for measuring delay: average length of queue and TIQD sampling.

Average Length of Queue

In the average queue length method, or the queue backup sampling method, the position of the rear of the queue is sampled at predetermined intervals, such as every 10 s. The time interval is referred to as the sampling interval. The position of the rear of the queue is recorded either in number of vehicles or in distance.

The queue position in number of vehicles includes all vehicles that previously stopped during the formation of the queue. Thus, from Figure 2 the queue position at sampling time 40 is recorded as 9 even though seven of the vehicles have already begun moving.

At each sampling time, adjustments are made for lane changing. Field observers note when a vehicle enters or leaves a lane via another lane or driveway and records the appropriate interval. Field notes for different lanes are later cross-checked and compared for the balance in lane changing. In treatment of loaded cycles, care is taken to double-check the number of vehicles accumulated in the queue at the beginning of the red to avoid cumulative errors.

When queue position is recorded in distance, the distance from the rear of the last queued vehicle to the stop line (entry to the intersection) is recorded in meters (feet). Lane changing is not recorded.

The position of the last queued vehicle at each sampling time is converted into TIQD by multiplying the total number of queued vehicles by the interval size. For some observations, portable tape recorders provide signals to tell observers when to sample queue lengths. In other field studies, special buzzer and bell signaling devices provide the needed signals.

In addition to sampling queue backup at 10-s intervals, recording the approximate time the last vehicle in the queue started for each cycle is possible. This queue-max method of sampling queue backup was tested by using film data and is explained later.

TIQD Sampling

With the TIQD sampling method, different observers simultaneously count during predetermined time intervals the number of vehicles joining the queue and the number of vehicles entering the intersection. The number of vehicles each observer counts during the interval is recorded at the end of the interval. Vehicles that enter or exit the queue via off-street side areas or other lanes must be counted either as in or out during the correct interval. The TIQD sampling method is similar in concept to the delay meter method (10).

Because of limited personnel available for field studies, only limited testing of this field method was possible; a 10-s sampling interval was used for 56 cycles of 110 s each.

Preliminary Field Studies

Preliminary field studies were undertaken to check criteria for determining when vehicles joined the queue; time-lapse photography and four field observers were used. For these studies a speed of approximately 4.8 km/h (3 mph), considered normal walking speed, was selected as a standard because observers in the field could most easily judge when a vehicle had slowed to that particular speed. The 4.8-km/h (3-mph) value was also consistent with the 3.2 to 8.0-km/h (2 to 5-mph) range indicated by the questionnaire as being most commonly used.

In these field studies, the observers, who were physically separated from one another, were told to raise a white placard when they filt that the next car joining

their queues had reached the 4.8-km/h (3-mph) speed. A time-lapse film taken of the observers permitted calculation of the time that each observer believed that the TIQD should begin for each vehicle. The film also was used to get the time each car crossed the stop line. The TIQD was then calculated for pairs of observers for each lane. Statistical tests were run on the mean delays of the lane-observer pairs. Results indicated that the average delays were not found to be significantly different at the 5 percent significance level (1). Accordingly, the 4.8-km/h (3-mph) standard was used in the rest of the study.

In the preliminary studies, observers also checked different systems for reminding observers when to sample queue lengths. Stopwatches, bell and buzzer systems, and portable tape recorders were tested. Portable tape recorders that signaled the sampling time interval periodically were found to be satisfactory, provided adjustments were made occasionally to keep the signal in synchronization with the cycle.

A 10-s sampling interval was used by observers in the field studies, since all intersections studied had pretimed signals with cycle lengths in multiples of 10 s. Thus, queue lengths were sampled at the same relative sampling points in each cycle. This type of sampling may introduce some systematic error as discussed later, but facilitates the computation of delay by cycle, which may be needed when the HCM is used for level-of-service determinations.

Another preliminary study investigated use of rubber cones and other methods for sampling the position of the rear of the queue by distance rather than by the number of cars in the queue. Such methods would be especially useful when the queues are very long. Results of these studies for a limited number of observations indicated that, for queues of passenger cars, average distance headway was 8.23 m (25.1 ft), average spacing between cars was 2.95 m (9.0 ft), and the standard deviation was 1.03 m (3.14 ft).

Figure 1. General relationships between three types of individual vehicle delay.

