Technique for Measuring Delay at Intersections

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This report presents our findings on a design for a simple, accurate technique for measuring vehicular delay on the approach to a signalized intersection. Precise definitions were established for four measures of performance: stopped delay, time-in-queue delay, approach delay, and percentage of vehicles stopping. Approach delay was selected as being most representative of intersection efficiency. Four manual methods using film taken at 10 intersections were tested in the laboratory. The values thus obtained were statistically compared with true values from time-lapse photography. The point sample, stopped delay procedure and the percentage of vehicles stopping method were selected as the most promising methods for practical use and were performed in the field at three sites. A user's manual for application of these two methods was produced but is not included in this report. Correction factors were developed to allow the field results to more accurately estimate the true values of stopped delay and percentage of vehicles stopping. Interrelationships among the four measures of performance were established so that approach delay could be estimated from a value for stopped time.

It has always been difficult to quantitatively define operational efficiency for approaches to signalized intersections by using traffic engineering techniques. In 1965, the Highway Capacity Manual (1) introduced the concepts of load factor and level of service in an attempt to relate intersection efficiency to some factor obtainable in the field. However, load factor has not received widespread acceptance, and several researchers have postulated that this measure may not be a reliable indicator of intersection performance. It has been generally agreed that some measure of vehicle delay should provide a practical and meaningful measure of performance.

There are many reasons for considering delay (and perhaps stops) a better measure than load factor. First, load factor is by definition a measure applied to each individual approach. To date, no method has been devised in which load factor can be used to provide a single measure of overall intersection operation. Second, load factor is not a good measure for locations with traffic-actuated signals. For example, a phase is considered "loaded" if traffic continually enters the intersection on green, but at the first major gap in traffic the green is terminated. This can be considered an efficient traffic-actuated controller and does not imply congested or near capacity conditions. Third, small changes in volume appear to cause large changes in the value for load factor; for example, relatively small increases in volume can bring load factor from 0.0 or 0.1 to 0.7 or higher in a short period of time. Also, conditions near capacity flow are not well defined, and conditions of over capacity flow are not described by load factor.

In view of these deficiencies, the need for a different measure of operating effectiveness of signalized intersections is apparent. This need has prompted several researchers to explore the use of delay to measure performance.

The scope and objectives of the present research were limited to the definition of several delay types and to the formulation of a practical and accurate method that can be used in the field to measure delay. A complete description of the research, including a user's manual, is given in a three-volume report of the Federal Highway Administration (2).

STUDY PROCEDURE

Most previous work related to delay measurement did not clearly describe either the phenomenon to be measured or the details of the measurement technique. The Federal Highway Administration, recognizing this deficiency, set out objectives for a research project that would provide a precisely defined technique for measuring vehicle delay at signalized intersections. The objectives of the study were

1. To identify and define various measures of vehicle delay on approaches to signalized intersections,
2. To select the delay measure most appropriate for use by practicing traffic engineers, and
3. To develop a field method for collecting data that would lead to the most appropriate measure.

Synopsis of Related Work

One early effort to quantify vehicle flow characteristics on approaches to intersections was reported by Greenshields (3). The use of a 16-mm camera to capture traffic flow for subsequent analysis in the laboratory made this early work particularly noteworthy. In 1940, Rivett (4) presented a report on the use of mechanical aids (a desk calculator) in collecting data on vehicle delay at intersections.

Certainly the most complete and probably most important work related to field measurement, in contrast to theoretical modeling, was conducted by Berry and others (5). This work led to the establishment of several techniques for measuring intersection delay. Also, Berry's work included the first major effort to define different types of delay and to estimate the interrelationships among delay types.

In a 1957 paper, Solomon (6) described a measurement technique that related to Berry's procedure but was applied to a different type of delay. In the late 1960s, May and Pratt (7) published an article that can be considered as the beginning of the search for a measure of intersection performance more easily applicable and more meaningful than load factor. May and Pratt suggested that performance would be better described by a measure of delay than by load factor. Then Sagi and Campbell (8) described a new technique that could be relatively easily applied and would give a value for vehicle delay on the approaches to traffic signals. Buehler, Hicks, and Berry (9) used a questionnaire to survey existing practices for delay studies, but the results did not point conclusively to one method or one delay type as being most widely used and accepted in the United States.

