Accuracy of Delay Surveys at Signalized Intersections

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Delay is an excellent tool for evaluating the operation of signalized intersections. However, it is not easily determined. This paper examines two approaches for measuring delay—a time-space diagram and a queuing diagram—and explains various problems related to each. The paper concludes that, while delay cannot be precisely measured, it can be a useful engineering tool if it is calculated properly.

A number of evaluation criteria are available to assess how well a lane at a signalized intersection operates under a given set of geometric and timing conditions. These criteria include the volume-to-capacity ratio, the reserve capacity, the probability of discharge, the load factor, and the average delay. Delay has a prominent place among these measures of effectiveness because it relates directly to the experience of the drivers and because its meaning is generally understood. The 1985 *Highway Capacity Manual* (*1*) uses delay as the sole basis for determining the level of service. The 1984 *Canadian Capacity Guide for Signalized Intersections* (*2*) identifies delay as the most powerful means of evaluating intersection operation, although it also recommends the use of other simultaneous measures. Nevertheless, although delay is an excellent evaluation tool, it is not easily determined.

Hurdle (*3*) discusses the principles behind analytical delay formulas. In a similar sense, this paper explains problems related to field measurement of delay in undersaturated conditions and shows that what is calculated is not always what is measured. Since direct measurements are not possible, surveys employ indirect techniques based on the time-space concept or on queuing theory. A detailed examination of both approaches shows that one of the major problems lies in the inherent vagueness of delay definition and in the different interpretations of the concept of delay. The paper explains relevant problems and concludes that, despite these difficulties, delay remains a good traffic engineering tool, provided it is calculated, measured, and used in a consistent fashion.

DELAY DETERMINATION IN A RECONSTRUCTED TIME-SPACE DIAGRAM

This method of delay measurement has not been commonly used, although it has been in existence for over 20 years. However, new electronic and computing developments have recently made it more appealing (*4*).

Figure 1 shows trajectories of two vehicles in a typical time-space diagram as used in signal design. In the figure, distance is horizontal and time is vertical. The driver of the first vehicle was forced to stop by the red signal, and the second vehicle moved unimpeded through the stopline during the green signal. In other words, the first vehicle experienced some delay while the second vehicle obviously had no delay. The wavy nature of the trajectories indicates speed noise (the fluctuation of speeds).

Trajectory 1 represents a vehicle that approached the intersection during a green interval. When it was some distance upstream, the signal changed to amber (Points *a*,*A*) and then to red. The driver slowed down and came to a complete stop (Points *b*,*B*). Vehicle 1 was stopped until shortly after the beginning of the green interval when the driver started accelerating (*C*) and continued the trip. The time during which the vehicle did not move (*B*−*C*) is called "stopped" delay (shown as d_s). This portion of the delay is rarely timed directly in intersection surveys; however, it can be as an indicator in floating car surveys. No travel time considerations are involved in stopped delay.

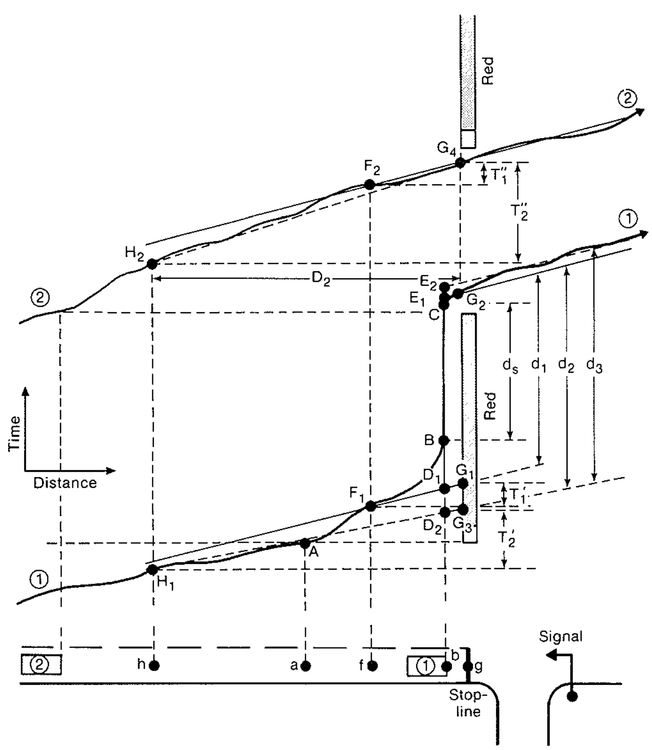

FIGURE 1 Schematic time-space diagram depicting delay factors at a signalized intersection approach.

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A common definition of delay is the time "lost" by the impact of the signal. (This paper does not consider delays caused by traffic or its overflow.) This delay involves some portion of the slowing down and speeding up process and can be represented by an approximation of the vehicle trajectory using straight lines. In the following discussion, this delay is called "overall delay" to distinguish it from stopped delay and from "total delay," which represents the sum of the delays experienced by individual vehicles.

An arbitrary point (f) with a corresponding point in time (F_1) can be employed to identify the approach part of the trajectory. The time when the vehicle crosses the stopline (G_2) is used for the discharge portion of the trajectory. The overall delay experienced by Vehicle 1 is represented by d_1 in Figure 1. This delay can be determined as the time difference between points F_1 and G_2 minus the free-flow travel time between point f and the stopline (g). This travel time, shown as T_1', is the vertical difference between F_1 and G_1. Nevertheless, it cannot be measured directly because Vehicle 1 did not cross the stopline until after it experienced delay. Other vehicles, however, can be employed instead. For example, Vehicle 2 was not impeded by other traffic or by the signal; consequently, its travel time (T_1'') between point f and the stopline (time F_2–G_4) can be used as a surrogate for T_1'. T_1' is usually determined as an average travel time for vehicles similar to Vehicle 2.