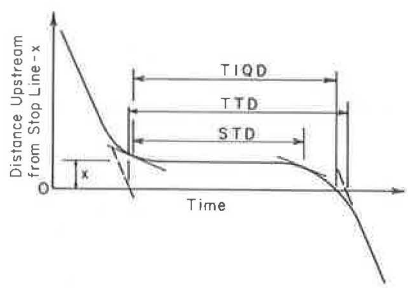
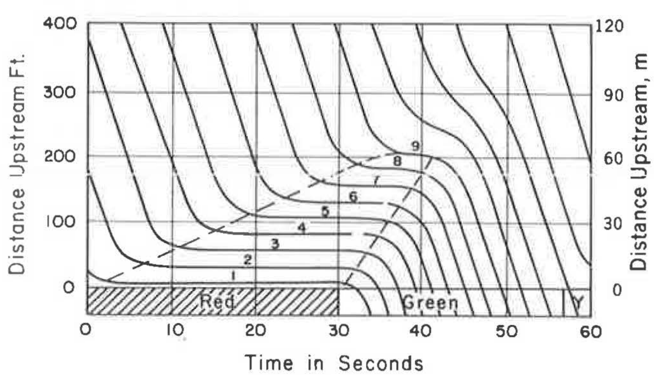


Figure 2. Time-space diagram based on 75 percent of vehicles stopping for signal.



COMPARISON FOR ONE CYCLE

Figure 2 shows a time-space diagram that is helpful in identifying how measurements are made for various methods of determining delay. TIQD, TTD, and STD have been scaled from this diagram for each of the delayed vehicles in this cycle as shown in Table 2.

Similarly, queue backup and STD have been sampled for each of the 10-s sampling points in this cycle. For computational purposes the sampled queues are considered to extend one-half the interval size either side of the sampling point. For computation of delay per cycle, queues recorded at the cycle changes are multiplied by one-half the interval size. Shown in Table 3 are sampling results, including use of a modified queue backup sampling, in which the maximum queue length and the time it occurred are also recorded and used in computations of queue backup delay.

Time-in-queue sampling by counting input to the queue and output from the intersection at 10-s intervals is illustrated in Table 4; data from the time-space diagram are used.

These examples do not illustrate the handling of vehicles changing lane, vehicles entering the queue from driveways, or loaded cycles. Procedures for adjusting the counts for these conditions were mentioned earlier.

DATA COLLECTION

Field data were collected both by time-lapse photography and by field observers for three urban intersection approaches, controlled by pre-timed signals, in Chicago and in Evanston. In addition, data taken by time-lapse photography for a fourth intersection were analyzed to provide some validation of sampling methods for loaded-cycle conditions. Characteristics of these four intersections are given in Table 5.

All data were taken for a peak direction of flow between 4:00 and 6:00 p.m. Three intersection approaches had no loaded cycles; however, the fourth had 57 percent

Table 1. Number of respondents by ranking of indicators of signalized intersection performance.

Type of Delay or Other Indicator	Most Useful				Easiest to Measure			
	Rank 1	Rank 2	Rank 3	Weighted Total	Rank 1	Rank 2	Rank 3	Weighted Total
TTD	16	3	4	58	5	4	2	25
TIQD (via meter)	6	12	5	47	0	8	6	22
STD	7	11	7	50	8	4	5	37
Average length of queue	2	6	7	25	8	8	4	44
Maximum queue per cycle	2	2	1	11	5	5	5	30
Vehicles stopped, %	0	2	4	8	2	7	3	23
Load factor	2	2	1	11	10	1	3	35

Table 2. Delays scaled from time-space diagram.

Vehicle Number	Delay (s) Base TIQD	TTD	STD	Vehicle Number	Delay (s) Base TIQD	TTD	STD
1	30	34	29	8	15	12	8
2	28	30	26	9	13	9	5
3	26	27	23	10	–	6	–
4	24	24	20	11	–	4	–
5	22	22	17	12	–	3	–
6	19	18	14	Total	194	204	153
7	17	15	11				

Table 3. Queues sampled from time-space diagram.

Type	Sampling Time 0 s	10 s	20 s	30 s	40 s	50 s	60 s	Max Queue Vehicles	Time (s)	Total Delay (vehicle-s)
Queue backup delay	0	2	5	7	9	0	0	–	–	230
Queue backup with max queue[a]	0	2	5	7	9	0	0	9	42	203
Stopped time delay	0	2	5	7	2	0	0	–	–	160

[a](10/2) (0) + 10 (2 + 5 + 7) + (42 - 35) 9 + 10 (0) + (10/2) (0) = 203 vehicle-s.