Much research has been directed toward theoretical models for estimating stops and delay. These models have been based on assumptions related to patterns of vehicle arrival and departure on an intersection approach. All the modeling work has suffered in one important aspect: No matter how simple the model, the basic assumptions have not been generally applicable to a wide variety of intersections. For example, one common assumption has been that vehicles arrive randomly. However, in an interconnected signal system this assumption does not normally hold true. Most of the modeling developed has contributed to a better understanding of traffic flow theory but has not been of practical use. The work by Sagi and Campbell was perhaps the best effort toward combining a certain amount of traffic flow theory with a practical field procedure.

In summary, most previous studies related to delay measurement techniques have had one or more of these deficiencies. (a) No clear definition of delay measures was given. (b) Much attention was paid to mechanical or electronic devices that merely serve as aids, while relatively little attention was paid to the validity of the procedure itself in providing good estimates of the delay measure. (c) Several new techniques reported in the literature have simply been old techniques applied in a slightly different manner. (d) Many studies relied on techniques that could be applied easily only under certain traffic or geometric conditions (for example, at intersections with a pretimed traffic signal control). These techniques are not well suited to general application. (e) Most modeling techniques used in the past are somewhat cumbersome for the practicing traffic engineer and are not particularly suited for application to a wide range of intersection types.

Study Execution

The approach used to achieve our research objectives was composed of the following steps.

1. A review of pertinent literature and previous research was made.
2. Several types of vehicle delay of the type found on approaches to signalized intersections were identified, and a precise definition was developed for each type.
3. The delay type that appeared to best portray the efficiency of intersection operation was selected. The term "approach delay" was used to identify this best measure.
4. Methods for field data collection were identified and defined. These methods were designed to collect and reduce traffic data so that the selected measure of approach delay could subsequently be estimated.
5. Using combinations of delay types and field data collection methods, a selection was made of the most promising methods to be tested during the research.
6. Ten intersection approaches from four urban areas and with differing physical and operational characteristics were selected for study.
7. For each study approach, two periods were filmed: 50 min during off-peak conditions and 50 min during peak conditions. Two cameras, one for time-lapse photography at 1 frame/s and one for real-time photography at 16 frames/s were run simultaneously during each study period.
8. The real-time film was viewed in the laboratory for simulation of manual field studies. The selected delay types and manual methods were used to collect data from the film.
9. The time-lapse film was used to obtain precise data on each vehicle observed on the study approach. For each study period a precise (also referred to as "true" in this report) value for each measure of delay and stops was obtained.
10. The true values were compared with the values obtained from the manual methods for each delay type and for each study technique. Statistical tests were used for the analyses.
11. The manual methods that appeared to best meet the objectives of the research were selected for field validation.
12. Three new study approaches were used to train a field crew in the selected methods, and two 1-h studies (covering peak and off-peak) were conducted at each approach. Time-lapse film was taken at the same time the field crew was performing each study.
13. In the laboratory the time-lapse film was analyzed and the measures of stops and delay were obtained. Statistical analyses were used to compare these values with those obtained by the field crew.
14. A final report and a user's manual were prepared.

VEHICLE DELAY

Characteristics and Definitions of Delay

Figure 1 describes the movement of vehicles along the approach to a signalized intersection. Three types of typical vehicle movements are shown. Also shown is the time-space relationship for an unimpeded vehicle with no stops or delays on the approach.

In the analysis of delay, at least two points along the approach to a signalized intersection must be found. First, the point at which a moving vehicle is considered to be leaving the approach should be fixed. Noting that one objective of this research was to develop an efficient and relatively simple method of manual data collection, the STOP line or the first crosswalk line traversed by the approaching vehicle was considered the most obvious point to use for definition of a leaving vehicle. If neither of these lines exists, some type of mark to denote the location of a STOP line could be made for the purposes of the field study. The second point is located upstream from the intersection under study. This point would be situated so as to include all delay (including deceleration-acceleration cycles) created by the signalized intersection under normal peak flow conditions. The location of this point would vary from intersection to intersection but would be based on the same criterion, that is, located far enough upstream to include all delays caused by the traffic signal but not so far upstream to include delays caused by other traffic signals or major cross-street flows.

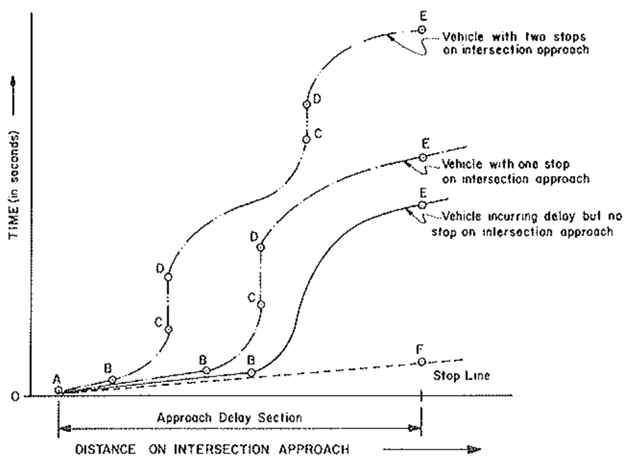
Various definitions and terms were utilized during the research and are recommended for future work in the analysis of intersection delay. The most important terms are defined in the following table.