It would appear that the overall delay has now been accurately determined. However, a closer examination of real-life situations (as shown in Figure 2) reveals a problem with the definition of reference point f (or F_1 and F_2 in time). Speeds of vehicles approaching a traffic signal are rarely constant, especially when drivers can observe the change from green to amber and red. Referring again to Figure 1, after passing point a, the driver of Vehicle 1 slowed down considerably when the signal changed. As a result, the previous F_1–G_1 straight-line approximation of Trajectory 1 does not apply. If another arbitrary point (h) further upstream were used, a linear approximation of the approach process would be different. Instead of G_1, point G_3 would probably be used. The average speed of Vehicle 1 between h and b, however, would be faster than that between f and b. Consequently, a larger portion of the deceleration would be included, and the delay (d_2), calculated on the basis of a more distant upstream point, would be longer than the previously determined delay (d_1).

An additional problem lies in the determination of the free-flow travel time between the reference point and the stopline for vehicles similar to Trajectory 2. Again, the average speed between h and g (the slope of the straight line between H_2 and G_4) is different than the average speed between f and g, (the slope between F_2 and G_4). After a longer duration of a green interval, drivers can hardly be expected to behave in the same way as drivers approaching a red signal. As a result, the measured travel time (T_2'') is somewhat different than the T_2' needed to determine the delay. Since points f and h are arbitrary and their choice influences the delay, the delay values cannot be considered absolute.

The issue becomes even more complex when considering the speed behavior of vehicles departing from a standing queue. For the straight-line approximation of vehicle trajectories, it is normally assumed that vehicles will travel from time point G_2 at the free-flow speed determined for the approach. Although this assumption may be true for vehicles that stopped farther upstream of the stopline, it apparently does not hold for the first few vehicles stopped during red. The discharge trajectories of these vehicles should not be approximated by lines that are parallel to the approach trajectories and pass through the point in time when the vehicle crossed the stopline (G_2). Rather, shifted lines should be used to represent the resumed movement downstream of the intersection. As a consequence, point E_1 should be replaced by E_2. The resulting overall delay (d_3) represents the longest but possibly the most correct value because it truly reflects the time lost because of signal operation.

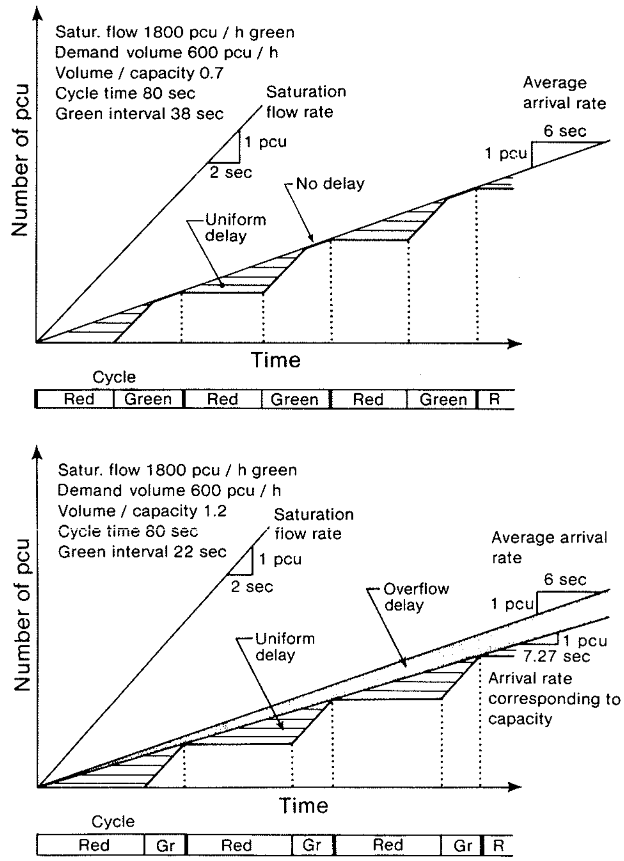


FIGURE 2 Signalized interaction delay interpretation in a deterministic queuing diagram (*2*).

The principles of an overall delay survey system that employs vehicle trajectories are discussed by Teply and Evans in a paper in this Record.

DELAY DETERMINATION USING A QUEUING DIAGRAM

Description

Delay measurements are usually based on the principles of deterministic queuing theory, as shown in Figure 2, rather than on assessing the arrival and discharge times of individual vehicles.

In contrast to time-space diagrams, the queuing diagram does not have a distance dimension. Vehicles "appear" at points on the arrival line and "disappear" at horizontally corresponding points on the discharge line (the saturation flow line). The horizontal distance between these points represents the delay for individual vehicles. Since these delays fill in the space between the arrival and discharge lines, the sum of all delays for all vehicles (the total delay) is represented by the area between both lines. The type of delay depends mostly on the definition of a vehicle's arrival and discharge times, as discussed in the previous section.

The focus of the following discussion is on uniform delay although most aspects also apply to overflow delay.

The vertical difference between both lines in the queuing diagram represents the number of vehicles accumulated at any given time (in other words, a queue). Because of the missing distance dimension, however, the diagram actually portrays a "stacking" of vehicles at the stopline, with arrivals at the top and departures at the bottom. This fact is important for delay measurements.