Table 4. Time-in-queue sampling from time-space diagram.

Item	Sampling Interval (s) 0 to 10	10 to 20	20 to 30	30 to 40	40 to 50	50 to 60	Total
Vehicle input	2	3	2	2	0	0	9
Vehicle output	0	0	0	4	5	3	12
Accumulation of vehicles	2	5	7	5	0	0	19

Note: Total cycle delay = 19(10) = 190 vehicle · s.

loaded cycles. Delay data for each lane were taken from the films. Included for each vehicle were the frame numbers (a) when the vehicle slowed to approximately 4.8 km/h (3 mph) at the rear of the queue, (b) when its rear wheels crossed the stop line at the intersection, (c) when it, as the last vehicle in the queue, began moving, and (d) when any lane changing occurred. These data, as well as the delays computed by the field methods, were punched on cards for computer analysis. All data were tabulated and analyzed by lane and by cycle.

When data for loaded cycles were taken from films, some individual vehicles were stopped in more than one cycle. The portion of the delay occurring in each cycle was assigned to that cycle.

REGRESSION ANALYSIS

A linear regression model was used to test the correlation between the base TIQD and the delay obtained by field methods for sites A, B, and C. Table 6 lists regressions plus the number of cycles (data points) included in each regression.

Equations resulting from the regressions are given below, as are values of correlation coefficients and the number of data points in each regression. These regression equations should not be interpreted to mean that accuracy is greater than would be expected from sampling data to the nearest 0.5 s.

Base TIQD = 4.906 + 0.937 (queue backup sampling) (1)

Base TIQD = -18.704 + 1.079 (queue backup sampling) (2)

Base TIQD = 18.230 + 1.030 (TIQD sampling) (3)

Base TIQD = 0.647 + 0.978 (queue backup with maximum queue) (4)

Regression equation 1 yielded a correlation coefficient of 0.971, indicating a high degree of correlation. The slope of 0.937 was found to be significantly different from 1.0 at the 5 percent significance level, but not at the 1 percent level.

Regression equation 4 yielded a slope of 0.978, an intercept of 0.647, and a correlation coefficient of 0.982. The slope was not found to be significantly different from 1.0 at the 5 percent level.

Regression equation 3 also yielded a high correlation coefficient of 0.966. The slope of 1.030 was not found to be significantly different from 1.0 at the 5 percent significance level.

A regression also was prepared to correlate base TIQD with queue backup delay based on queue length rather than number of vehicles in the queue.

Base TIQD = 65.098 + 0.799 (queue backup: distance) (5)

This sample for 20 cycles at site B yielded a correlation coefficient of 0.906, somewhat poorer than that yielded when number of vehicles is used for queue backup sampling. However, further tests are needed of use of distance as a measure of queue backup, since use of distance sampling is about the only practical method when queues are very long.

Regression equation 2 for only 20 cycles at a through plus left turn lane at site A yielded preliminary information that queue backup sampling is useful in measuring delay for such lanes (correlation coefficient of 0.947); more study is needed for locations with heavier turning movements and more opposing flow.

These regression results indicate that sampling queue backup is very promising for use when data are collected for revising the signalized intersection chapter of the HCM. The simplified queue backup method correlates reasonably well with base TIQD. Use of the modified queue backup sampling method, plus additional data on when the maximum queue length occurs, should improve the correlation with base method TIQD.

The time-space diagrams of 15 cycles for each of the two lanes of the south approach of Green Bay Road at Central Street, Evanston (site D), had been plotted by Centeno (7), based on time-lapse photography taken at

Table 5. Characteristics of four study sites.

Site	Intersection	Cycle Length (s)	Red Phase (s)	Northbound Lanes	Lanes Studied	Turns Right	Turns Left
A	Sheridan at Noyes, Evanston	90	30	2	2	None	Yes
B	Sheridan at Foster, Evanston	90	32	2	1	None	None
C	Sheridan at Glenlake, Chicago	110	22	3	Middle and center	None	None
D	Green Bay at Central, Evanston	90	60	2	2	Yes	Yes[a]

Note: No parking was permitted at study sites.
[a]No opposing flow during northbound phase of three-phase signal.

Table 6. Regressions and number of cycles for three sites.

