# Microscopic and Macroscopic Approaches to Delay Estimation with Oversaturated Conditions

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## Abstract

Chapter 16 of the 2000 Highway Capacity Manual (HCM) [1] contains a widely recognized and well-accepted procedure for calculating per-vehicle control delay at signalized intersections. Appendix F of that chapter discusses the relationship between various components of control delay using cumulative arrival and departure curves. The delay obtained from these curves has certain limitations that need to be recognized if proper conclusions are to be drawn. To illustrate these limitations, a comparison is made between the delay obtained from cumulative curves and the delay obtained through a detailed analysis of vehicle trajectories. A comparison of the control delay obtained from trajectory analysis and that obtained from cumulative arrival/departure curves shows that the cumulative curves omit certain valid portions of the control delay, while including other portions of time that are not delay at all.

Taking a macroscopic approach to oversaturated delay estimation, the HCM procedures for dealing with oversaturated conditions are described and their shortcomings are explored using an example of a multi-period analysis of an oversaturated approach to a signal. It is demonstrated that the current HCM equations can overestimate multi-period delay and that the assumption of a capacity that is constant from cycle to cycle can underestimate delay at high values of the v/c ratio.

## Introduction

There are two basic approaches to estimating control delay on a signalized approach. The first is macroscopic, analytical modeling as implemented in the HCM and other traffic analysis tools. The second involves a microscopic approach in which each vehicle is treated individually. This paper will explore both approaches, attempting to reconcile their results and identify their current shortcomings in multi-period oversaturated conditions.

## The Microscopic Approach

The microscopic approach is generally implemented in a simulation model that processes individual vehicles and accumulates performance measures based on their progress through the system. A variety of tools are available for this purpose, with each tool offering a slightly different interpretation of the vehicle trajectories. In a recent study [2], Dowling described vehicle trajectory analysis as "*the only appropriate method for comparing results between tools, validating the model results against field data, or using the outputs of other tools to compute level of service as defined by the Highway Capacity Manual.*" With that in mind, we will examine the characteristics and interpretation of vehicle trajectories and their relationships to the performance measures used for highway capacity analysis.

The development of performance measures is relatively straightforward with undersaturated operation in which vehicles join a queue on the red phase, then move up and depart on the green phase. It becomes more complicated, however, when volumes exceed capacity and the move up process is distributed over a few cycles. An example involving oversaturated operation will be used to illustrate the complexities and to compare the interpretation of the trajectories with the HCM definition of delay, which is based on cumulative arrival and departure relationships. It is difficult to compare the performance measures from vehicle trajectories with the HCM measures because the random portion of the control delay is not reflected in the cumulative arrival and departure curves, nor is the portion of the control delay associated with deceleration or post-stop bar acceleration. In addition, as we shall soon see, queue move-up delay is over-represented when using a cumulative arrival/cumulative departure approach.

## Definitions

The definitions in this paper conform to common usage but it is necessary to add a few terms for purposes of this analysis:

- **Delay Zone** = Segment length over which control delay is measured. Includes a portion of the approach link at the intersection and a portion of the departure link. For our examples, the delay zone is 4300 feet long with 4000 feet on the approach link and 300 feet on the departure link.
- **Acceleration and Deceleration Distance** = Distance that the vehicle covers while accelerating from a complete stop to its desired free flow speed or vice versa.
- **Acceleration and Deceleration Delay** = Time that the vehicle takes to accelerate from a complete stop to its desired free flow speed minus the time that the vehicle would have taken to traverse the acceleration distance had it been able to travel consistently at its desired free flow speed
- **Free-Speed Move-Up Time** = Time that the vehicle would have taken to travel between queues if it had been able to move at its desired free flow speed
- **Interaction Delay** = Delay resulting from travel speeds that are lower than the desired free flow speed due to restrictions caused by other vehicles. It is not part of control delay.

## Vehicle Trajectory Analysis Example

Figures 1 through 3 document the differences between delay as represented by cumulative arrival curves and true control delay as given by an analysis of vehicle trajectories.

Figure 1 provides an instructive example of how control delay accumulates for a single vehicle traversing a signalized intersection using trajectory analysis. In this example, the vehicle initially travels at a free flow speed of 40 feet per second. It enters the delay zone at distance 0 and travels at the free flow speed for 60 seconds until it reaches a distance of 2400 feet. The vehicle then decelerates to a stop over a distance of 1000 feet, taking another 60 seconds to cover this distance. The 60 seconds of deceleration time can be decomposed into 35 seconds of deceleration delay and 25 seconds of time traveling at the free flow speed. The average speed during deceleration is 16.7 fps (1000 feet/60 seconds).

The vehicle then stops for 80 seconds, all of which is delay time. No progress forward is made. The speed is zero during this period. The vehicle takes 50 seconds to move up from its first stop to a second stop. The 50 seconds of move-up time can be decomposed in 40 seconds of move-up delay and 10 seconds of time traveling at the free flow speed. The average speed during move-up is 8 fps (400 feet/50 seconds). The vehicle then stops for another 90 seconds, all of which is delay time. No progress forward is made and the speed is zero during this period.