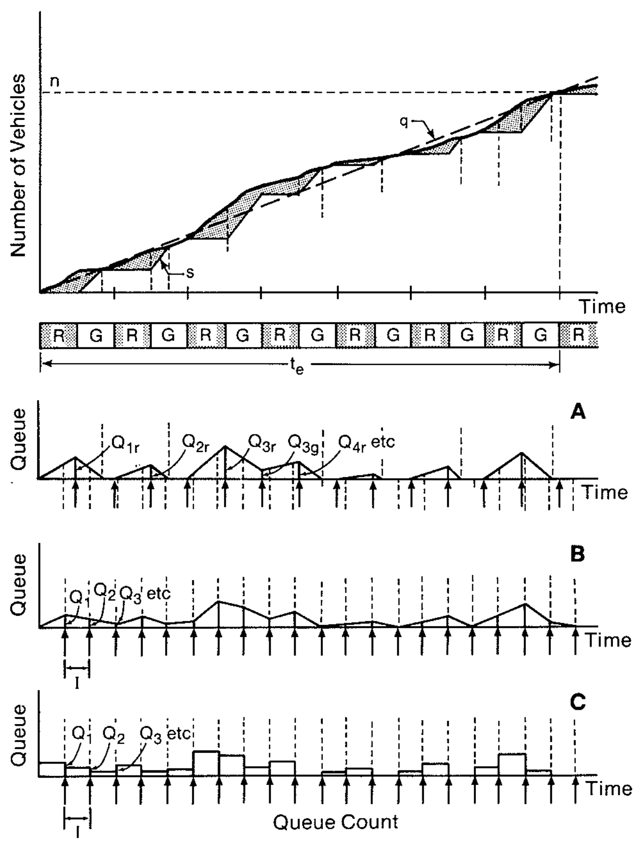
There are several ways in which a queuing diagram can be interpreted and used to determine delay. The top portion of Figure 3 depicts a fixed time signal operation with a relative steady arrival rate (q), subject to some random fluctuations. The rate of discharge during green intervals is represented by a constant saturation flow (s).

Queues (the vertical dimensions in the top portion of Figure 3) can be transferred to the diagram in Figure 3A. A linear representation of the development and decay of queues can employ only the most significant points in time, such as the ends of the green and red intervals and periods without queues. As a result, the total area of Figure 3A is approximately equal to the area between the arrival and discharge lines in the top portion of the figure. The average delay during the survey period can then be determined as the sum of the areas in Figure 3A divided by the total number of vehicles, i.e.,

$$D = \frac{\Sigma D_i}{n} \tag{1}$$

Since delay is usually surveyed over a limited number of cycles, it is not completely impractical to determine the individual areas in Figure 3A. Figure 4A shows the basis for this calculation. Apparently, areas in the top portion of Figure 4 equal areas in Figure 4A, i.e.,

$$\Delta ABC = \Delta A_1B_1C_1 \tag{2}$$



NOTE: Upward-pointing arrows indicate the points in time when a queue count is taken.

FIGURE 3 Transformations of a typical signalized interaction queuing diagram for various types of delay surveys: A, counting queues at the beginnings and ends of red intervals; B, counting queues at regular intervals "out-of-step" with the signal cycle, assuming linear growth or decay of queues during individual intervals; C, counting queues at regular intervals "out-of-step" with the signal cycle, assuming constant queues during individual intervals (*1*).

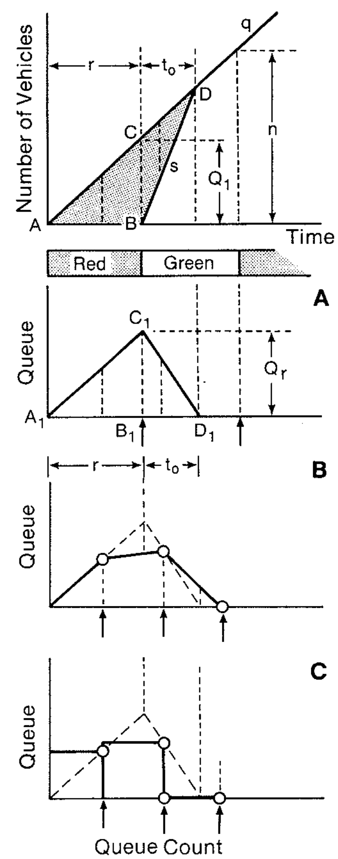


FIGURE 4 Delay calculations based on queue surveys shown in Figures 3A, 3B, and 3C.

and

$$\Delta BCD = \Delta B_1C_1D_1 \quad (3)$$

To determine area ΔBCD, the value of t_o is needed. This factor represents vehicles that joined the queue during the green interval. It can be calculated from the top portion of Figure 4 as follows:

$$q(r + t_o) = st_o \quad (4)$$

That is,

$$t_o = \frac{qr}{s - q} \quad (5)$$

where

r = red interval (sec);
s = saturation flow (veh/hr), measured directly; and
q = arrival rate (veh/hr).

The delay in Figure 3A is then the sum of all areas in the diagram divided by the total number of vehicles (n), i.e.,

$$d = \frac{1}{n}\left[\frac{1}{2}\,r\,Q_{1r} + \frac{1}{2}\,r\,Q_{1r}\right] + \left[\frac{1}{2}\,r\,Q_{2r} + \frac{1}{2}\,r\,Q_{2r}\frac{q}{s - q}\right] + \left[\frac{1}{2}\,r\,Q_{3r} + \frac{1}{2}\,g\,(Q_{3r} + Q_{3g})\right] + \ldots \quad (6)$$

where Q_{ir} equals queues at the end of red intervals and Q_{ig} equals queues at the end of green intervals, both expressed in number of vehicles.