Regression Number	Type of Lane	Number of Cycles Used: Site A	Site B	Site C (per lane)	Total
1 and 4	Through	20	20	28	96
2	Left	20	—	—	20
3	Through	—	—	28	56

5 frames/s. Base TIQD values for the 30 cycles varied from 87 to 1071 vehicle-s/lane/cycle. These time-space diagrams provided an opportunity to apply the TIQD sampling and queue backup methods to loaded cycles. A sampling interval of 10 s was used for these data also. Each of the two lanes of this approach was treated separately. For curb-lane traffic, 6 of 15 cycles were loaded; for center-lane traffic, 11 cycles were loaded. Left turns made from this center lane were unopposed since this intersection is controlled by a three-phase signal.

The regression of the base TIQD on the TIQD sampling method for the curb lane produced the equation

$$\text{Base TIQD} = 3.668 + 0.957\ (\text{TIQD sampling}) \quad (6)$$

The regression for the center lane yielded

$$\text{Base TIQD} = 32.945 + 0.933\ (\text{TIQD sampling}) \quad (7)$$

The correlation coefficients obtained for each of the lanes were almost identical: 0.968 for the curb lane and 0.967 for the center lane. Significance tests run on the slopes and intercepts revealed that the intercepts were not found to be significantly different from zero and that the slopes were not found to be significantly different from one at the 5 percent significant level.

Similar regressions were run for the queue backup method, yielding the following:

$$\text{Base TIQD} = 67.512 + 0.860\ (\text{queue backup}) \quad (8)$$

for the curb lane and

$$\text{Base TIQD} = 7.652 + 1.007\ (\text{queue backup}) \quad (9)$$

for the center lane. A regression run for 30 data points for the two lanes combined yielded

$$\text{Base TIQD} = 53.135 + 0.883\ (\text{queue backup}) \quad (10)$$

The correlation coefficients were 0.967, 0.958, and 0.970 respectively for the three equations. These results indicate that these methods could work well for loaded conditions. Supposition is indicated since the data were not collected by field observers but were taken from time-space diagrams. Caution should be exercised, therefore, in viewing the results reported as indicative of the method's accuracy when field observations are taken under saturated traffic flow conditions in which lane changing occurs.

Centeno (7) attempted to make stopped-time delay observations in the field to correlate with film data for peak-hour conditions at Green Bay Road and Central Street. However, he found that he could not sample stopped-time delay for the long queues with some exceeding 194 m (636.5 ft). Samples taken after the beginning of the green require simultaneously observing the back of the queue and identifying how many vehicles have started near the front of the queue. Accordingly, he limited himself to analyzing data taken from films.

LENGTH OF SAMPLING INTERVAL

To determine whether varying the size of the interval used would drastically affect the results obtained with queue backup sampling, a computer program was written in which the individual vehicle data taken from the films were used to compute the total delay per cycle. The computer program used only intervals that were evenly divisible into the cycle length. Accordingly, the analysis was performed separately on the data from the 90-s and the 110-s cycles. For the 90-s cycle, intervals of 5, 6, 9, 10, 15, 18, and 30 s were used; for the 110-s cycle, intervals of 5, 10, 11, and 22 s were used.

A regression equation was developed between the delay for the queue backup method, calculated from field data, and the delay for 10-s sampling intervals, calculated by computer program. Based on the data from the through lanes of sites A, B, and C, the relationship developed was

$$\text{Film queue backup} = 4.437 + 0.999\ (\text{field queue backup}) \quad (11)$$

The number of cycles was 95, and the correlation coefficient was 0.961. The intercept and the slope were not found to be significantly different from zero and one respectively at the 5 percent significance level. The indication then is that the standard for when a vehicle was considered stopped was uniformly applied in the field and when data were taken from the films.

Regression equations then were developed for each sampling interval to compare the base TIQD with the queue backup sampling from film data. The data from the first two sites (90-s cycles) were combined, giving a total of 60 cycles. The two lanes of the third site (110-s cycles) were also combined, resulting in a total of 56 cycles.

For the data from the 90-s cycle, the coefficient of correlation values were above 0.96. However, the intercepts and slopes of the equations were not found to be

statistically different from zero and one respectively at either the 5 percent or the 1 percent significance levels for all intervals of 15 s or lower (5, 6, 9, 10, and 15 s). For the data from the 110-s cycle, the coefficients of correlation were above 0.96 only for intervals below 12 s. The 22-s interval equation gave a correlation coefficient of 0.86. The intercepts of the 5, 10, and 11-s interval equations were not found to be statistically different from zero at the 5 percent significance level. The slopes were found to be significantly different from one for all equations at the 5 percent significance level. Thus, the queue backup method does not give good results at large sampling intervals.