Term	Description
Approach delay section	Section where most or all approach delay is incurred
Approach free flow time	Time used by unimpeded vehicle to traverse approach delay section
Approach time	Time used by any vehicle to traverse approach delay section
Approach delay	Approach time minus approach free flow time
Stopped delay	Time vehicle is stopped, with locked wheels, equal to stopped time
Time-in-queue delay	Time from first stop to vehicle's exit across STOP line, equal to time in queue
Percentage of vehicles stopping	Number of vehicles incurring stopped delay divided by number of vehicles crossing STOP line

One important distinction should be noted here: Vehicles moving along an approach experience a series of "times," the sum of which will be equal to the approach time. The term "delay" is not always synonymous with time. For example, for a given vehicle approach, delay is the difference between two measured times, while stopped delay is in fact equal to stopped time.

The above definitions can be better understood by referring to Figure 1, in which the approach delay section lies between point A and the STOP line. The approach

Figure 1. Time-space relationships.



time of a vehicle incurring delay is the time in seconds from zero to point E. The approach delay is the difference between points E and F. Stopped delay is the difference between points C and D, and time-in-queue delay is the difference between points C and E.

Descriptive Analysis of Delay Types

Of the many types of delay, past research and present practice suggest that three are of practical use. In addition, the number or percentage of vehicles forced to stop is another important flow characteristic that should be considered. Thus, the four measures of intersection performance selected for study were (a) approach delay, (b) stopped delay, (c) time-in-queue delay, and (d) percentage of vehicles stopping.

Most researchers agree that, although the best indicator of intersection performance is approach delay, this is difficult to obtain in the field. Therefore it was abandoned in favor of more easily measured factors.

Approach delay, unlike other measures, relates to the total time during which drivers and passengers are delayed and thus can easily be used in analyses of road-user time costs. Stopped delay is an obvious measure to the driver but can overstate efficiency of operation under conditions where the length of stop is short and is followed by slow movement in a long sluggish queue. Time-in-queue delay will often lie between the values for stopped delay and approach delay. However, for any given vehicle, time-in-queue delay can be greater than approach delay. Under certain traffic conditions, this measure can overstate the amount of delay being incurred by motorists.

During the study, approach delay was considered the best measure to describe operation effectiveness on the approach to a signalized intersection. Approach delay, although technically more difficult to collect in a direct manner, appeared to be better than either stopped delay or time-in-queue delay for describing and comparing intersection operation.

Percentage of vehicles stopping was not directly comparable to the delay measures. In the research, this measure of intersection performance was considered useful and was selected for testing along with three manual methods related to delay.

INTERSECTION DELAY MEASUREMENT PROCEDURES

Definition and Analysis of Basic Procedures for Estimating Delay

Review of the literature and of possible techniques not previously described led to the establishment of four basic procedures that could be used in estimating delay. All past and present efforts were categorized as one of the four. In several cases, a method contained elements from two or more of the basic procedures. The four procedures are (a) point sample, (b) input-output, (c) path trace, and (d) modeling.

The point sample method is based on a periodic sampling of some factor (such as number of stopped vehicles) on the intersection approach. In essence, it is a series of instantaneous samples having an interval of time between each sample. An example of this technique is the method commonly known as the Berry-VanTil procedure.

The term "interval sample" might also be used to describe the input-output method. It is similar to the point sample method but uses an infinitely short interval (zero) between samples and a long sample period of, say, 10 or 15 s. The factor being measured is observed at its beginning (input) and end (output) points.

The path trace is based on a sample of individual vehicles using the study approach. Data on each vehicle sampled is recorded over the period of time the vehicle is within the study area (for example, the approach delay section). Using measurements on the sample group of vehicles, a statistical expansion of the data to represent all vehicles is made. This method is very similar to a traffic engineering spot-speed study.

The use of modeling in estimates of delay can include a wide range of field and analysis techniques. All methods that use one or more theoretical assumptions regarding arrival patterns, departure patterns, driver behavior in queues, and traffic signal operation are in this category.