The variable q can be averaged by

$$q = \frac{n}{t_e} \quad (7)$$

where t_e is the evaluation time.

To simplify these equations, it is usual to account not for a full value of t_o but only for discharge of vehicles in the queue at the end of the red interval, i.e., $t_o' = Q/s$. Another alternative is to assume that the discharge takes place during the total green interval, i.e., $t_o' = Q/g$. These changes will cause delay to be somewhat underestimated or overestimated.

Most delay surveys employ delay counts at regular intervals, out of step with the cycle time, to provide for random sampling. Two of these techniques are illustrated in Figures 3B, 3C, 4B, and 4C. Based on Figures 3B and 4B, average delay is then

$$d = \frac{1}{2n}\,I\,\Sigma\,(Q_i + Q_{i+1}) \quad (8)$$

where

I = duration of the survey interval,
n = total number of vehicles, and
Q_i = queue at the beginning of survey interval i (0, 1, 2 . . .).

The most common technique, described in the *Highway Capacity Manual* and illustrated in Figures 3C and 4C, assumes that a vehicle observed in the queue has been stopped for an average of the interval between counts. The average delay is then

$$d = \frac{I\,\Sigma Q_i}{n} \quad (9)$$

All three methods shown in Figures 3 and 4 can be considered reasonable approximations of the delay since the over- and underestimations appear to cancel each other. Naturally, they cannot be expected to produce identical results. In fact, in situations such as high arrival fluctuations, platooning, or overflows, the results will vary significantly.

Problems

Earlier sections of this paper have illustrated the vagueness of delay definitions and the differences in measurement techniques. There are, however, additional problems with using the basic deterministic queuing diagram for delay calculation and surveys.

The following questions are asked most frequently:

- Does the stacking of vehicles at the stopline introduce errors in delay determination?
- Since delay surveys are based on the counting of vehicles stopped in a queue, should overall delay or stopped delay be measured?
- What is the relationship between overall delay and stopped delay?

The Effect of Stacking Vehicles

When determining the arrival rate (q) in the queuing diagram, the average value is generally based on the number of vehicles that pass through an intersection approach lane during the survey period, as shown in Figure 3 and Equation 7. The time-space diagram in Figure 5 confirms that this rate is correct at a point some distance upstream of the queue. In the straight-line approximation of vehicle trajectories, however, vehicles are joining the end of the queue at a different rate. Since the end-of-queue shock wave travels backward, the rate of end-of-queue arrivals must be greater than the upstream rate of flow.

The arrival flow at the end of the queue can be determined easily from the spacing of arriving vehicles, their speed, and the spacing of vehicles in the queue. In the specific example in Figure 5,

- Arrival flow (q) = 900 veh/hr (one vehicle every 4 sec);
- Saturation flow = 1,800 veh/hr (one vehicle in 2 sec);
- Arrival speed = 50 km/hr = 13.9 m/sec;
- Arrival spacing = 4 × 13.9 = 55.6 m;
- Spacing of vehicles in the queue = 6.0 m; and
- Distance to be travelled by consecutive vehicles to reach the end of the queue = 55.6 − 6.0 = 49.6 m.

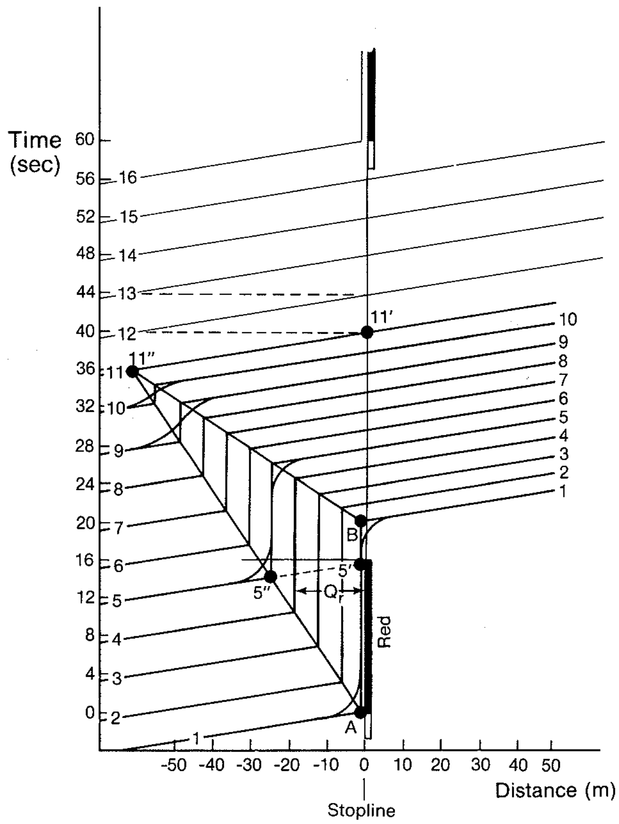


FIGURE 5 Time-space diagram of traffic conditions analyzed in Figures 6 and 7.

The rate of vehicle arrivals at the end of the queue can be calculated as follows:

$$\frac{1}{q_e} = \frac{49.6 \text{ m/veh}}{13.9 \text{ m/sec}} = 3.57 \text{ sec/veh} \tag{10}$$

Therefore, the rate of flow at the end of the queue is

$$q_e = \frac{3{,}600 \text{ sec/hr}}{3.57 \text{ sec/veh}} = 1{,}008 \text{ veh/hr} \tag{11}$$

An identical result can be obtained by calculating the speed of the shock wave and the rate at which vehicles cross it.

