

Measuring Delay and Simulating Performance at Isolated Signalized Intersections Using Cumulative Curves

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A new method for directly measuring total delay at isolated signalized intersections uses cumulative arrival and departure curves. This method of measuring total delay is an application of queueing theory that can be used for actuated and for pretimed signals. The data requirements of this method are greatly reduced by approximating the cumulative curves with piecewise linear curves and concentrating only on critical movements. As a result, a single observer can collect the data for all critical movements at an intersection, because only one critical movement occurs at a time. Plotting the data in the form of cumulative curves allows direct measurement of total delay, queue length, and percent of vehicles required to stop. The data collected for the delay measurement are used to simulate graphically the performance of a signalized intersection under different demand and control conditions. A set of cumulative arrival curves and a specified signal control strategy enable construction of cumulative departure curves for the critical movements. For actuated signals, the different critical movements must be simulated concurrently, because the timing for one movement influences the other movements. This graphical simulation method helps to visualize the flow behavior at an intersection and provides an alternative to computer simulation methods, which remove the user from the underlying processes.

Measuring delay at a signalized intersection is of little value in and of itself. The only reason to measure the delay is to compare with delay measurements for other intersections or for the same intersection but under different control, demand, or design conditions. To evaluate the delay at the same intersection under different conditions without resorting to trial and error, the delay with the proposed changes must be predicted. The most common method of measuring delay is the point sample stopped delay procedure, which measures delay under existing conditions but cannot be used to predict delay under different conditions. Furthermore, the value of stopped delay must be artificially converted to a value of total delay. Because the cost to vehicle occupants is a function of total delay, it is most representative of intersection efficiency.

MEASURING DELAY

The usual measure of performance of a signalized intersection is delay. The average delay value at an intersection can be estimated empirically or measured directly using any of a number of methods. However, the accuracy of estimating delay empirically is questionable, because delay is a complex

variable that depends on many factors. The 1985 *Highway Capacity Manual* (HCM) (1) recommends using the point sample stopped delay procedure to measure delay in the field for existing conditions. The common practice is to measure stopped delay and then artificially convert it to total delay. Measuring stopped delay is straightforward, but no easy method exists for measuring total delay in the field. In fact, however, total delay can be measured quite easily by using cumulative arrival and departure curves. This method of measuring total delay is an application of ideas from queueing theory that are discussed by Newell (2).

Cumulative Curves

If the arrival times are known for individual vehicles approaching an intersection and the departure times are known for individual vehicles crossing the stop line, then cumulative arrivals and cumulative departures can be plotted against time for any movement, as shown in Figure 1. Each step represents the arrival or departure of one vehicle at that point in time. For the cumulative arrival curve to be most useful, the steps should represent the times when vehicles would arrive at the stop line in the absence of other vehicles. As described by Hurdle (3) and Tepley (4), this type of queueing diagram portrays stacking of vehicles at the stop line, with arrivals at the top of the stack and departures from the bottom of the stack. For this type of queueing diagram, the vertical distance between the two curves at any point in time represents the number of vehicles in the queue (queue length).

For vehicles in a single lane, the service order is first-in-first-out (FIFO). Thus, the horizontal distance between the two curves at any vertical position may be interpreted as the total delay that vehicle experiences. For a multiple-lane approach, the service order is not necessarily FIFO, but the interpretation is still useful because of the concern with average total delay instead of total delays for individual vehicles, and the combined total delay for all vehicles does not change if two or more vehicles trade places. The combined total delay all vehicles experience at the intersection for this movement is simply the area between the cumulative arrival curve and the cumulative departure curve, regardless of the order in which the vehicles are served.

If the cumulative arrival and departure curves for a movement are drawn on a larger scale reflecting a period of time that covers several cycles, then the steps for individual vehicles can be ignored, and the curves will look smooth, as shown in

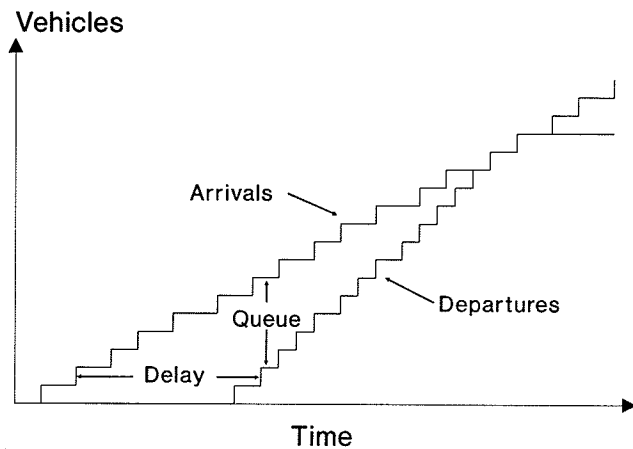


FIGURE 1 Cumulative vehicle arrivals and departures.