How well each of the four basic procedures related to the objectives of the research was analyzed.

The point sample method has several advantages. First, the technique is self-correcting in that an error or omission in one sample will have almost no effect on the overall result, because each sample is independent of the previous one. Second, the technique is not dependent upon signal indications, except for the restraint of periodicity. This restraint refers to the need for a set of data points arrayed throughout the signal cycle and providing a representative sample of all traffic conditions in the cycle. A disadvantage of this method is that the accuracy of an observer's point sample might be considerably reduced if the count (say, of stopped vehicles) becomes quite high.

The input-output method suffers from one important disadvantage. The field data should be corrected for vehicles that enter or leave the study area between the point of input and the point of output. Correction factors should be applied at the beginning and end of the study period, and also at regular intervals throughout the study, to compensate for observer errors.

The path-trace method was considered simple to perform in the field and would yield, from a single study, all four measures of delay and stops described earlier. However, it was hypothesized that a very large sample of vehicles would be needed to provide an estimate of delay within reasonable levels of confidence.

Because modeling methods were considered too esoteric and difficult to apply to varying intersection conditions, we eliminated this category.

Selection of Methods to Be Tested

To provide a guide for selection of the most promising two or three delay measurement methods, a matrix of the four basic methods applied to the three basic measures of delay was developed to give 12 possible study methods. Each of these was then judged against a framework of eight criteria. For each, an overall utility score was obtained that served as an indication of the method's effectiveness in meeting the objectives of the research.

Factors such as field manpower requirements, need to establish base speed, and generalized application were among the eight selection criteria. One important criterion was whether a method depended upon continuous observance of traffic signal indications. If so, the method was considered less useful.

The procedures selected for testing were (a) point sample, stopped delay, (b) point sample, time-in-queue delay, (c) path trace, and (d) percentage of vehicles stopping.

Following selection of three delay procedures and a fourth related to percentage of vehicles stopping, a detailed study design was developed for each. It was decided that no electronic or complex mechanical devices would be used in applying the methods to the 20 film segments in the laboratory. In this way, a truly simple manual technique would be tested.

Description of Manual Methods Tested

The point sample, stopped delay technique was designed for intervals between samples of 15 or 13 s, the latter value being used at locations having pretimed signal controllers. For all but 2 of the 20 film segments studied, a two-person team was used to obtain the samples on a lane-by-lane basis. A third person, using a stopwatch, gave a cue at each sampling point. The team noted the number of stopped vehicles in each lane at each sampling point. The total stopped delay was computed by multiplying the interval between samples by the number of vehicles counted in all samples.

The point sample, time-in-queue delay technique was designed identically to the point sample, stopped delay method. Only the phenomenon being observed was different. Following a stop, a vehicle continued to be in queue until it crossed the STOP line.

The path-trace technique was performed by a three-person team for each of the 20 film segments. One person served as sample selector. This person counted vehicles crossing into the approach delay section at its upstream end. A previously fixed sample rate based on volume was used for each film, and the sample selector gave a cue to one of the two observers each time a selected vehicle approached the entry point of the section. The observer started a stopwatch when the vehicle entered the section and noted the elapsed time of all actions such as stop, start, change lane, and leave section at STOP line. This technique led to estimates of total volume, stopped delay, time-in-queue delay, approach delay, and percentage of vehicles stopping.

The fourth manual method was a count of all motorized vehicles crossing the STOP line. The count was categorized into stopping or not stopping. Any vehicle that stopped one or more times on the intersection approach was counted as one vehicle in the stopping category. The results from this method give estimates of both total volume and percentage of vehicles stopping.

DATA COLLECTION AND REDUCTION

Study Sites and Filming Procedures

Ten approaches to signalized intersections were used; each approach was filmed for two 50-min periods. Table 1 gives a list of the sites and basic characteristics of each. The study sites represented a broad range of geographic, geometric, and traffic conditions. The research methods were general in that they could be successfully used in varied situations and would not be dependent on specific features of an intersection.

A 16-mm camera with a crystal speed control was used to film 50 continuous min at exactly 16.0 frames/s. Color film was used and then studied in the laboratory in a real-time mode for the four manual methods described earlier.

An 8-mm camera with an intervalometer set at exactly 1.0 frame/s was run simultaneously at each site with the 16-mm camera. Color film was used and then studied in the laboratory in a time-lapse mode on a projector-analyzer.

Laboratory Work

Each of the four manual methods was performed on each of the 20 films, and arithmetic values for various delay measures were computed. All of the data were taken on a lane-by-lane basis, and the final summary of values for each method was given by lane and also for the total approach.