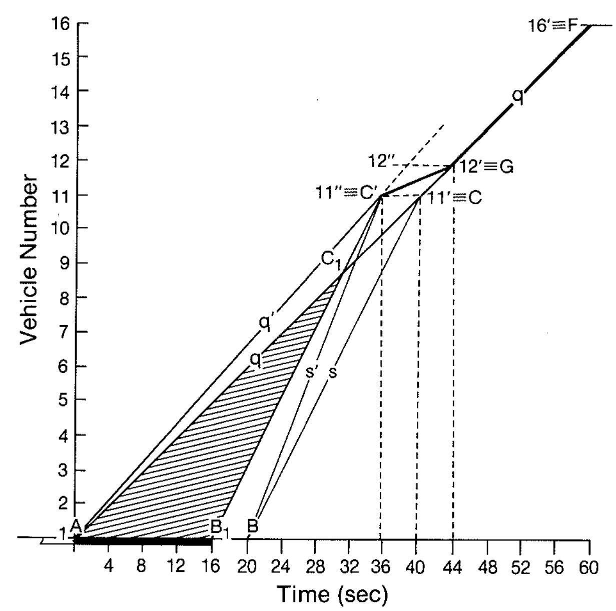
This rate of flow can be transferred into the queuing diagram in Figure 6. As a result of this rate at the end of queue, Vehicle 11 appears in the diagram not at Second 40 (10 headways of 4 sec each) but at Second 35.7 (10 headways of 3.57 sec each).

Provided there is no overflow (no spillover of the queue into the next cycle), vehicles can be considered discharged once they have moved from the queue and resumed their speed. Consequently, the appropriate saturation flow is the discharge from the queue (at the front shock wave), not the one at the stopline. It can be calculated in the same way as the flow arriving at the end of queue. Vehicles in the queue start moving not when the previous vehicle is 2 sec × 13.9 m/sec = 27.8 m away but 6.0 m less, i.e., 21.8 m. Therefore, the headway is 21.8 ÷ 13.9 = 1.57 sec, and the resulting saturation flow at the front of the queue is 3,600 ÷ 1.57 = 2,293 veh/hr (as opposed to the 1,800 veh/hr at the stopline). This is clearly shown in Figure 6 since Vehicle 11 did not encounter any delay and, as a result, the saturation flow line at the front of the queue must connect with the arrival rate at the end of the queue at Point 11". The flow rate at the front of the queue results from the following calculation: for 10 headways (i.e., 11 vehicles), 35.7 − 20.0 sec were needed, or 1.57 sec per headway. Therefore, the flow was 2,293 veh/hr.

When there is no queue, arriving and discharging vehicles must be counted at the stopline. Naturally, the discharge rate equals the arrival rate, and no vehicle is delayed. The return of the count to the stopline from the upstream end of the queue causes a longer headway between the last vehicle in the queue and the first unimpeded vehicle. In Figures 5 and 6, Vehicle 11 arrived at (and was discharged from) the queue at Second 35.7 while Vehicle 12 arrived at (and was discharged from) the stopline at Second 44. In other words, the headway was more than 8 sec. After that, the count continued at the stopline and the original arrival rate of one vehicle in 4 sec was resumed. The consequences for the queuing diagram are shown in Figure 6.

While the events with the vertical stacking of vehicles at the stopline were represented by the shape *ABCF*, the diagram corrected for the effect of horizontal queuing is represented by *ABC'GF*. The distortion is caused by the changing point of reference. Nevertheless, the areas of the two triangles that identify the total delay, ΔABC and $\Delta ABC'$, are identical. As a result, the simpler form *ABCF* yields correct delay values.

Both analytical formulas and survey calculations based on queue counts, however, usually fully or partially neglect the fact that vehicles accelerating from the stop upstream of the stopline encounter delay until they reach the previous full speed (see Figures 1 and 5). For most delay interpretations, it is assumed that the saturation flow discharge starts at the



Note: Points A and B correspond to straight-line first vehicle trajectory representation in Figure 5. For uniform delay formulas, Point B_1 is usually used.

FIGURE 6 The effect of "stacking" of vehicles at the stopline.

end of the red interval or an "effective red," which is usually only slightly longer than the actual red interval. Consequently, the triangle included in delay calculations in Figure 6 is reduced to ΔAB_1C_1, which is smaller than the correct ΔABC. The resulting average delay is even shorter than that shown in Figure 1 as the difference between d_3 and d_1 (or d_2, depending on the reference point).

Nevertheless, in typical situations, analytical delay formulas and direct measurement of vehicle arrivals and discharges yield adequate approximations of uniform delay values.

Overall Delay versus Stopped Delay

As shown in Figure 5, Vehicle 5 would not be considered a stopped vehicle since it was not yet part of the stopped queue at the end of the red interval. It was still in motion some distance from the end of the queue, although the straight-line approximation of its trajectory indicates that it belongs to the queue. As a result, in the queuing diagram in Figure 7, only four vehicles constitute the queue at the end of the red interval. This observation can be generalized: when watching a stopped queue grow, the rate of arrivals given by the line AC does not apply. The rate-of-arrival line should connect the time points at which vehicles stopped—line A_1C_1 in Figure 7. Although the rate-of-arrival line is not used in this technique, the survey calculations attempt to approximate the individual areas below it, as shown in Figures 3 and 4.