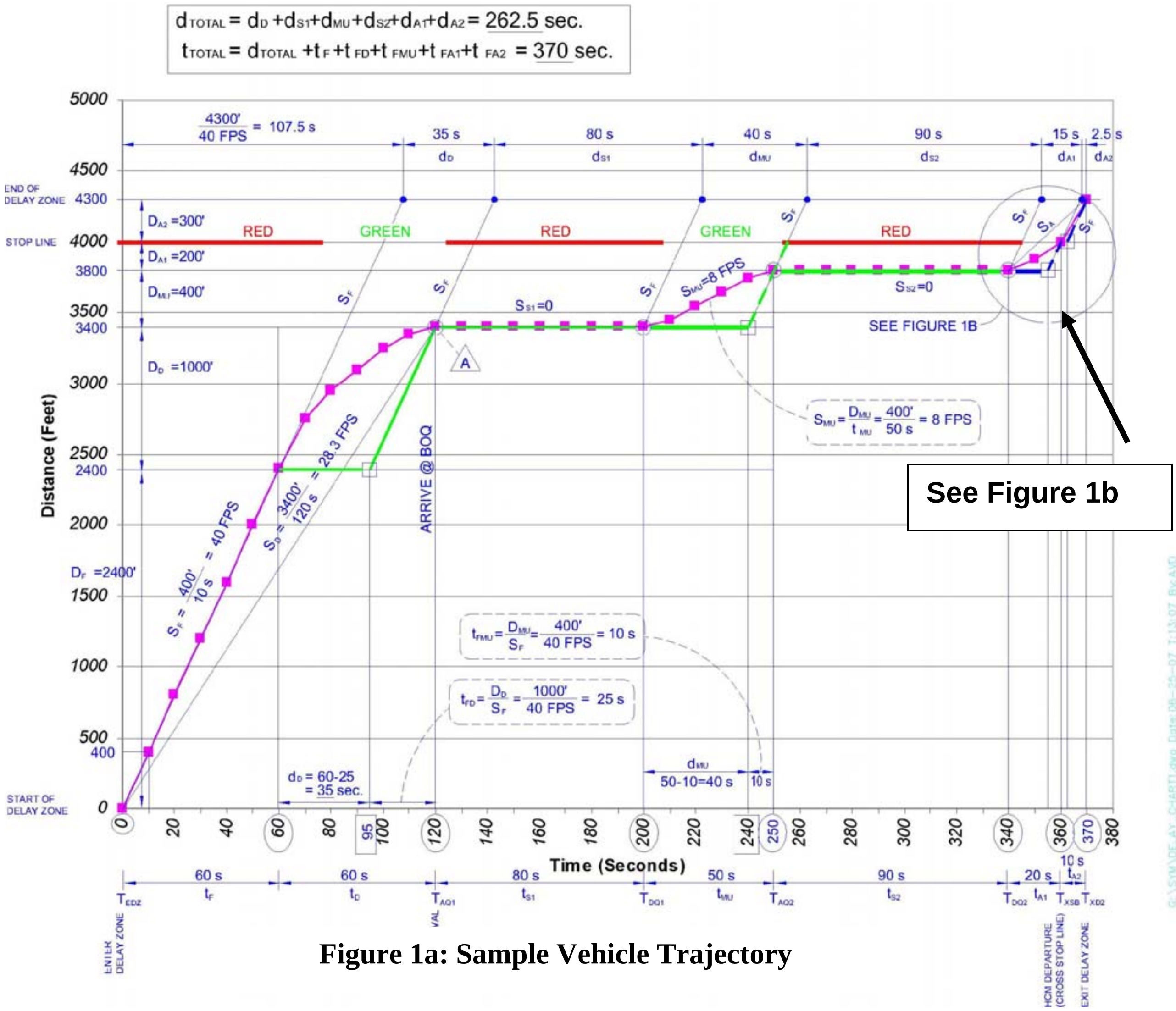



**Figure 1a: Sample Vehicle Trajectory**

The vehicle then accelerates back to the free flow speed. A portion of this acceleration occurs prior to the stop bar. The vehicle travels 200 feet in 20 seconds to reach the stop bar. This 20 seconds of pre-stop bar acceleration time can be decomposed into 15 seconds of acceleration delay and 5 seconds of time traveling at the free flow speed. The remainder of the acceleration occurs after the stop bar. The vehicle travels 300 feet in 10 seconds to reach the end of the delay measurement zone. This 10 seconds of post-stop bar acceleration time can be decomposed into 2.5 seconds of acceleration delay and 7.5 seconds of time traveling at the free flow speed. The average speed during acceleration is 16.7 fps: (200 feet + 300 feet)/(20 seconds+10 seconds).