The time-lapse work involved studying each vehicle individually and determining the frame numbers at which the vehicle performed some action (i.e., stop, start, change lane, cross STOP line). Some 22 000 vehicles were included in the 20 films.

The data on each vehicle were punched onto standard cards, and a computer program developed during the research ran an error check on the data. Following corrections of the data base, the program calculated and summarized all possible measures related to stops and delay for each film. Recognition of vehicles that either entered or left the approach delay section at some intermediate point was given in the time-lapse work and was deemed important in computing true values for stops and delay. Also, all lane changes were noted from the time-lapse film, and this information was used to properly assign various types of delay to each lane.

During filming, data reduction, and analysis, tight control was maintained on all aspects of the work to ensure precise results. Such factors as calibration of stopwatches, camera speed, and projector speed were checked regularly.

DATA ANALYSES

Two general types of analysis were performed on the data. First, regressions of real-time values on the corresponding time-lapse values were derived and analyzed; second, regression analyses were made to compare the interrelationships among delay types. From the time-lapse film the following measures were obtained: (a) stopped time (equal to stopped delay), (b) time in queue (equal to time-in-queue delay), (c) approach delay, (d) percentage of vehicles stopping, and (e) volume estimate. From the real-time manual methods, the following measures were derived and are listed with their coded designation.

Measure	Coded Designation
Point sample, total stopped time	M1T
Point sample, stopped time per vehicle	M1PV
Point sample, time in queue	M2
Point sample, time in queue per vehicle	M2PV
Path trace, stopped time per vehicle	M3A
Path trace, time in queue per vehicle	M3B
Path trace, approach delay per vehicle	M3C
Path trace, percentage stopping	M3D
Path trace, volume estimate	M3E
Percentage of vehicles stopping	M4
Volume estimate from M4 study	FV

Ratio comparison was another type of analysis made. Several measures derived from the real-time studies were used to form a ratio with the true value of the corresponding measure derived from time-lapse film.

Statistical Terminology

The regression relationships discussed in the following sections are reported on the basis of the line of best fit in the form $Y = bX + a$, where Y is the variable plotted on the vertical axis, b is the slope of the regression line, X is the variable plotted on the horizontal axis, and a is the intercept of the best fit line at the vertical axis.

Also reported is the coefficient of determination (R^2) value for each regression line. This value relates to the amount of scatter of the data points about the regression line. A high value (greater than 0.90) indicates that the regression relationship is very strongly linear. The standard error is another statistic reported and is an indication of the range of values about the mean value that will encompass the true mean. Thus, if a value is reported as 1.10 ± 0.04, the indication is that 68 percent of the time the true mean value will lie between 1.06 and 1.14.

The term "significant" is also used in reporting the analyses. In this research, all tests were carried out by using Student's t-test at the 0.05 significance level, and all tests were of the two-tailed variety; i.e., significance would be declared if the statistic or value from the data set was either greater or less than the hypothesized value.

Manual Methods Compared With Time-Lapse Results

Table 2 summarizes the regression lines obtained when measures of delay, stops, and volume were compared with the corresponding measure derived from time-lapse photography.

Both of the point sample methods, M1 and M2, demonstrated a high level of precision: R^2 equals 0.99. This is an indication of a very strong linear relationship between the stopped time or time in queue derived from the field study and the true values. As noted in Table 2, the upward bias of the slope of the point sample lines is significantly different from 1.0, and in the case of total time in queue (M2T) the intercept is negative and significantly different from 0.0.

One definite conclusion reached from studying these relationships was that an upward bias existed in the point sample method, whether it was applied to stopped time or to time in queue. Thus, if the method had been applied in the field, the estimate of stopped time or time in queue would have been higher than the true value.

For the path-trace study, five measures were computed and each regressed against the true value of the measure obtained from the time-lapse work. Table 2 shows that except for the volume estimate all measures had a regression line slope not significantly different from 1.0. Thus, it can be said that the path-trace method is quite accurate but not as precise as the point sample methods, as is evidenced by lower values of R^2.

Interrelationships Among Delay Types

An important part of this research was the determination of the relationship between the true value for a measure and all other measures.