Figure 2. The cumulative arrival curve for isolated intersections will be approximately linear, with small fluctuations reflecting the randomness of the arrivals. Changes in the slope over a period of several cycles reflect changes in the actual arrival rate. The cumulative departure curve will be essentially flat during the time when the signal is red for that movement (except for right-turn-on-red movements). When the signal turns green, the slope of the departure curve will change within a few seconds to reflect flow at the saturation flow rate. This slope will remain essentially constant (except for unprotected left-turn movements) until the queue of vehicles disappears, at which point the departure curve is the same as the arrival curve until the red phase begins and the departure curve becomes flat again. During cycles in which the movement is oversaturated, the queue will not vanish before the red phase begins, and the cumulative arrival and departure curves will not meet.

Clearly, this method of measuring total delay would be more useful than measuring stopped delay. However, collecting individual arrival and departure times for each vehicle could be prohibitive, unless automatic equipment that can measure and record the data is available. Although one person could probably record the individual arrival times, another

person would be needed to collect individual departure times. Furthermore, errors would be highly likely, leading to arrival and departure curves that either cross or never meet. Simplification is required for this method of measuring total delay to be practical and useful.

Data Requirements

The objective of the simplification is to minimize the data required for measuring average total delay with an appropriate level of accuracy. Figure 2 shows that the area between the two curves for a single cycle is nearly a triangle, which suggests that the smooth cumulative curves might be approximated by piecewise linear curves, as shown in Figure 3. Now, instead of accounting for individual vehicles, only the corners of the triangles need be defined.

The cumulative departure curve can be represented by a piecewise linear curve, if the appropriate segments are selected. The time when the signal is red can be treated as linear, because the cumulative departure curve must be straight and flat, except for right-turn-on-red movements. The departure curve for lanes with right-turn-on-red movements could be approximated with a piecewise linear curve by moving the point at the end of the red phase up by an amount equal to the number of vehicles that depart during the red phase. The cumulative departure curve is also nearly linear when the signal is green (except for unprotected left-turn movements); the slope of this curve will equal either the saturation flow rate or the arrival rate if the queue has already vanished. The important points for the piecewise-linear departure curve are those that define the triangle representing combined total delay for all vehicles during the cycle. These points occur when the green phase begins, when the queue vanishes (if it vanishes), and when the red phase begins.

For nonisolated intersections, the arrival of platoons would require recording data for individual vehicles, because the cumulative arrival curves are not linear over intervals comparable to the cycle length. However, for isolated intersections, the arrivals are random. Thus, the cumulative arrival curve can be approximated by a piecewise-linear curve, as long as one or two points are known for each cycle. The points

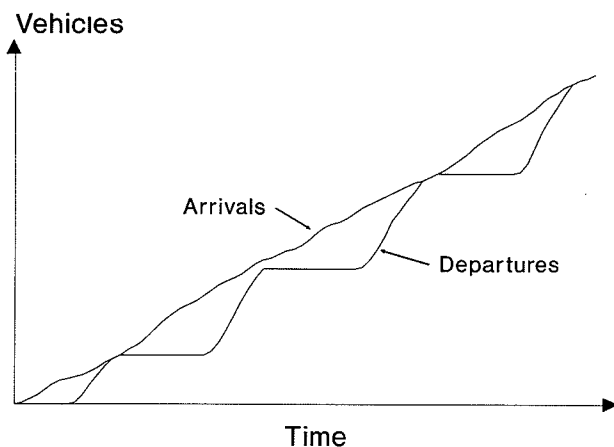


FIGURE 2 Smooth cumulative curves for several cycles.

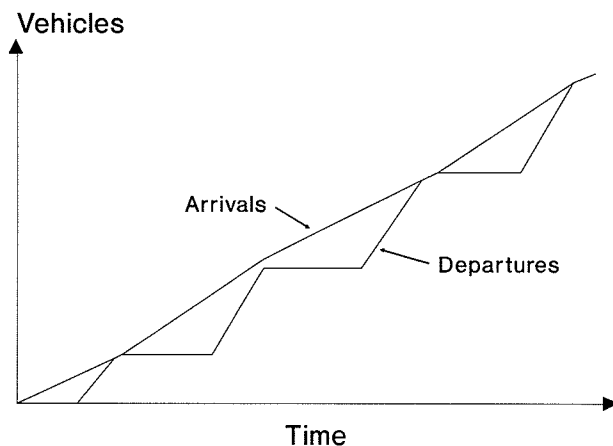


FIGURE 3 Piecewise-linear cumulative curves.

when the queue vanishes and when the red phase begins define the cumulative arrival curve. If the queue has not vanished when the red phase begins, then the number remaining in the queue can be added to the cumulative departure curve to define a point on the cumulative arrival curve. Thus, separate arrival data are not necessary, because the cumulative arrival curve can be constructed from data collected for the cumulative departure curve.