FIGURE 1B

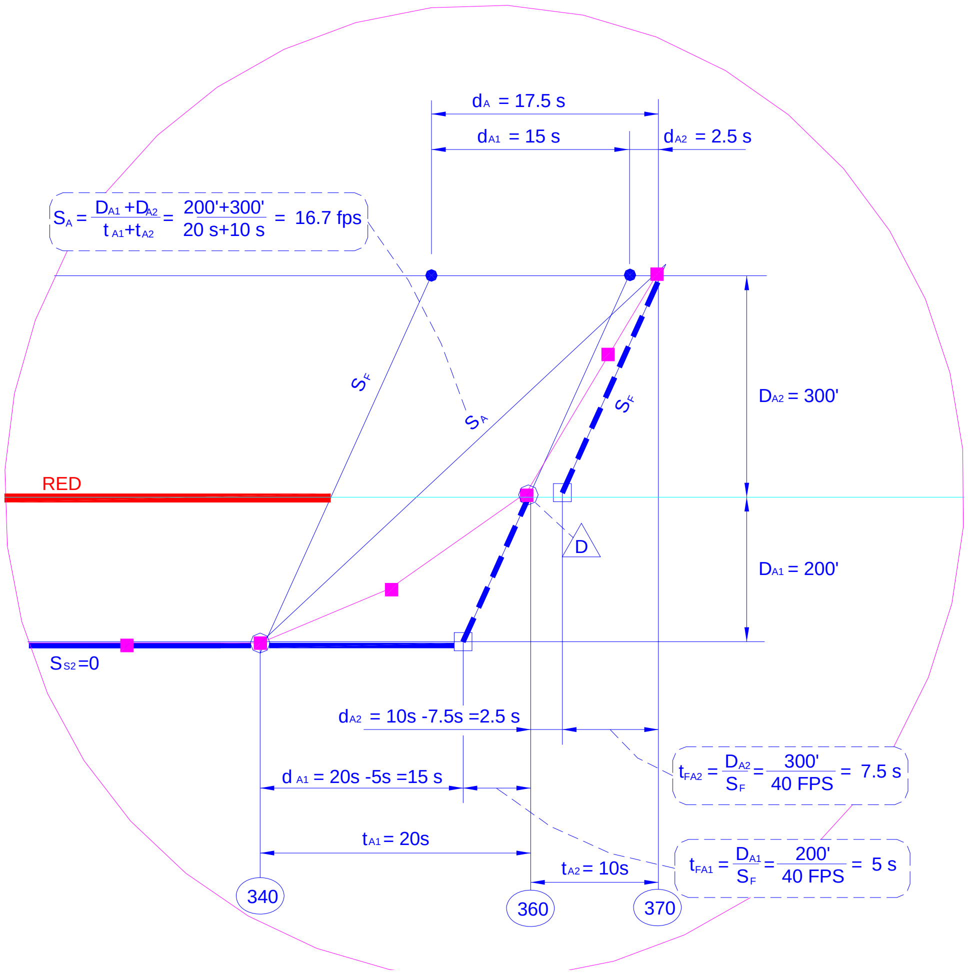



**Figure 1b: Expanded view of the intersection in Figure 1a**

Summarizing, the vehicle experiences 262.5 seconds of delay which is composed of 35 seconds of deceleration delay, 170 seconds of stop delay, 40 seconds of move-up delay, and 17.5 seconds of acceleration delay. The vehicle spends an additional 107.5 seconds of time traveling at the free flow speed: 25 seconds of which occurs during the deceleration period, 10 seconds of which occurs during move up, and 12.5 seconds of which occurs during acceleration (the remaining 60 seconds occurs at the start of the period under free-flow conditions).

In referring to a free flow speed component of travel time, it is not suggested that vehicles accelerating, decelerating or moving-up between queues are at any time during these maneuvers actually traveling at the free flow speed. What is meant by a free flow speed component is that, <u>if</u> these vehicles were traveling at the free flow speed during the maneuver, it would still take this amount of time to cover the positive distance that they are moving forward. For example, assuming 250 feet is covered during queue move-up and the free flow speed is 50 feet/second, if the vehicle could travel at this free flow speed it would still take 5 seconds to cover this distance. This 5-second portion of the actual queue move-up time is not delay and must be subtracted out.

Trajectory analysis gives a true picture of vehicular delay. The only component of delay that is not represented by this single-vehicle diagram is interaction delay, which is not a part of control delay. In setting up our trajectory analysis, we would like to minimize the amount of interaction delay that is captured by making the delay zone as short as possible. The longer we make the delay zone, the more unwanted interaction delay between vehicles will occur. However, attempts to reduce interaction action delay by reducing the length of the delay zone can lead to a situation where significant amounts of deceleration or acceleration delay go unmeasured because they occur outside the delay zone. Free flow speeds may not be accurately obtained as well if the delay zone is too short. Consequently, a certain unknown amount of interaction delay will almost always be included in our control delay measurement. Fortunately, under most conditions of interest, interaction delay is relatively small in comparison to control delay and can be ignored.

Figure 2 tracks the vehicle previously shown in Figure 1, but this time using a typical set of cumulative arrival and cumulative departure curves. As in Figure 1, Vehicle X stops at the back of the queue (thus "arriving") at time point 120 and vehicle X eventually crosses the stop bar (thus "departing") at time point 360. In a traditional cumulative arrival/cumulative departure analysis (the type of analysis discussed in Appendix F of Chapter 16 of the Highway Capacity Manual) control delay is equated to the area between the two curves.