Table 3 lists the statistical qualities of the interrelationships. It is interesting to note that time in queue accounts for about 97 percent of approach delay and stopped time for about 76 percent of approach delay. The three linear relationships of delay with percentage stopping are not strong. The last relationship in Table 3 represents an attempt to develop a linear, as opposed to a curvilinear, relationship between percentage stopping and approach delay. By taking the log of the value for approach delay per vehicle, a strong linear relationship does result. This could be very significant because, of all field procedures, perhaps the easiest and least costly to perform is the study of percentage of vehicles stopping. If a good predictive relationship exists between percentage stopping and approach delay, the percentage stopping study might be used by jurisdictions lacking manpower to perform the more elaborate delay studies.

One potential disadvantage of using percentage stopping values for estimating delay is that, when conditions force all vehicles to stop, delay can increase drastically while percentage stopping remains constant at 100 percent. Because the final recommendations of this study did not include the use of percentage stopping values to estimate delay, this potential difficulty was not explored in detail.

Other Analyses

In addition to the analyses described above, several other factors were studied. First, each of the four basic measures was regressed against a ratio of volume to service volume at level of service C. The R^2 values for these plots ranged from 0.47 to 0.63, indicating that considerable scatter in the data points existed. One interesting fact was observed from these plots: All of the low delay locations were controlled by an interconnected signal system, while most of the high delay locations operated with isolated local control.

For the path-trace method, an analysis was made of the sample size necessary to achieve reasonable results. Depending on delay type, from 1200 to 2700 vehicles would be needed in a path-trace sample to obtain delay estimates at the 95 percent confidence level.

Finally, an analysis of arithmetic ratios was made. The value for a given measure taken from the real-time studies was divided by the true value for the same measure. Ratios were computed for the two methods that were finally recommended: point sample, stopped delay and percentage of vehicles stopping.

The ratio analyses can be summarized by the following observations. (a) There appears to be a strong upward bias in the estimate of stopped time from the point sample method when compared with the true value. It is interesting to note that only three of 20 ratios were below 1.000 and that all three occurred in peak-hour studies under heavy volume conditions. (b) For percentage stopping, the estimate from the manual method was always greater than the true value. (c) For volumes taken from the percentage stopping study, no correcting factor is necessary to achieve an accurate estimate of true volume.

Table 1. Study sites.

Film	Intersection	City, State	Direction Traffic Approached From	Type of Signal Control	No. of Moving Lanes on Approach	Signal System Operation	Exclusive Left-Turn Lane
1, 2	Pleasant St.* and Massachusetts Ave.	Arlington, Mass.	South	Pretimed	3	No	Yes
3, 4	Massachusetts Ave.* and Everett Ave.	Cambridge, Mass.	North	Pretimed	2	Yes	No
5, 6	Washington St.* and Madison St.	Alexandria, Va.	South	Pretimed	4	Yes	No
7, 8	Leesburg Pike* and Haycock Rd.	Falls Church, Va.	East	Semiactuated	2	No	No
9, 10	University Blvd.* and Viers Mill Rd.	Wheaton, Md.	East	Fully actuated	4	Yes	Yes
11, 12	Classen Blvd.* and N.W. 23rd St.	Oklahoma City, Okla.	North	Pretimed	3	No	Yes
13, 14	N.W. Expressway* and Pennsylvania Ave.	Oklahoma City, Okla.	West	Fully actuated	4	No	Yes
15, 16	Broadway Blvd.* and Craycroft Rd.	Tucson, Ariz.	East	Fully actuated	5	No	Yes
17, 18	Congress St.* and Granada Ave.	Tucson, Ariz.	West	Fully actuated	4	No	Yes
19, 20	Speedway Blvd.* and Mountain Ave.	Tucson, Ariz.	East	Semiactuated	3	Yes	Yes

*Street traffic approached on.

Table 2. Regressions of manual measures versus time-lapse values.

Method	Measure	Intercept[a]	Slope[a]	R^2
Point sample	M1T	-1350 ± 823	1.15[b] ± 0.03	0.99
	M1PV	-0.42 ± 0.64	1.10[b] ± 0.02	0.99
	M2T	-2010[b] ± 860	1.18[b] ± 0.02	0.99
	M2PV	-0.65 ± 0.79	1.12[b] ± 0.02	0.99
Path trace	M3A	-0.01 ± 2.54	0.99 ± 0.09	0.86
	M3B	-1.49 ± 3.09	1.04 ± 0.09	0.88
	M3C	-1.53 ± 2.38	1.04 ± 0.06	0.93
	M3D	-1.47 ± 3.83	0.98 ± 0.06	0.94
	M3E	90.07[b] ± 46.41	0.89[b] ± 0.04	0.96
Percentage stopping	M4	4.26[b] ± 1.21	0.96 ± 0.02	0.99
	FV	17.02[b] ± 5.70	0.98[b] ± 0.01	0.99

[a] Reported as the coefficient ± standard error.
[b] Intercept significantly different from 0.0 or slope different from 1.0 by a statistical test criterion: Student's t-test at 0.05 significance level.