Although collecting arrival and departure data for individual vehicles might be more accurate, the loss of accuracy in using the piecewise-linear curve method is small compared to the combined total delay for all vehicles during a cycle. Such inaccuracies include errors caused by treating the arrival and departure curves as piecewise linear and errors caused by the choice of points defining the departure curve. These inaccuracies can be shown by superimposing piecewise-linear curves over the actual curves, as seen in Figure 4. As Figure 4 shows, the errors are small compared to the total area between the two cumulative curves. Thus, when the piecewise-linear curve method is used, only a few time values and vehicle counts need be recorded for each movement during a cycle, as shown in Figure 5. The times needed are those when the green phase begins, when the queue vanishes (if it vanishes), and when

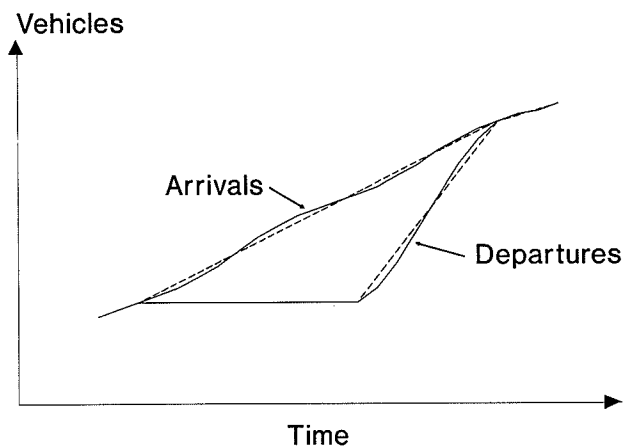


FIGURE 4 Superimposed smooth and piecewise-linear curves.

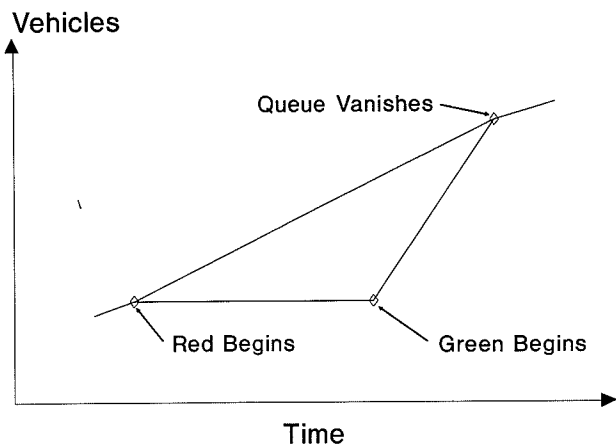


FIGURE 5 Minimum data requirements for measuring delay.

the red phase begins. Cumulative vehicle counts are needed when the queue vanishes and when the red phase begins. If the queue has not vanished when the red phase begins, then the number remaining in the queue must also be recorded. The cumulative curves can now be plotted quickly, and anything of interest can be measured directly from the plot.

Critical Movements and Lanes

The delay of all movements need not be measured to get a meaningful measure of delay for the intersection. Only the critical movements need be studied, because they control the timing of the intersection. The delay vehicles experience in a critical movement will be greater than the delay of vehicles in the other movements that occur at the same time in the cycle. The critical movements can be identified as those generally having the longest queue during a particular phase in the cycle. For actuated signals, a phase terminates only after the queue for the critical movement has vanished or the green time has reached the maximum value. At least two critical movements control the timing, but there can be more if more than two signal phases are present. Usually the through movements control the timing, in which case the turning movements might not need to be measured. However, some intersections have separate left-turn phases with heavy volumes, in which case the critical turning movements must also be measured.

For each critical movement selected for delay measurement, only the lanes with the longest queues need be measured because these critical lanes control the timing of the intersection, and the delay for vehicles in a critical lane will be greater than the delay of vehicles in the other lanes. Again, this method is not applicable for lanes with unprotected left turns, but the delay for other lanes in the same movement can be determined nonetheless. If a specific movement has more than one critical lane or if the critical lane is not obvious, then the data can be collected for the group of lanes as a whole. However, if one of the critical lanes is easier to observe than the others, data for this lane only would suffice.