Similar reasoning applies to the front shock wave. Vehicles actually depart from the queue sooner than indicated by straight-line approximation of their trajectories in the time-space diagram, which roughly corresponds to line B_1C_1 in Figure 7. As mentioned above, however, the correct line (BC) is usually not considered.

The consequences of these considerations depend on the way a delay survey is carried out and interpreted.

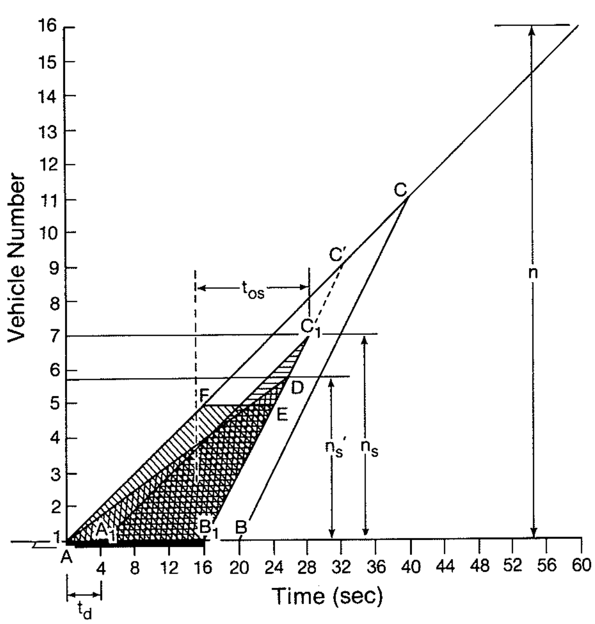


FIGURE 7 The effect of counting stopped queues on the value of delay.

Counting Queues at Regular Intervals Out of Step With Signal Cycle This method is discussed in the *Highway Capacity Manual* and by Buehler et al. (*4*). Only those vehicles standing in the queue are included. Therefore, the correct total delay in Figure 7 given by the triangle ΔABC is reduced to triangle $\Delta A_1B_1C_1$, which includes only stopped delay.

The area of $\Delta A_1B_1C_1$ in Figure 7 can be approximately calculated as

$$D_s = \frac{1}{2}(r - t_d)n_s \tag{12}$$

where

D_s = total delay (veh-sec),
t_d = deceleration delay (sec), and
n_s = number of vehicles stopped (veh).

Since $q(r - t_d + t_{os}) = st_{os}$, where t_{os} = time needed to dissipate the standing queue (including vehicles stopped during the dissipation) (sec),

$$t_{os} = \frac{q(r - t_d)}{s - q} \tag{13}$$

As mentioned, the acceleration delay is usually not included, even in the analytical formulas.

Therefore,

$$n_s = st_o = \frac{sq(r - t_d)}{s - q} \tag{14}$$

and

$$D_s = \frac{sq(r - t_d)^2}{2(s - q)} \tag{15}$$

The relationship between overall delay and stopped delay is then

$$\frac{D}{D_s} = \left[\frac{sqr^2}{2(s - q)}\right]\left[\frac{sq(r - t_d)^2}{2(s - q)}\right]^{-1} = \frac{r^2}{(r - t_d)^2} \tag{16}$$

When the ratio between overall delay and stopped delay is surveyed and calculated in this fashion, it depends not on arrival or discharge rates but solely on the duration of the red interval and on the deceleration delay t_d.

The deceleration delay can be considered relatively constant in most urban situations. For instance, at a 50 km/hr approach speed and a deceleration rate of 3.0 m/sec², the deceleration delay would be 4.6 sec. (A similar value can also be assumed for the neglected acceleration delay.)

For very long red intervals, the ratio would apparently approach 1.0, which would mean that the surveyed values (of stopped delay) should be close to those calculated (of overall delay). For short red intervals, however, the ratio may be a very high value. For example, if the effective red interval (which usually includes amber) is 18 sec and t_d = 5.0 sec, the ratio is 2.25. This means the calculated delay would be 2.25 times longer than the surveyed one.

These examples also indicate that it is not appropriate to use a fixed coefficient in an analytical formula to convert the delay into stopped delay.

Counting Queues at End of Red and Green Intervals This technique is not as common as the previous one, but it is used when a cycle-by-cycle reconstruction of the queuing diagram is needed. As explained above, when counting the number of vehicles stopped in a queue, the correct area of the triangle ΔABC in Figure 6 is reduced. The survey calculations (as shown in Figures 3 and 4) assume, however, that the area can be approximately reconstructed from the queue at the end of the red interval (and, if there were an overflow delay, from the queue at the end of the green interval).

Figure 7 illustrates the type of distortion that takes place. Since only four vehicles have been included in the queue, the calculated rate of arrival is not five vehicles. Therefore, instead of four headways in 16 sec, only three headways would be used, which corresponds to one vehicle in 5.3 sec. This average headway represents 675 veh/hr, not the correct value of 900 veh/hr.

The area of total delay that would be used for calculations is then given by the triangle ΔAB_1D. The resulting average delay value would again reflect stopped delay rather than overall delay, with a similar impact on their ratio as in the previously mentioned technique.

Even if this problem could be eliminated by including vehicles that are about to join the standing queue, survey crews usually have difficulty accounting for vehicles that join a moving queue after the beginning of the green interval. Such vehicles are represented, for instance, by Trajectories 6 through 10 in Figure 5. They do not have to come to a full stop as their simplified straight-line trajectories suggest. In Figure 7, excluding Vehicles 6 through 10 would "cut off" the top of the delay triangle and cause the total delay to be represented by the area AB_1EF. This shape would also correspond to the queue dissipation calculation mentioned with the survey techniques that count queues at the ends of green and red intervals.