Table 3. Interrelationships of time-lapse measures.

Y Axis	X Axis	Intercept[a]	Slope[a]	R^2
Stopped time per vehicle	Approach delay per vehicle	-0.99 ± 1.41	0.76 ± 0.04	0.96
Stopped time per vehicle	Time in queue per vehicle	0.49 ± 1.07	0.78 ± 0.03	0.97
Stopped time per vehicle	Percentage stopping	-9.54 ± 4.97	0.54 ± 0.08	0.72
Time in queue per vehicle	Approach delay per vehicle	-1.99 ± 0.88	0.97 ± 0.02	0.99
Time in queue per vehicle	Percentage stopping	-11.62 ± 6.60	0.67 ± 0.10	0.70
Percentage stopping	Approach delay per vehicle	26.89 ± 5.58	1.03 ± 0.15	0.72
Percentage stopping	Log_{10} approach delay per vehicle	-14.04 ± 4.62	54.97 ± 3.33	0.94

[a] Reported as the coefficient ± standard error

SUMMARY OF RESULTS

The following points provide a synopsis of both the performance of the manual methods and the statistical analyses of the data. M1 and M2 refer to point samples of stopped time and time in queue respectively, M3 refers to the path-trace method, and M4 refers to the percentage stopping method.

1. M1 was somewhat simpler to explain to field personnel and to perform than M2 or M3.
2. M2 was slightly more difficult to perform than M1 or M3 because observers must continuously study all approach traffic.
3. All four manual methods, M1, M2, M3, and M4, appear to be quite precise in predicting the true value of stops or delay. M3 does appear to be slightly less precise than the others, however.
4. M1 and M2 are somewhat less accurate (slope of regression line greater than 1.0) than M3 in predicting delay. At least two possible reasons for the overestimation of delay by point sample methods have been identified. First, there may be a tendency for observers to concentrate more on the upstream end of the queue and thus to add vehicles into their counts while delaying slightly the subtraction of vehicles that have actually departed from the front end of the queue prior to the sampling point. Second, there may be skew in the distribution of stopped time and time in queue such that the use of 15 s (or 13 s) as the average time stopped for each vehicle observed gives biased results.
5. M4 may provide a simple method of estimating approach delay by use of a logarithmic relationship.
6. The addition of various independent variables to the regression equation of delay obtained from M1 or M2 results regressed on the true value of delay does not significantly improve the predictive power of the equation.
7. Stopped time averages about 76 percent of approach delay, while time in queue averages about 97 percent of approach delay. M1, M2, and M3 all provide estimates of delay that can be used with considerable precision to estimate approach delay.
8. Mechanical aids accompanying manual methods may be useful. In M1 and M2, an audible cue from a cassette recorder eliminates the need to be constantly checking a stopwatch. For M3, the sample selector would benefit from a simple digital hand counter for vehicles crossing into the section. Likewise, observers performing the M4 study would find such a counter with at least two buttons useful for recording stopping and not stopping vehicles.

FIELD VALIDATION

Two methods, M1 and M4, were selected as best for general use by traffic engineers. The methods were found to give accurate estimates of stopped delay, percentage of vehicles stopping, and total volume. The principal reason for selecting M1 over M2 was that the time-in-queue procedure was considered by field personnel to be more difficult to perform than the stopped time procedure. M3 was eliminated because of the large sample size required to achieve good results.

The purpose of the field validation was simply to apply the selected methods to an actual field study and to compare the results with those derived from time-lapse

Table 4. Validation regression relationships of field versus time-lapse values.

Measure	Slope[a]	Intercept[a]	R^2
Stopped time	1.04[b] ± 0.01	350 ± 254	0.99
Percentage stopping	1.00 ± 0.04	5.46 ± 2.39	0.99
Volume	0.97 ± 0.01	32.02 ± 12.20	0.99
Stopped time per vehicle[c]	1.05[b] ± 0.01	0.31 ± 0.26	0.99

[a] Reported as the coefficient ± standard error.
[b] Intercept significantly different from 0.0 or slope different from 1.0 by a statistical test criterion: Student's t-test at 0.05 significance level.
[c] Using time-lapse volume for divisor of field stopped time.

photography run simultaneously with the fieldwork. In this manner, a check was made of how well the methods provided reliable measures of delay and stops.