The critical lanes and movements can be identified by observing the intersection for a few cycles immediately before collecting the data for measuring delay. Of course, the delay for all movements or lanes could be measured using this method if they are of interest or if the critical movements or lanes are difficult to distinguish. Collecting data for all movements or lanes might be necessary to calculate the overall level of service for the intersection on the basis of the average delay of all vehicles using the intersection, but this procedure would require more observers or more time to collect the data.

Data Collection

This procedure for measuring total delay can be carried out quickly by one person, because only one critical movement occurs at any time. Although measuring the delay of the critical movements one at a time is easier, measuring them concurrently takes less time and is more useful. Concurrent measurement allows a better estimate of the average delay for the intersection, because it ensures that all arrival patterns are for the same time of day. Also important is collecting

data for all critical movements concurrently for actuated signals to identify the relationships between the movements. This method of measuring total delay can be used for actuated and for pretimed signals. For pretimed signals, the time values when the green and red phases begin only have to be recorded once, because they are the same for every cycle. The cumulative counts and the time the queue vanishes must be recorded every cycle, but a residual queue for some of the cycles is likely.

Data should be collected for about 10 cycles, which would cover a period of 10 to 20 min. This period is long enough to provide meaningful average total delay values but not long enough for the arrival patterns to change significantly. The observer should be positioned both to see the departing vehicles and the changing traffic signal and to glance upstream to get an idea of the location of the end of the queue. Thus, the only logical location for observing departures is at the stop line. When two movements are being observed concurrently, the only possible location for the observer is at the imaginary intersection of the two stop lines. For one person to observe and record data for two or more movements concurrently, having some sort of device for recording times is helpful (and perhaps necessary). This device could be a portable computer or calculator with a time module that can record time values every time a key is pressed, or the observer could use a tape recorder to record counts verbally and later measure the times from the tape.

Modern traffic control systems that can automatically record output from the detectors could be used for this procedure. However, the data might not be useable if it already has been processed. Detector counts and time information are useful for this method of measuring delay, but such values as percent occupancy and flow are not. Detector position and length are also important. Only short detectors near the stop line can collect departure data. Detectors from multiple lanes that are hooked up together and detectors that are longer than one vehicle can provide occupancy but not accurate counts. Thus, they are not useful for this method of measuring delay.

Evaluation

Before making any calculations, the cumulative arrival and departure curves for each critical movement should be plotted against time. This procedure allows for quick determination of whether the data are meaningful and helps to understand what is happening at the intersection. When measuring two or more movements concurrently, the data for each movement should be plotted using the same time scale on the same graph, as shown in Figure 6, or with one graph above the other. This procedure shows the relationships between the different movements, which are especially important for actuated signals.

The delay calculation is now easy, because the cumulative arrival and departure curves outline a series of triangles, one for each cycle. The delay for each cycle is the area of the triangle that is one-half the base (red time) times the height (number of vehicles to depart between start of green and end of queue). Thus, the calculations can be done by hand. If the queue does not clear, then the additional delay can be broken up into triangles with bases equal to the cycle length and

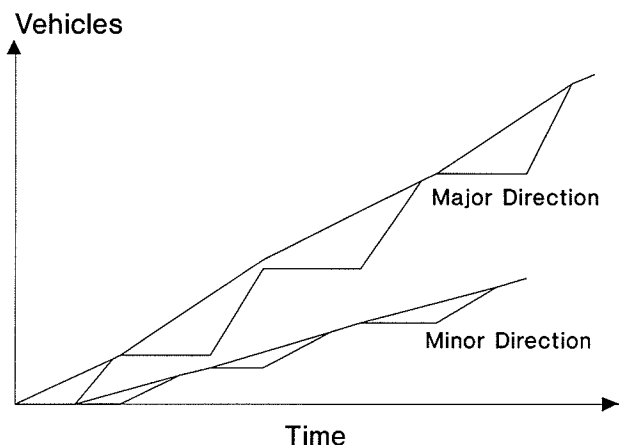


FIGURE 6 Simultaneous plot of curves for two directions.

heights equal to the number of vehicles left in the queue when the red phase begins, as indicated by the dashed lines in Figure 7. The average total delay for a single movement is the sum of the combined total delays for each cycle divided by the total number of vehicles to pass. Once the average total delay for each critical movement is obtained, the volume-weighted average total delay for the intersection can be obtained.