When calculated with an area of AB_1EF, the total delay is

$$D_c = \frac{qr^2(1 + y)}{2} \tag{17}$$

where

$$y = \frac{q}{s} \tag{18}$$

The ratio of overall delay to the delay calculated in this fashion is then

$$\frac{D}{D_c} = \left[\frac{qr^2}{2(1 - y)}\right]\left[\frac{qr^2(1 + y)}{2}\right]^{-1} = \frac{1}{1 - y^2} \tag{19}$$

Contrary to previous stopped delay considerations, the result is completely independent of the signal timing.

Since $y = q/s$, the distortion depends solely on the relative magnitudes of the arrival and saturation flows. When the arrival rate is very small, the ratio would be close to 1.0; for conditions close to capacity, the ratio would be very large.

The cases represented in Equations 16 and 19 are rather extreme. In most situations, the measurements are subject to both errors. As a result, the ratio of the calculated overall delay to the measured stopped delay would depend on the duration of the red interval as well as on arrival and saturation flows.

PRACTICAL COMPARISONS

To test the findings of this paper, delays were surveyed at intersections along St. Albert Trail in the city of St. Albert. Two different techniques were used:

1. A vehicle trajectory survey to represent overall delay values (described in a paper by Teply and Evans in this Record); and
2. A queue length count at 15-sec intervals, assuming constant queues during individual intervals (*1*), which yields rough stopped delay values.

The southbound direction was assessed during the morning peak period and the northbound direction during the afternoon peak. These directions experience heavy commuter flows at the intersection of St. Albert Trail and Hebert Road.

The results of the comparison are shown in Figure 8. With the exception of the intersection at Hebert Road, all average delays were relatively short. As expected, the delay based on queue counts was usually shorter than that based on vehicle trajectories. Several irregularities, however, are obvious and are discussed below.

Giroux Road (a.m. and p.m.)

For this intersection, the average delay surveyed by vehicle trajectories was shorter than that based on overall queue counts. The intersection has a very short red interval in the surveyed direction along St. Albert Trail. Local drivers slow down well upstream of the intersection, which was not accounted for in the trajectory survey distance base. Consequently, the overall delay was underestimated. On the other hand, the stops are brief—shorter than the counting interval. As a result, the assumption that vehicles were stopped for the whole duration was incorrect, and stopped delays were overestimated. In addition, the flow in the surveyed direction was light.

St. Vital and St. Anne (a.m.)

These intersections produced similar results but for a different reason. Signal progression at these intersections was difficult, and platoons of vehicles arrived just at the end of the red interval and were forced to stop for several seconds. As a result, vehicles were not stopped for the whole interval between counts. (The coordination at these intersections has since been re-designed).

Hebert Road (a.m. and p.m.)

Because of the magnitude of its delay, this intersection yielded the best illustration of the measurement problem. The ratio of measured average overall and stopped delays was 1.35 in

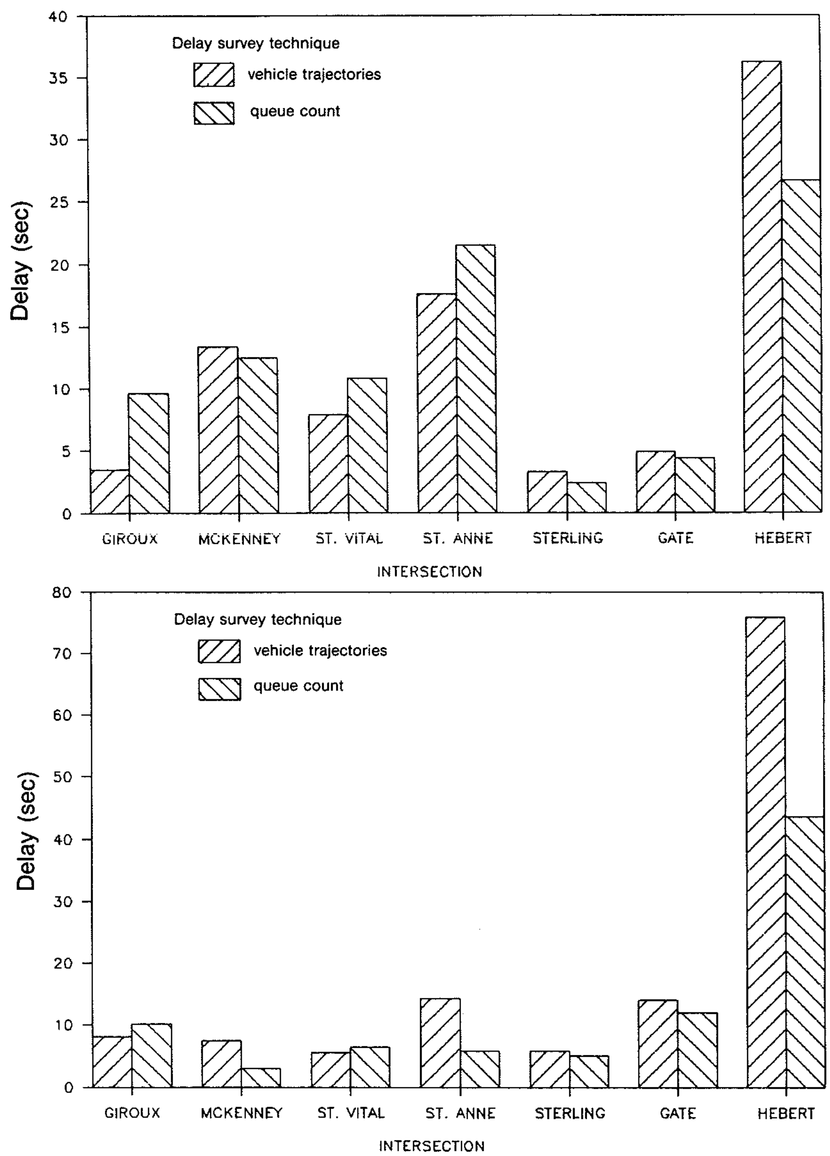


FIGURE 8 Comparison of delays measured by two different survey methods. The two diagrams are based on different scales.