The scope of the validation work was described as including three sites different from those used for the 20-film periods. The two methods selected for validation were to be applied for two 1-h periods at each site, one period during off-peak traffic conditions and the other during peak conditions. During the same periods, 8-mm films of the study approach were to be taken at 1 frame/s.

The three sites were in Tucson, Arizona, and a field crew was trained prior to performing the two manual techniques. A total of six data points resulted, two for each site. The sites represented different approach widths, number of lanes, signal operation and phasing, and traffic volumes.

During the validation work, the length of stopped queues varied from several vehicles to 25 or 30 vehicles/lane. Thus, it was concluded that a wide range of conditions was encountered by field personnel and that the results of the validation were sound.

Following the field studies and the simultaneous filming, all data were reduced. Comparisons were made between the true values (from time-lapse film) for stops, delay, and volume and the values derived from the manual methods.

Table 4 summarizes the regression relationships of the validation work. The upward bias in estimates from the point sample, stopped delay method was confirmed. Also, the slight upward bias in estimates of percentage of vehicles stopping was confirmed. The estimates of total volume as computed from the M4 study appear to be accurate; no bias occurred in either direction.

After the two field methods had been defined, analyzed, and field tested, a small, easy to use manual was prepared. The intent of this user's manual was to provide all basic information needed to successfully apply the two recommended field methods: point sample, stopped delay and percentage of vehicles stopping. The manual will be distributed by the Federal Highway Administration to engineering agencies.

CONCLUSIONS AND RECOMMENDATIONS

It is recommended that the point sample, stopped delay study be used for field measurement of delay and that the percentage of vehicles stopping study be retained as a practical and useful procedure.

For the point sample, stopped delay study, it is recommended that the value for stopped time from the field be corrected by applying a 0.92 multiplier to obtain a more accurate estimate of true stopped delay.

For the estimate of volume from the percentage of vehicles stopping study, it is recommended that the field value be used directly, with no correcting factor.

The value resulting from a field study of percentage of vehicles stopping should be corrected by a multiplier of 0.96 to achieve a more accurate estimate of the measure.

Once the recommended field data corrections have been made, stopped delay per vehicle multiplied by 1.3 will yield a good estimate of approach delay per vehicle.

It is concluded that all four of the manual methods tested can be relatively easily applied by typical traffic engineering agencies and can also yield fairly precise and accurate estimates of delay. Therefore, although two of the methods were recommended for inclusion in the user's manual, the other two methods (point sample, time in queue and path trace) might be considered in future work for special application.

One other conclusion that was reached after extensive study was that intersection delay studies should not, in most cases, be performed on an individual lane basis. Rather, an entire approach should be studied at one time. Although in theory it is possible to study several lanes individually on an approach, in practice there are numerous complicating factors that increase manpower requirements and reduce the reliability of the study results.

ACKNOWLEDGMENTS

We wish to acknowledge the support and assistance received during the research from Robert O. Kuehl, professor of statistics at the University of Arizona. Also, the cooperation of the Tucson Traffic Engineering Division is appreciated. S. L. Cohen of the Office of Research, Federal Highway Administration, served as contract manager for the study and contributed many useful ideas to the research and to the final report.

REFERENCES

1. Highway Capacity Manual. HRB, Special Rept. 87, 1965.
2. W. R. Reilly, C. C. Gardner, and J. H. Kell. A Technique for Measurement of Delay at Intersections. JHK and Associates, Vols. 1, 2, and 3; Federal Highway Administration, Repts. FHWA-RD-76-135, 136, and 137, 1976.
3. B. D. Greenshields. A Photographic Method of Investigating Traffic Delays. Proc., Michigan Highway Conference, 1934.
4. I. Rivett. A Simple Method for Tabulating Traffic Delay. Traffic Engineering, Sept. 1940.
5. D. S. Berry. Field Measurement of Delay at Signalized Intersections. HRB, Proc., 1956, pp. 505-527.
6. D. Solomon. Accuracy of the Volume-Density Method of Measuring Travel Time. Traffic Engineering, March 1957.
7. A. D. May and D. Pratt. A Simulation Study of Load Factor at Signalized Intersections. Traffic Engineering, Feb. 1968.
8. G. S. Sagi and L. R. Campbell. Vehicle Delay at Signalized Intersections, Theory and Practice. Traffic Engineering, Feb. 1969.
9. M. G. Buehler, T. J. Hicks, and D. S. Berry. Measuring Delay by Sampling Queue Backup. TRB, Transportation Research Record 615, 1976, pp. 30-36.

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