If the measured delay is found to be unacceptably high, then potential improvements related to signal timing and detector configuration can be identified on the basis of the field observations or inspection of the cumulative plots. For pretimed signals, whether the green times are too long or too short compared to the cycle length should be readily apparent. For actuated signals, similar observations apply to the setting of maximum green time, but the situation is complicated by the importance of the location and length of detectors when the signal is actuated. Another value that can be measured directly and may be of particular interest is the percentage of vehicles stopped, which can be obtained by adding the vertical heights of the triangles for each cycle and dividing by the total cumulative vehicle count.

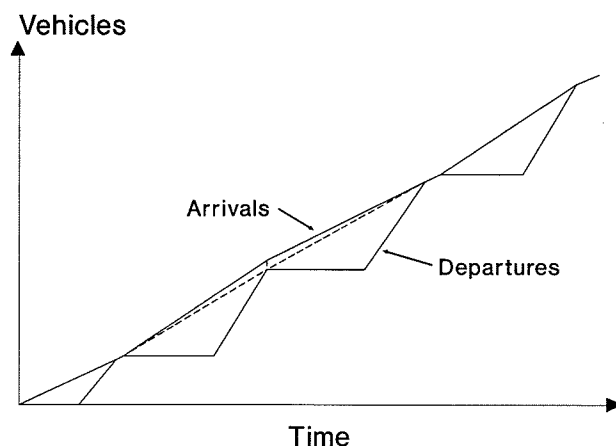


FIGURE 7 Calculation of delay from measured data.

Comparison with Other Methods of Measuring Delay

The HCM (1) describes a method for empirically estimating the delay at a signalized intersection. That method is useful for comparing different geometric and signalization designs, but the HCM recommends measuring delay in the field for existing conditions, because delay is a "complex variable that is sensitive to a variety of local and environmental conditions." Measuring delay directly using cumulative curves is much more believable and probably even faster than measuring all the factors and making all the calculations involved in the HCM method. Also, the HCM (1) allows no evaluation of parameters that are particular to actuated signals, such as extension times and detector placement.

Hurdle (3) mentions that most analytical delay models use unrealistic assumptions and so their delay estimates are not accurate, especially when the intersection movements are close to saturation. He suggests developing new models that would take more account of variation in demand. These models would require more detailed information about traffic patterns. The same problem can be approached from a different angle. Delay can be measured directly instead of collecting all the data needed for a delay formula from an analytical model.

Reilly et al. (5) performed an extensive study that compared different methods for field measurement of delay at intersections. The various methods were classified into four families: input-output, path trace, point sample, and modeling. The input-output methods involve recording the number of vehicles entering and leaving a section of the approach during some interval. The delay can be obtained by subtracting the time that would be spent in the zone under free-flow conditions from the actual time spent in the zone. However, corrections are needed to account for vehicles entering or leaving the zone in between observation points, and close time coordination among the observers is necessary.

The path trace methods involve taking a sample of individual vehicles and recording the times each vehicle enters the section, stops, starts, and leaves the section. The time-lapse photography and test car techniques are examples of this method, as is the license plate study technique, although it does not usually record stops and starts. The manpower requirements are high for the path trace method, and the computations can be both complicated and time consuming.

The point sample methods periodically record some value such as the number of vehicles stopped. Reilly et al. (5) recommended using the point sample stopped delay procedure and then converting stopped delay to total delay. Total delay is most representative of intersection efficiency, but it is difficult to measure in the field. The conversion factor, which is determined by comparing stopped delay measurements with detailed time-lapse photographs, depends on the operation of the signal and the average queue length. Measuring stopped delay requires two people for data collection for each movement, unless the measurements are done sequentially for the different movements. Although stopped delay can be measured for a before-and-after study, it does not provide any information useful for predicting the performance at the intersections under different conditions. Thus, the delay at the intersection after any changes have been made will not be known until the changes are in place, which leads

to a trial-and-error procedure for finding signal control strategy improvements.

Modeling methods involve a combination of field measurements and theoretical assumptions that are used to predict which vehicles are delayed and by how much. Modeling methods help minimize the field effort, but practitioners will not use methods that are too complex. The accuracy of the modeling method depends on the validity of the theoretical assumptions, which can involve arrivals, departures, queue behavior, and signal operation. If the assumptions do not apply to all lane groups, different lane groups must sometimes be treated separately. Other problems with modeling methods, as mentioned by Teply (4), are the vagueness of delay definitions and different interpretations of the concept of delay.

The procedure for measuring total delay using cumulative curves is a modeling method based on queueing theory and is consistent with Teply's (4) discussion of the use of queueing diagrams. It was specifically designed to be as simple as possible so that practitioners would use it. A minimum amount of data can be recorded by one person in the field. The basic assumption is that the arrival and departure rates remain essentially constant between times when the signal changes or when the queue vanishes. The assumptions apply to all lane groups, so all lane groups are treated similarly.