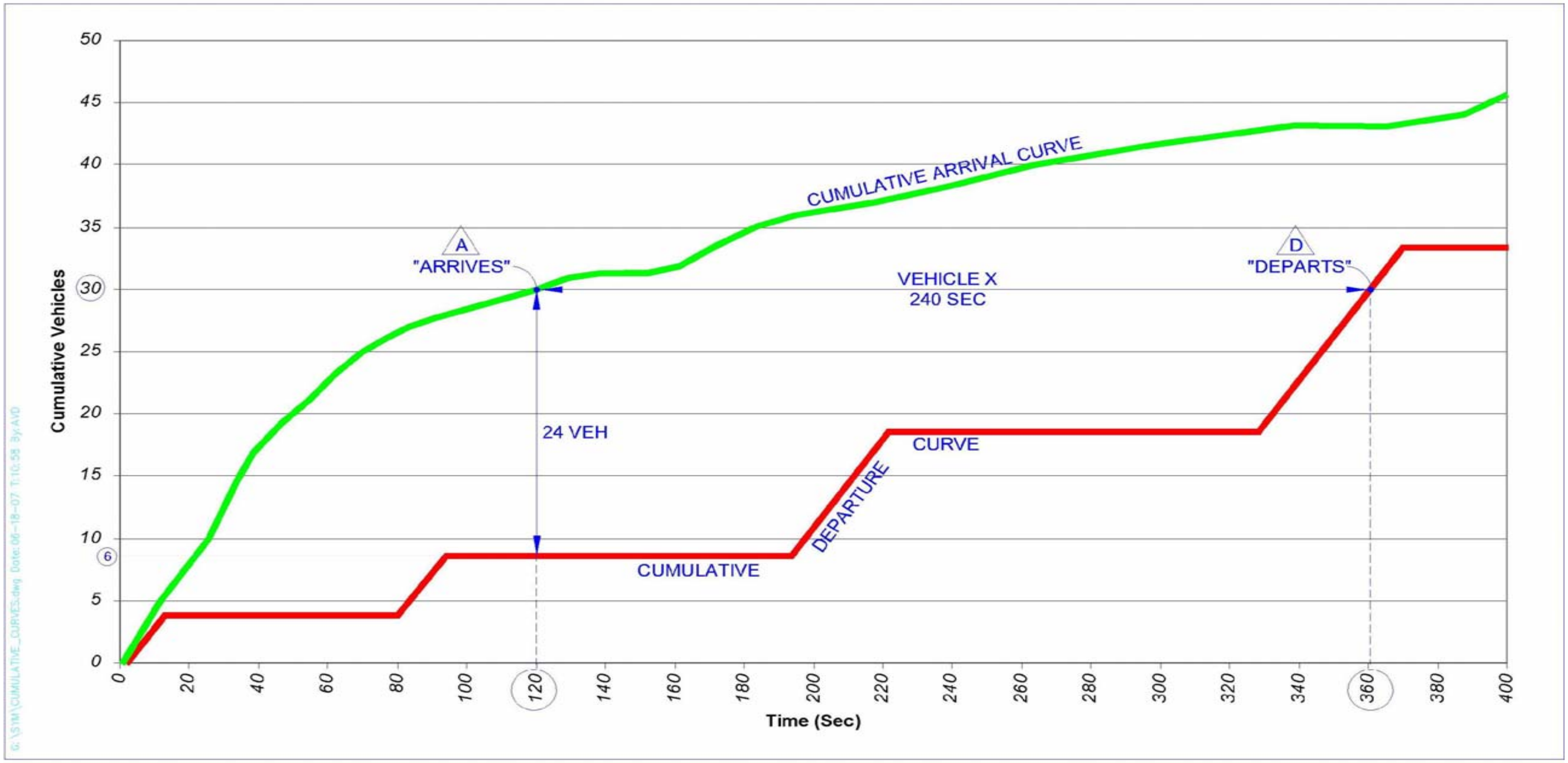
There are three principal problems with this approach. The first and most obvious is that none of the deceleration delay is accounted for in the area between the curves since, by definition, all of the deceleration delay occurs before the vehicle arrives at the back of the queue.

Analyzing the movement of vehicles between the two curves, we can see the second problem with this view of delay. Upon arriving at time point 120 there are 24 other vehicles situated between the stop bar and Vehicle X. Contrary to popular belief, the vertical distance of 24 vehicles is not necessarily the length of the queue at time 120 because some of the vehicles may be in motion, either moving-up between queues or accelerating towards the stop bar just prior to departure. This is an important distinction because, as we observed during the trajectory analysis, the time spent by vehicles in motion can only partially be construed as delay time. This leads us to conclude that the horizontal dimension covered by vehicle X in Figure 2 is not the delay experienced by Vehicle X since it includes the "free flow speed" portion of the move-up time as well as the "free flow speed" portion of the pre-stop bar acceleration delay.

This means that, once more contrary to popular belief, the time spent by Vehicle X between the cumulative arrival and cumulative departure curves is not its control delay, or even its stopped delay, but is rather made-up of the following 5 components: 1.) stopped delay, plus 2.) move-up delay, plus 3.) the free flow speed portion of the move-up time, plus 4.) the pre-stop bar acceleration delay, plus 5.) the free flow speed portion of the pre-stop bar acceleration delay. To convert this time to pure delay, we must subtract out the two free flow speed components.

The third problem is that none of the post-stop bar acceleration delay is accounted for in the area between the curves.

FIGURE 2 - CUMULATIVE CURVES



Continuing our example, Figure 3 shows the simplified cumulative arrival/cumulative departure curve view of the world converted into a trajectory analysis. This view ignores deceleration delay, as well as the portion of acceleration delay that occurs downstream of the stop bar. This can be represented graphically by having vehicles approach the queue at free-flow speed (Line A on the figure) and depart the stop line at free flow speed (Line B in the figure). In the naïve world of cumulative arrival and departure curves, the vehicle is added to the cumulative arrival curve (and delay time begins) when the vehicle arrives at the back of the first queue. The vehicle is then added to the cumulative departure curve (and delay time ends) when the vehicle departs the stop bar. In this example, delay time begins at T = 120 seconds and ends at T = 360 seconds, for a total delay value of 240 seconds, 22.5 seconds less than the 262.5 seconds of delay obtained through proper trajectory analysis.

It is possible to reconcile the 262.5 seconds of delay produced through proper trajectory analysis and the 240 seconds of delay given by the cumulative curves. First, the deceleration delay (35 seconds) is added to the cumulative curve delay (240 seconds) to obtain an adjusted delay of 275 seconds. The portion of the acceleration delay (2.5 seconds) that occurs downstream from the stop bar is also added in to obtain a new adjusted delay of 277.5 seconds. Finally, as previously discussed, it is necessary to subtract out the free flow speed portion of the move-up time (10 seconds) and the free flow speed portion of the pre-stop bar acceleration time (5 seconds) to obtain a final adjusted delay of 262.5 seconds, which now matches the delay from the trajectory analysis. This last adjustment is required because the cumulative procedure fails to account for the fact that not all of the time spent between arrival at the back of the queue and departure from the stop bar is delay time, some of the time is being productively used to cover the distance (600 feet in this case) between the back of the queue and the stop bar (600 feet/40 fps = 15 seconds).

The Highway Capacity Manual delay formula also contains a random element of delay that is not directly reflected in the cumulative arrival and departure curves. Consequently, the delay calculated via these formulas would be somewhat higher than 240 seconds. Unfortunately, this delay element is added in a macroscopic fashion, which makes it impossible to translate into the microscopic situation shown here.