the a.m. peak and 1.73 in the p.m. period. The volumes were very heavy (over 2,000 veh/hr in the peak directions in three lanes). The ratio of overall delay and stopped delay determined using Equation 16 was 1.2 for both periods. The ratio calculated using Equation 19, which reflected the effect of vehicles that joined the queue during the green interval, was between 2.1 and 2.4 for both a.m. and p.m. periods. Assuming that delay surveys based on the reconstructed vehicle trajectories yield a nearly correct average delay value, the ratios of measured values (1.35 and 1.73) fall within the range of expected magnitudes (1.2 and 2.1 or 2.4). Naturally, a perfect match can hardly be expected for the reasons discussed in this paper.

CONCLUSIONS

The discussion in this paper shows that delay cannot be precisely measured. As a result, a perfect match between an analytical delay formula and measured delay values cannot be expected.

Specific findings, some of which are illustrated in Figure 9, can be summarized as follows:

- Uniform delay formulas slightly underestimate overall delay because they neglect a portion of the acceleration delay.
- For a similar reason, typical delay surveys underestimate delays.
- Delay surveys based on the reconstruction of individual vehicle trajectories yield a reasonable approximation of average overall delay at signalized intersections. The values are not exact because of the arbitrary nature of the reference distance.
- The fact that uniform delay formulas and delay surveys based on queue counts do not account for the rate of arrival at the end of the queue and the rate of discharge at the front of the queue does not distort the resulting delay values.

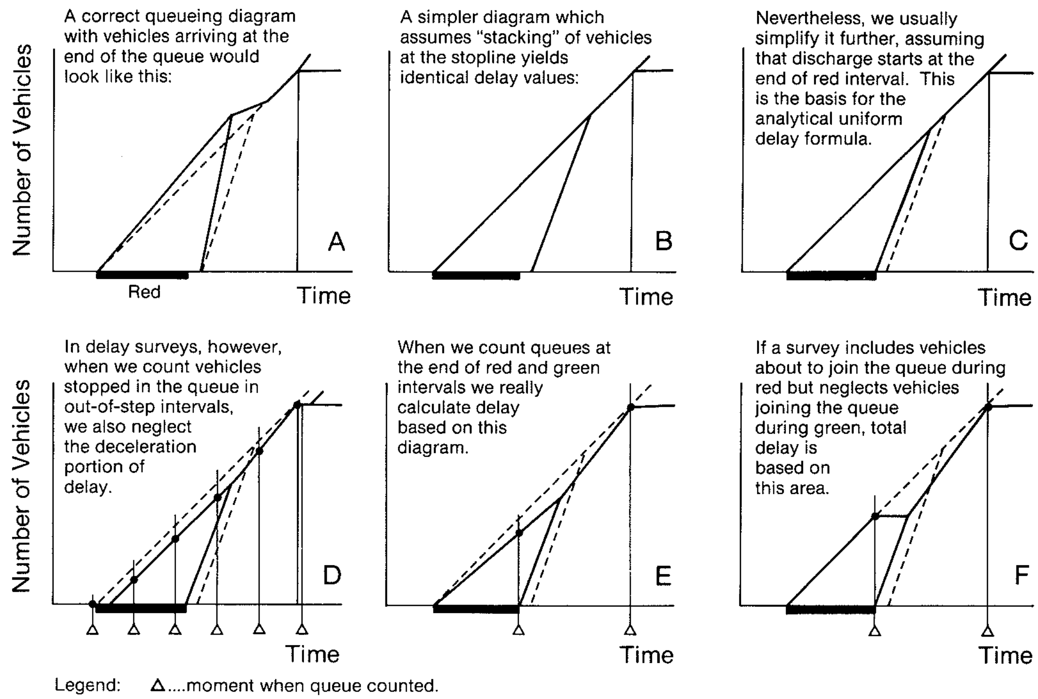


FIGURE 9 Schematic representation of the findings related to the applications of queuing diagrams.

- Different delay survey methods based on queue counts cannot be expected to yield identical results because of different assumptions in the application of queuing theory.
- Delay surveys based on stopped queue counts produce stopped delay values. In situations with low volumes and short red intervals, these techniques may overestimate stopped delay to the point of exceeding overall delay values. (Overall delay includes deceleration and acceleration delays.)
- The ratio between delay and stopped delay is not constant and depends mostly on the duration of the red interval. As a result, a fixed coefficient for all timing conditions is not appropriate.
- The ratio between measured values of overall delay and stopped delay is also not constant. In most situations, it depends not only on the duration of the red interval but also on the relationship between arrival and saturation flows. As a consequence, an accurate estimation of this ratio is difficult.
- In some situations, such as where the red interval is very short and drivers are familiar with the signal operation or in coordinated systems where vehicles encounter delays shorter than the queue count interval, the value of stopped delay calculated from the queues may be longer (incorrectly) than the overall delays determined from vehicle trajectories.

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