Measuring total delay directly eliminates the need for conversion factors and allows direct comparison with theoretical formulas that also give total delay. Other methods for measuring average total delay are available, but measuring total delay directly provides information that might be useful for other purposes, such as predicting the performance of the intersection under different demand or control conditions.

SIMULATING PERFORMANCE

Using the method described, the delay at an intersection can be determined for the existing signal timing and detector configuration. If the delay is judged to be unacceptable, some potential improvements for the signal timing or detector configuration may be identified on the basis of the field observations or inspection of the cumulative plots. To predict the performance of an intersection with the proposed signal control strategy, a simple procedure would allow simulation of various signal control strategies before field testing and installation. Field testing more than one alternative scheme would be impractical because of the expense and time involved. To compare performance of the proposed signal control strategy with that of the existing strategy, the simulation could use the piecewise-linear arrival curves obtained for the delay measurement (assuming these curves were typical for that day and time period). Predicting a new cumulative arrival curve is not necessary to evaluate how different signal control strategies will serve a given arrival pattern. Furthermore, simulating the different critical movements using arrival curves obtained at the same time will more accurately reflect how timing for one movement influences the other movements.

To evaluate how the existing or proposed signal control strategies would serve the intersection under different demand conditions, the simulation could use a different set of cumulative arrival curves. These new cumulative arrival curves could be obtained by appropriately scaling the cumulative arrival

curves from the delay measurement to reflect an expected increase or decrease in demand. This method would allow evaluation of a long-term change in the arrival rate because the proposed signal control strategy has changed the performance of the intersection.

Given a set of cumulative arrival curves and a specified signal control strategy, the cumulative departure curves can be constructed for the critical movements. For a pretimed signal, the beginnings of the green and red phases are known. What remains to be determined is the time at which the queue vanishes. Thus, what is needed is a measure of the saturation flow rate. For an actuated signal, the beginning of the green phase also must be determined, but it depends only on the end of the green phase for the previous movement, which in turn depends on the time at which the queue vanishes. Thus, the start of one green phase must be determined on the basis of the start of the previous green phase. (Again, what is needed is a measure of the saturation flow rate.)

Saturation Flow

An estimate of the saturation flow is needed to predict when the queue will vanish with the proposed signal control strategy, given cumulative arrival curves. The data from the delay measurement can be used to create a plot of the number of vehicles departing from the queue versus the time from the start of the green phase until the queue vanishes. The most useful form of the data is a scatter diagram with a curve fit of the points, as shown in Figure 8. Each data point represents the total number of vehicles that departed between the start of the green phase and the time the queue vanished (or the time the red phase began if the queue did not vanish) during one of the cycles used for the delay measurement. Although start-up losses are associated with each cycle, at the end of this period the vehicles are departing at the saturation flow rate. The start-up losses are about the same for each cycle, and they are not likely to change when the signal control strategy is changed. The start-up losses must be included because the saturation flow curve will be used for the simulation to estimate how many vehicles will depart by a certain time after the green phase begins.

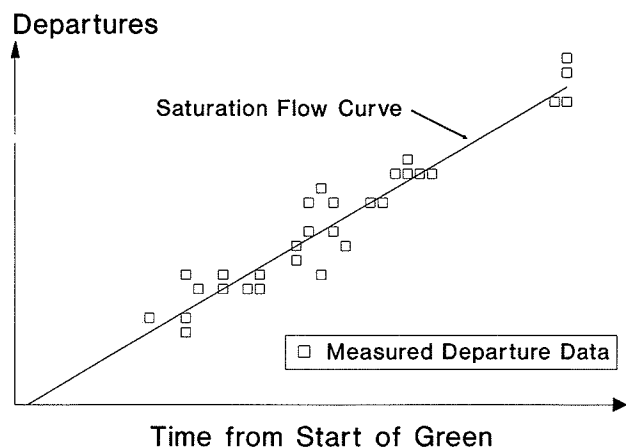


FIGURE 8 Determination of saturation flow curve.

Simulation of Pretimed Signals

The main objective of the simulation is to construct a piecewise-linear cumulative departure curve for a specified signal control strategy and set of cumulative arrival curves. A graphic method based on piecewise-linear cumulative curves, that is similar to that used in the delay measurement, will be used to simulate intersection performance. Again, this method is not applicable for lanes with unprotected left turns, and it applies to semi- or full-actuated and pretimed signals.