Since some of the errors in the cumulative arrival/cumulative departure procedure result in the control delay being underestimated (failure to include deceleration delay or acceleration delay past the stop bar) while others result in the delay being overestimated (inclusion of free flow speed move-up time and free flow speed pre-stop bar acceleration time), the errors may, to a large degree, cancel each other out. For example, initial simulation testing has shown that, under a rather wide range of over-saturated conditions, the free flow speed move-up time and free flow speed pre-stop bar acceleration time make up about 10% of the control delay. Coincidentally, the acceleration delay and post-stop bar deceleration delay also sum to about this 10% value, producing overall delay results that look fairly good. However, it should be recognized that this counter-balancing effect is not guaranteed, and conditions can arise wherein the errors become significant.

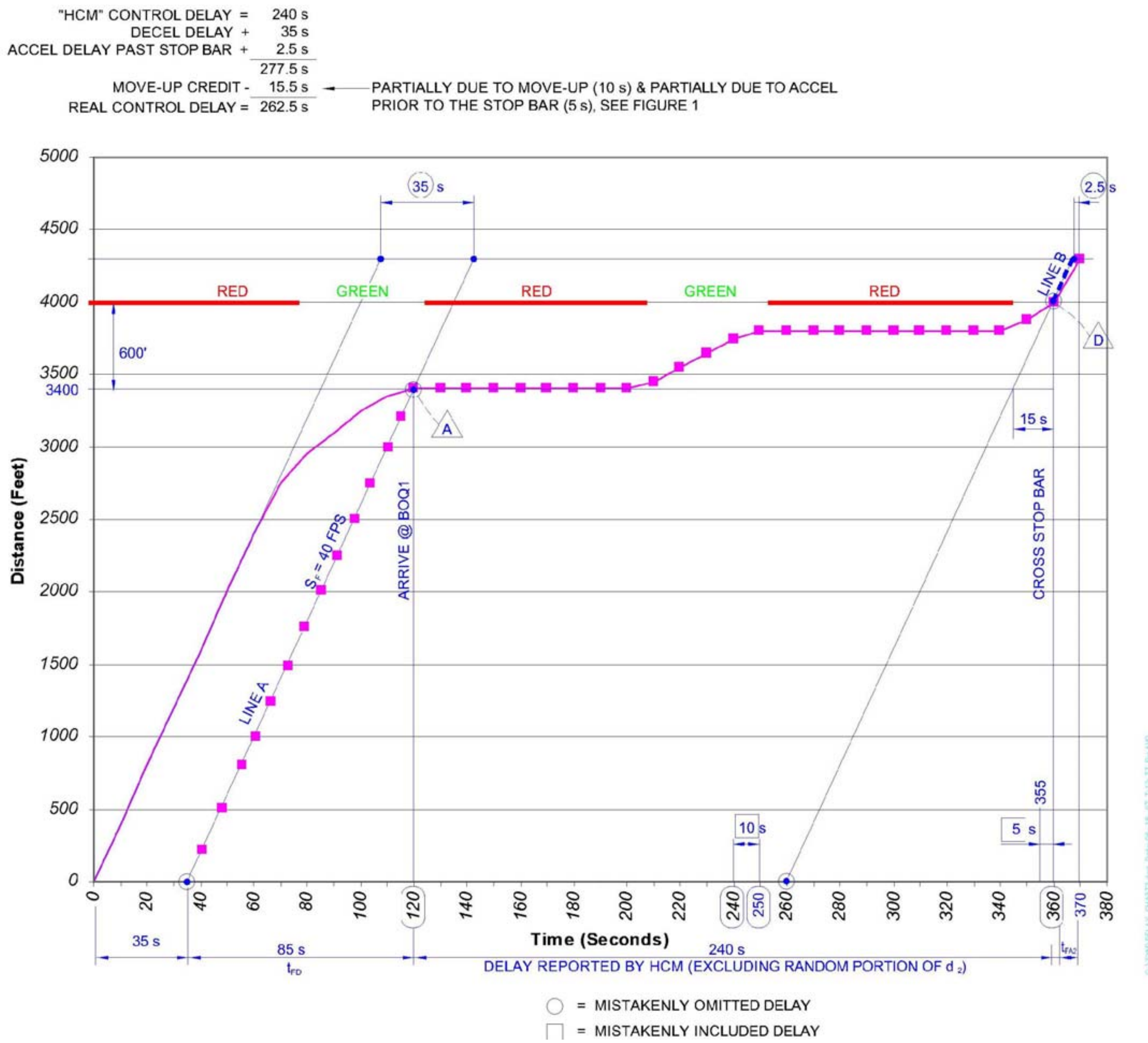



**Figure 3: Delay reconciliation**

# The Macroscopic Approach

The Highway Capacity Manual (HCM), 2000 edition prescribes a procedure for estimating control delay on an approach to a signalized intersection. This paper describes the basis for delay estimates as implemented in the current edition and raises some questions about the need for further evolution of the HCM procedure. It also compares the HCM delay formulation with the delay accumulation process of microsimulation tools

## Basis of Delay Computations

Delay is estimated in all traffic analysis tools by accumulating the number of vehicles in a portion of the roadway over time. Analytical delay models, such as the HCM, use a geometric formulation to determine the area of the delay polygon.

## HCM Uniform Delay, d1

A signalized approach with through movements only, pretimed control and a single green interval per cycle may be represented by a simple triangle whose area may be computed from the values of cycle length, red time and the arrival and departure rates. The simplifying assumption here is that all cycles have identical values of these four parameters. With pretimed control, the cycle length and red time are constant by definition. The HCM procedure also makes the assumption of constant departure rates.

Some variation in arrival rate must be expected from cycle to cycle. When v/c ratios approach 100%, some cycles will have more arrivals than departures and the assumption of a closed delay triangle will no longer be valid. When v/c Ratios exceed 100%, the whole concept of the delay triangle no longer applies. So the use of the delay triangle will always underestimate the delay on a signalized approach. The magnitude of the error will increase with the v/c ratio.