The results seem to indicate that the queue backup method should be used with small sampling intervals. Errors involving the maximum queued vehicle may be significant when the queue is long. Overcoming this effect may be possible by recording, in the field, the time the maximum queued vehicle starts forward. Getting this time exactly may be difficult; however, if a readily visible timing device were used, the observers may be able to estimate the time the queue ends to some fraction of the interval. Such a timing device for obtaining this information might be a 10-s stopwatch that emits an audible signal every 10 s and could be attached to the observer's clipboard.

An attempt was also made to determine whether the use of a nonintegral 11-s sampling interval significantly affects the results obtained with the queue backup method. The data selected to perform this analysis were taken from the time-lapse films of the traffic at site B, Sheridan Road and Foster Street. Delay was computed by cycle for each of the 40 cycles. Regressions of the base TIQD on the queue backup delay were performed for results obtained by using both the 10-s integral and the 11-s nonintegral sampling intervals. The regression equations are shown below.

$$\text{Base TIQD} = 23.089 + 0.923 \text{ (queue backup)} \quad (12)$$

for the 10-s interval and

$$\text{Base TIQD} = 16.607 + 0.949 \text{ (queue backup)} \quad (13)$$

for the 11-s interval. The correlation coefficients obtained from each of the regressions were 0.965 and 0.946 respectively. Thus, the delay computed by using the queue backup method is highly correlated with the true values for both the 10-s and 11-s sampling intervals.

This limited analysis indicates that the choice of a sampling interval for use in the queue backup method can be either an integral or nonintegral subdivision of the cycle length for intersections similar to those studied here. Results obtained by using either of these interval types should not be significantly different from one another, provided that the sizes of the intervals are of the same order of magnitude.

PERSONNEL REQUIREMENTS

Queue backup sampling normally requires one person per lane for long queues. When queues are not long, or when the number of queued vehicles is approximately the same per lane, one observer is sufficient for the simplified method of queue backup sampling. When observations are also made of the time the maximum queued vehicle starts as part of queue backup sampling, the field work is more difficult. More study is needed of this maximum-queue option in queue backup methodology, especially for lanes where left turns are permitted and vehicles change lanes.

If the observer at the back of the queue observes queue position in meters (feet) rather than in number of vehicles in the queue, he or she usually can collect data on the queue positions for each of two lanes. Observers can devote all of their time to identifying the position of the rear of each queue.

Time-in-queue sampling requires more care in field application to avoid error from vehicles changing lanes and entering from driveways and other side entrances. If there are many lane changes, one observer may be needed to handle lane changes only. In studies of intersection performance for intersection capacity purposes, personnel counting entering volumes per cycle might be able to collect the output count data for the time-in-queue sampling; thus, only one additional person per lane would be needed at the rear of the queue to implement this method of measuring delay.

In general, the less complex queue backup method is simpler to use in the field than the sampling of stopped-time delay method because the observer need not count vehicles that are starting at the front of the queue.

CONCLUSIONS

This investigation of field methods for measuring TIQD used only a limited number of intersection approaches. The following conclusions, therefore, apply primarily to approach lanes with traffic and physical conditions similar to those studied.

1. Pending further validation under a wide variety of conditions, queue backup sampling appears to be very promising for field use in a nationwide effort to measure delay at signalized intersections because the number of personnel and amount of equipment required are minimal, data collecting is simple, and the method has reasonably close correlation to TIQD. The method gives evidence of being compatible with other data-gathering procedures for analyzing intersection capacity and performance by cycle.
2. Both queue backup sampling and TIQD sampling measure TIQD in the field reasonably well for the conditions encountered in this study. These conditions included few left-turning vehicles, little lane changing, and unsaturated traffic flow. Accuracy of queue backup sampling can perhaps be improved by collecting data on the starting times of the last queued vehicle in each cycle.
3. Simplified queue backup sampling requires fewer personnel and is easier to perform in the field than TIQD sampling under most conditions. However, if the additional data obtained by the TIQD sampling method (i.e., saturation flows or entering volumes) are needed for capacity studies, using this method warrants further consideration.
4. In queue backup sampling by distance, somewhat poorer correlations with base TIQD were yielded when the position of the rear of the queue was sampled in meters (feet) than when counts were made of the actual number of vehicles in the queue. However, the limited experience with this distance-sampling method indicates that the method is easy to use in the field because there is no need to count vehicles and to keep track of lane changing.
5. The sampling interval selected for use in the field in the queue backup method may either be an integral or nonintegral subdivision of the cycle length. Limited tests conducted with these two different sampling rates yield similar results. Also, the accuracy of the results using the queue backup method appears to be dependent on the selection of a relatively small sampling interval, such as 10 s.