Constructing the departure curve for one cycle requires several steps, and then the process is repeated until the end of the arrival curve is reached. First, a point on the arrival curve (near time 0) is selected as the starting point for the first cycle (corresponding to the start of the red phase for the movement being modeled). The departure curve is flat during the red phase, which lasts for a known amount of time. At the end of the red phase, the green phase starts, and the vehicles depart at the saturation flow rate (except for start-up delays). By referring to the saturation flow curve, the time and vehicle count at which the cumulative departure curve meets the cumulative arrival curve (when the queue vanishes) can be determined to within about one vehicle. Because the saturation flow curve already accounts for start-up delays, no correction is necessary. At this point, the departures continue at a rate equal to the arrival rate until the end of the green phase is reached. Finally, the red phase for the next cycle begins at this new position on the arrival curve. During some cycles, the queue will not vanish before the red phase begins, in which case a residual queue is left. A simulation of one movement for several cycles at an intersection with a pretimed signal is shown in Figure 9.

The red phase of one movement consists of the all-red times and the green phases of all the other movements. The amber times are considered parts of the appropriate green phases because vehicles will tend to continue to depart at the previous rate (either the saturation flow rate or the arrival rate) for most of the amber time. This approximation is sufficient because the saturation flow curve has already accounted for the start-up delays. All of the components of the red phase can be determined from either the signal timing plan or from the field data that were collected for the delay measurement. Of

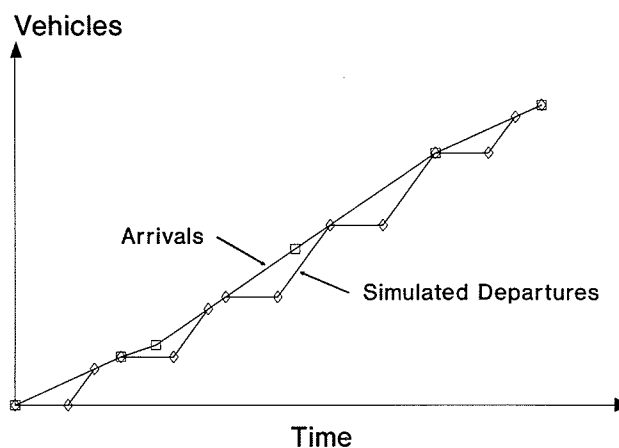


FIGURE 9 Simulation of a pretimed signal.

course, the proposed signal changes could involve some of these values, in which case the proposed values will be known and should be used for the simulation. For pretimed signals, performing the simulation for one critical movement at a time is sufficient (and easiest). The beginnings of the red and green phases are known, and the only parameter to be estimated is the time at which the queue vanishes.

Simulation of Actuated Signals

For actuated signals, the beginning of the green phase for one movement depends on the end of the green phase for the previous movement. Thus, the simulations for the different critical movements must be performed concurrently to alternate between pairs of cumulative curves each time the end of the green phase is determined for a particular movement. The total all-red time must be accounted for somewhere in between the green phases, but it can be inserted anywhere as long as it is used in the same place for every cycle. Although the all-red times occur at different times within the cycle, they all can be lumped together for the simulation, because for any given movement, all that really matters in this method is the total red time between green phases for that movement.

A conservative prediction of the time when the queue vanishes for an actuated signal will produce the most realistic results. Trying to squeeze the most out of every second of green time leads to unrealistically short cycle lengths because less time for one movement leads to less time for the next movement. An extra green time included in the simulation would account for less than ideal combinations of detector configuration and vehicle extension time. For example, if the detector extends all the way to the stop line, then any vehicle extension time should be included in this extra green time because the signal will remain green for this amount of time after the end of the queue has passed. Similarly, an appropriate extra green time should be included for detectors that are too long and detectors that are located upstream of the stop line but have extension times that are too long.

The first few cycles of a simulation of an actuated signal may not be indicative of the actual performance because of the dependence on the choice of initial conditions. Because the simulations must be done concurrently, all movements cannot begin at the same stage in the cycle. For example, if one movement begins at the start of the red phase, then the other movement should begin at the start of the green phase, and the number of vehicles in the queue for this movement must have some initial value. The timing depends on the length of this queue, and the simulation will require a few cycles to forget the initial value. A similar argument applies to pretimed signals. In this case, the simulation should begin with a typical residual queue (which may be zero). The simulation can be warmed up by running through the arrival curve several times until appropriate initial queues are established.

Evaluation

After performing the simulation, the delay at the intersection with the proposed signal control strategy or different arrival rate is calculated as described in the section on measuring

delay. The average total delay is obtained by finding the area between the cumulative arrival and departure curves and dividing by the number of vehicles. The sections between the curves for each cycle are no longer exactly triangles, because the points that define the cumulative arrival curve are not the same as the points that define the cumulative departure curve. Treating the areas as if they were triangles defined by the cumulative departure curve gives areas that are approximately equal to the combined total delay.