## HCM Incremental Delay, $d_2$

This term is a correction for random and oversaturation effects. It is also derived analytically based on a coordinate transformation technique originally proposed by Whiting and refined for signalized delay applications by Akçelik [3]. To understand the incremental delay formulation, we must first introduce the concept of *deterministic queue delay (DQD).* The DQD is zero at v/c ratios less than 1.0. At v/c ratios above 1.0, a residual queue will exist at the end of the analysis period because more vehicles will have arrived than the signal can accommodate. By the HCM definition of delay, i.e., *the delay experienced by all vehicles that* <u>*arrive*</u> *during the analysis period*, the delay to residual vehicles that accrues in the time following the analysis period must be taken into account.

The formulation illustrated in Figure 4 recognizes that delay accrues when the vehicular input to a system exceeds the output for a period of time. The HCM uses this formulation to estimate delay that accrues at a signalized intersection when the volume exceeds the capacity over the analysis time period, $T_p$. The delay in Figure 4 is represented by the area of the "delay triangle" shown on the figure.

When demand exceeds capacity, some of the vehicles arriving during $T_p$ will depart during the subsequent period. The time required to clear all vehicles arriving during $T_p$ is shown above as $T_c$. Because the HCM defines delay in terms of the delay experienced by *all vehicles that arrive* during the analysis period, the delay computations must include the delay to those vehicles that arrive during $T_p$ and depart during $T_c$.

This definition differs from the delay definition used by most simulation tools, which deal with the delay *experienced during* the analysis period. The HCM definition includes all of the area within the delay triangle, shown above as the sum of the areas $D_p$ and $D_c$. The simulation definition includes only that portion of the area that falls to the left of $T_p$, i.e., the area shown as $D_p$.

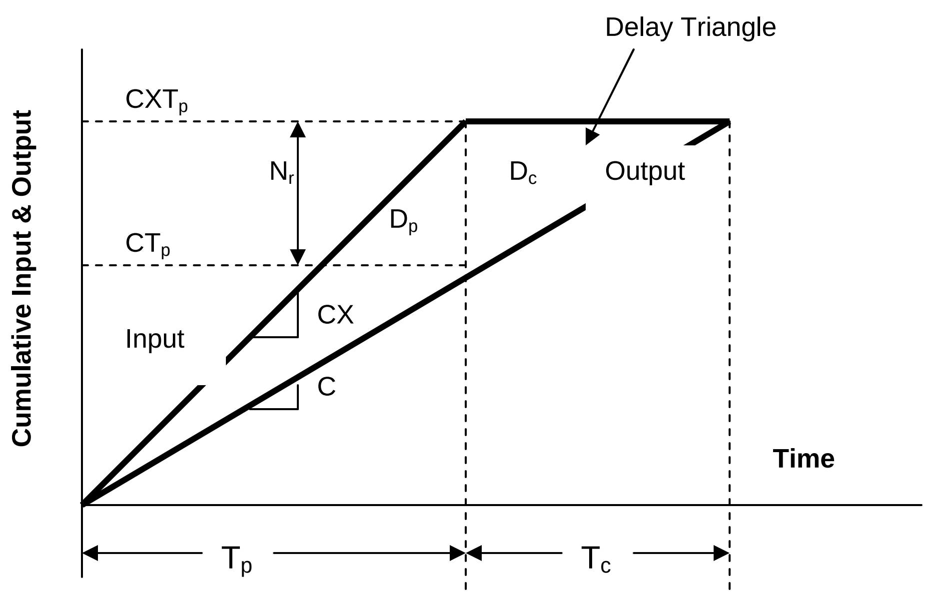



**Figure 4: Deterministic queue delay formulation**

The area within the delay triangle is referred to as the "deterministic queue delay", or DQD. The DQD may be determined as DQD = 5* $T_p$ * (X-1)

So, the question now is "how does the DQD fit into the incremental term of the HCM delay equation?" First let's look at the plot of the DQD as a function of the v/c ratio for a given analysis period length as shown in Figure 5. Note that the DQD is zero at v/c values up to 1.0, increasing linearly beyond that point.

Now let's look at the HCM incremental delay equation:

$$d_2 = 900T\left[(X-1)+\sqrt{(X-1)^2+\frac{8kIX}{cT}}\right]$$

Where:

- T is the time period, referred to in the DQD derivation as $T_p$
- X is the v/c ratio
- c is the capacity (vph)
- k is a coefficient that accounts for randomness in arrivals ( $0 < k < 0.5$). A value of 0.5 indicates that the variance of the arrival rate equals the mean arrival rate.
- I is a coefficient that accounts for the metering effect of upstream signals. (1.0 if there is no metering effect

A plot of the effect of k on the incremental delay value is shown in Figure 5:

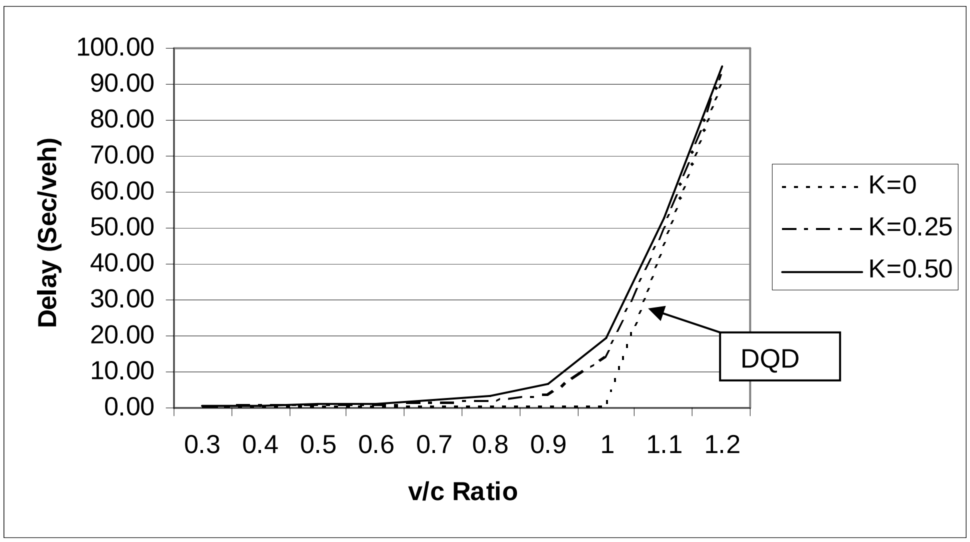



**Figure 5: Delay *vs.* v/c ratio for different values of k**

Note that when k=0, the incremental delay term matches the DQD exactly. At other values of k, the incremental delay is asymptotic to the DQD at both ends. So the incremental delay is essentially a mathematical conjecture designed to fit the DQD, taking account of the randomness of arrivals.

## Multiple Period Analysis for Oversaturation

There is no process built into simulation tools that is analogous to the HCM incremental delay term. The effects of random arrivals are handled implicitly by the stochastic nature of simulation models. The effects of oversaturation are not, however, fully recognized by simulation. It has already been pointed out in Figure 4 that the definition of delay in simulation tools is different than the HCM definition. The two definitions can only be reconciled by multiple period simulation analysis when v/c > 1.0 during any time period. The multiple period analysis must encompass a time frame that has no initial or residual queue.

The multiple period analysis procedure is illustrated and compared with the simulation process in Figure 6, as an extension of the single period concept shown in Figure 4. The HCM uses the concept of "initial queue delay", or $d_3$, for these computations.

### HCM Initial Queue Delay, $d_3$

This term is added to account for the fact that vehicles arriving during a period with an initial queue will experience additional delay as a result of this queue. The HCM initial queue delay model is described in Appendix F to HCM Chapter 16.

Figure 6 illustrates that the simulation definition breaks the four periods up vertically to deal with each period separately. The HCM definition breaks the periods up horizontally to deal with the vehicles that arrive during each of the periods. Because the two definitions are different, substantial differences between the HCM and simulation delay estimates can be expected in each period. Over the whole time frame, however, it should be possible to reconcile the differences and obtain comparable delay estimates.