RECOMMENDATIONS FOR FURTHER RESEARCH

The methods used in this study to measure TIQD were field tested under limited conditions. To adequately evaluate the potential of these methods for use in further studies to replace load factor as an indicator of signalized intersection performance, several conditions should be investigated.

1. Further field testing should be conducted of queue backup sampling methods under saturated flow conditions to better determine the method's abilities to predict TIQD under loaded conditions. Since these heavy-volume conditions are often of most interest, this recommendation should receive high priority in further research.
2. Further field testing is necessary for left-turn lanes, where the length of the queue continually varies because of the blocking effects of left-turning vehicles and vehicles changing lanes, to better determine the predictive ability of the method under such conditions.
3. The ability of field personnel to record lane changes accurately under various traffic conditions should be field tested to determine whether this possible source of error in sampling the number of vehicles in the queue can be minimized.
4. A further investigation of queue backup sampling should be conducted in which the position of the last vehicle in the queue is recorded as a distance upstream from the intersection. Different types of markers alongside the approach roadway should be used to facilitate estimation of distances. Refinements should be made in the field procedures for observing the actual position of the rear of the queue at each sampling time and in the application of the method to lanes with left-turning vehicles and with commercial vehicles. Queue lengths could be identified by distance markers; each marker might correspond to a number of equivalent passenger vehicles. Delay could then be computed in seconds per equivalent passenger vehicle. This method would avoid calibrating queue lengths due to variations in number of commercial vehicles.
5. The use of a maximum queue correction should be investigated in the field for the queue backup method based on the length of maximum queue (in numbers of vehicles or in distance) and the time the last queued vehicle starts. Such an investigation should determine (a) the ability of field personnel to collect these data and (b) whether these maximum queue data improve the ability of queue backup methods to predict TIQD sufficiently to warrant any extra personnel.

REFERENCES

1. M. G. Buehler and T. J. Hicks. An Investigation of Field Methods for Measuring Time-in-Queue Delay at Signalized Intersections. Department of Civil Engineering, Northwestern Univ., Evanston, Ill., MS thesis, 1975.
2. H. Sofokidis, D. L. Tilles, and D. R. Gieger. Evaluation of Intersection-Delay Measurement Techniques. HRB, Highway Research Record 453, 1973, pp. 23-48.
3. D. S. Berry. Field Measurement of Delay at Signalized Intersections. HRB, Proc., Vol. 35, 1956, pp. 505-522.
4. M. Norman. Level of Service Indicators at Signalized Intersections: Random vs. Platooned Vehicle Arrivals. Department of Civil Engineering, Northwestern Univ., Evanston, Ill., MS thesis, 1975.
5. S. L. Cohen. Application of Network Simulation Models to the Analysis of Intersection Performance. Federal Highway Administration, Sept. 1973.
6. Validation of Traffic Simulation Model Components. Traffic Research Corp.; Bureau of Public Roads, U.S. Department of Commerce, Dec. 1966.
7. F. Centeno. Methods of Measuring Delays for Evaluating Service Volumes at Signalized Intersections. Department of Civil Engineering, Northwestern Univ., Evanston, Ill., MS thesis, Aug. 1973.
8. G. S. Sagi and L. R. Campbell. Vehicle Delay at Signalized Intersections, Theory and Practice. Traffic Engineering, Feb. 1969, pp. 32-40.
9. D. Solomon. Accuracy of the Volume-Density Method of Measuring Travel Time. Traffic Engineering, March 1957, pp. 261, 262, and 288.
10. SDS Delay Meter Manual. SDS Technical Devices Ltd., Winnipeg, Manitoba, Canada.
11. D. S. Berry and C. J. Van Til. A Comparison of Three Methods for Measuring Delay at Intersections. Traffic Engineering, Dec. 1954, pp. 93-99.