The first step in evaluating the results of the simulation is to compare it with the performance under the existing demand and control conditions. Weighting the delays of the various movements by volume may be necessary to get an appropriate intersection average for comparison. If for some reason the results of the simulation are questionable (either too good or too bad), then the existing conditions could be simulated and compared with the actual performance to determine if a data or methodological problem exists. If the results are accepted and the delay does indeed decrease, then the decrease should be weighed against the effort required to establish the improved signal control strategy.

APPLICATION

The procedures were applied to the intersection of Edgewater Drive and Hegenberger Road in Oakland, California. This intersection is not completely isolated, but it fits the definition because Edgewater has no other signalized intersections and the nearest signalized intersections on Hegenberger are about $\frac{1}{2}$ mi away in both directions. This method of measuring total delay was developed and improved by practicing on videotapes of this intersection and by field testing the method there.

Individual vehicle arrival and departure times were collected for several cycles for two different signal timing plans, and the average delay was calculated from the data by finding the area between the smooth cumulative arrival and departure curves. These delay values were compared to delay values obtained using piecewise-linear cumulative curves. The results for Edgewater Drive are presented in Table 1. The values using the piecewise-linear curves differ by only a few percent from the more accurate values using the smooth curves.

Table 1 also presents the results of applying the graphical simulation method to the second signal timing plan. The average delay from the simulation differs from both of the measured delay values by only a few percent. Other simulations performed on this intersection indicated that the average delay

TABLE 1 COMPARISON OF MEASURED AND SIMULATED DELAY VALUES FOR EDGEWATER DRIVE

	Average Delay (sec)		Difference
	Smooth Curves	Piecewise Curves	
Timing Plan 1 - Measured	21.4	22.3	+4%
Timing Plan 2 - Measured	27.9	28.5	+2%
Timing Plan 2 - Simulated	N/A	27.5	-1% ^a
Timing Plan 2 - Difference	N/A	-4%	N/A

^a Compared to measured value for timing plan 2 using smooth curves.

could be reduced by about one-fourth if the signal timing were changed from semiactuated to full-actuated.

A detailed comparison between the results from this method and results from analytical models and other methods of measurement and simulation has not been performed because of its time and expense. Such a detailed comparison could usefully be the focus of further research.

CONCLUSION

Cumulative arrival and departure curves can be used to measure total delay at isolated signalized intersections with either semi- or full-actuated or pretimed signals. By approximating the cumulative curves with piecewise-linear curves and concentrating only on critical movements, the necessary data can be collected by a single observer for all critical movements at an intersection, because only one critical movement occurs at a time. Plotting the data in the form of cumulative curves allows direct measurement of total delay, queue length, and percent of vehicles required to stop. This method compares favorably with other more common methods of measuring delay, such as the point sample stopped delay procedure, because it measures total delay directly.

The data collected to measure delay by means of cumulative curves also can be used to predict the performance of a signalized intersection under different demand and control conditions. This simple procedure allows simulation of various proposed signal control strategies before field testing or implementation. Given a set of cumulative arrival curves and a specified signal control strategy, the cumulative departure curves for the critical movements can be graphed. An estimate of the saturation flow is used to predict the time at which the queue will vanish with the proposed signal control strategy. The graphical simulation method provides a simple alternative to computer simulation models and helps in visualizing the behavior at the intersection. The use of cumulative curves presents the information in a manner that allows insight into both the cause and effect of the relationship between signal control strategies and intersection performance.

LIMITATIONS

The accuracy of this method depends on the validity of the assumption that the cumulative arrival and departure curves can be approximated with piecewise-linear curves. Using piecewise-linear cumulative curves to measure delay and sim-

ulate performance is only applicable to isolated signalized intersections and is not appropriate for lanes with unprotected left turns. Nonetheless, the delay for other lanes in the same movement as lanes with unprotected left turns can be measured. The departure curve for lanes with right-turn-on-red movements could be approximated with a piecewise-linear curve by moving the point at the end of the red phase up by an amount equal to the number of vehicles that depart during the red phase.

The advantage of this method is that the data collection and calculations can be performed by a single person in a limited amount of time, if the study concentrates only on the critical movements and lanes. If necessary, measuring delay for all movements or lanes with this method is possible but would require more observers or more time to collect the data. This method of measuring total delay is valid both for undersaturated and oversaturated movements. Oversaturated movements would require a count of the residual queue at the end of the green phase. In some cases, this queue could grow to be quite long, in which case a second observer might be necessary for collecting data.

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