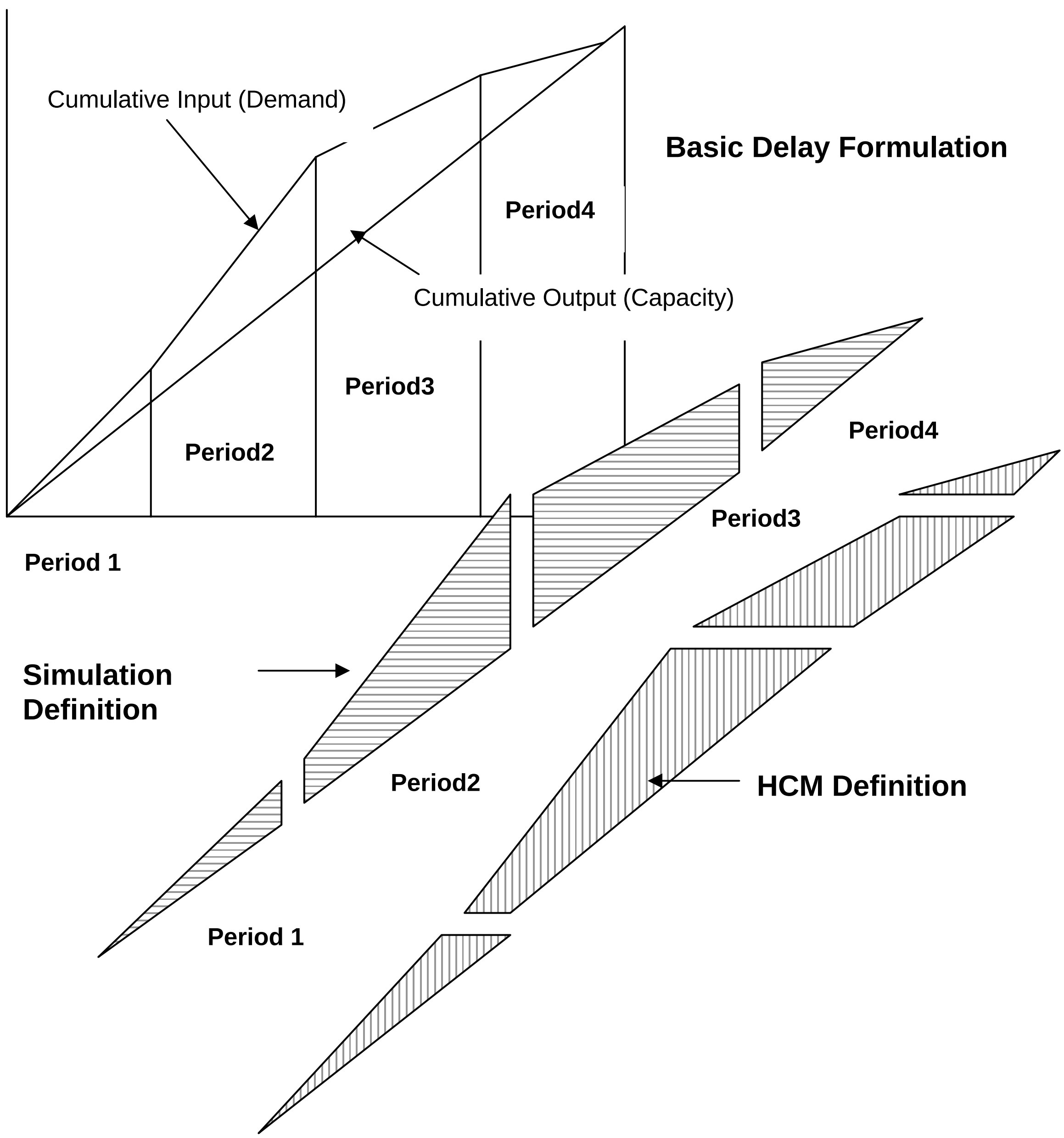



**Figure 6: Comparison of HCM and simulation delay definitions for four periods of oversaturated operation**

## Revisiting the HCM Delay Model Formulation

The delay estimates from microsimulation are derived by analysis of the time-space trajectories of each vehicle over small time slices of, typically 0.1 to 1.0 seconds. There may be, as we have pointed out, some differences in the way that the delays are assigned to analysis periods, but the delays for each vehicle are all accumulated with no vehicles missed or double counted.

On the other hand, the three term analytical formulation of the HCM attempts to piece the various delay components together in a geometric analogy. Vehicles are not dealt with individually and there remains some question as to whether the geometric pieces fit together in a way that ensures that all delays are represented once and only once.

The problem shows up in the incremental delay term, $d_2$, which represents the combined additional delay resulting from random arrivals and oversaturation effects. These two effects are independent and have been combined into a single term for simplicity. Referring back to Figure 5, we see that when the $d_2$ calibration term, k, is zero (representing a state of no randomness) the $d_2$ curve follows the DQD line. As k increases, the $d_2$ curve separates from the DQD line and becomes asymptotic at both ends. So the random delay and the oversaturated delay may be separated as follows:

- The oversaturation delay (i.e., the delay resulting from v/c > 1.0 for the period) is equal to the DQD. This represents the additional delay to vehicles that must be accommodated in a subsequent period. Note that DQD = 0 when v/c <1.0.
- The random delay, resulting mostly from occasional cycle failures in an undersaturated period, is equal to the difference between the $d_2$ and the DQD at the specified v/c value.

For the most part the mathematical abstraction of $d_2$ produces credible approximations at least in terms of internal consistency. A notable exception occurs when the analysis period begins with an initial queue, and the $d_3$ term must be added to the $d_2$ term. The $d_3$ term is formulated to remove the oversaturation delay in $d_2$, but not the random delay. It is difficult to accept the idea that random arrivals joining the back of a queue from the previous period will have a significant effect on the delay. In fact, the way the HCM procedure is currently applied; random arrivals joining a long queue will have the same effect on the delay as random arrivals that arrive unimpeded at the stop line.

The best way to correct for this error would be to reduce the value of k in the '8kIX' part of the $d_2$ equation to zero during the time that unmet demand exists because the effect of randomness is more or less negligible during that time.

The time intervals for d3 shown in Ch 16 Appendix F are

- t = unmet demand time
- T= analysis period length.

The '8kIX' term in $d_2$ should be multiplied by (T-min(t,T))/T. This would have the effect of applying the random delay only when the initial queue has been satisfied.

This would be an easy change to implement. Exhibit F16-4 establishes 5 cases for the selection of delay model variables. The d1 term is computed by different equations for different cases but the $d_2$ term is always computed by Equation 16-15. Equation 16-15 should be used for $d_2$ under Cases I and II. For Cases III, IV, and V, the $d_2$ term should be computed using the modification described above.

We will use a simple experiment to illustrate the problem and its solution. Consider a single lane approach carrying only through traffic. The signal is pretimed on a 90 second cycle with 25 seconds green, 4 seconds yellow and 1 second all red. The saturation flow rate is 1800 vphgpl. Assuming the startup lost time is equal to the extension of effective green time into the yellow, the capacity will be 1800 * 25/90 = 500 vph. The approach demand volumes for the four periods are 150, 125, 115 and 110 vehicles per 15 min period. Based on queue accumulation due to oversaturation, the delay would be 975 veh-min. This would be the expected delay value if all arrivals and departures were completely uniform. This is the procedure that would be applied, for example, to a freeway with a temporary condition of oversaturation. Delay values above this level must be the result of intra-cycle queues and random effects.

The results of the HCM analysis of this approach indicate that the estimated delay is 1457 veh-min. Applying the suggested adjustment to the $d_2$ term reduces this delay to 1291 veh-min. These results suggest that the existing procedure overestimates the delay by 166 veh-min, or about 13%.

## Comparison of the HCM Results with Microsimulation

It is interesting to compare the delay results with those obtained from microsimulation tools that account for random arrivals implicitly in their queue accumulation and discharge process. Delay is defined differently by different microsimulation tools. At this point, CORSIM's control delay measure is closest to the HCM control delay definition. So CORSIM will be used for purposes of this example to represent microsimulation tools.

A comparison of the delay components associated with the HCM and microsimulation is presented in Figure 7. The microsimulation results were based on the average values of 100 runs each. The randomization was removed selectively from the arrivals and departures to examine the three conditions:

1. Uniform arrivals and departures: This is a test condition to compare with the queue accumulation delay and the HCM uniform delay.
2. Random arrivals with uniform departures: This condition is represented in the HCM procedures, which assume a constant saturation flow rate.
3. Random arrivals and departures: This condition is represented by typical microsimulation applications.

The following observations are offered from Figure 7:

We would expect the "uniform arrivals and departures" condition to give the lowest delay of all of the simulation runs. We would expect a value close to the queue accumulation delay. The results (1004 veh-min) were slightly above the queue accumulation delay (975 veh min) probably reflecting the cyclical peaks in the queues.

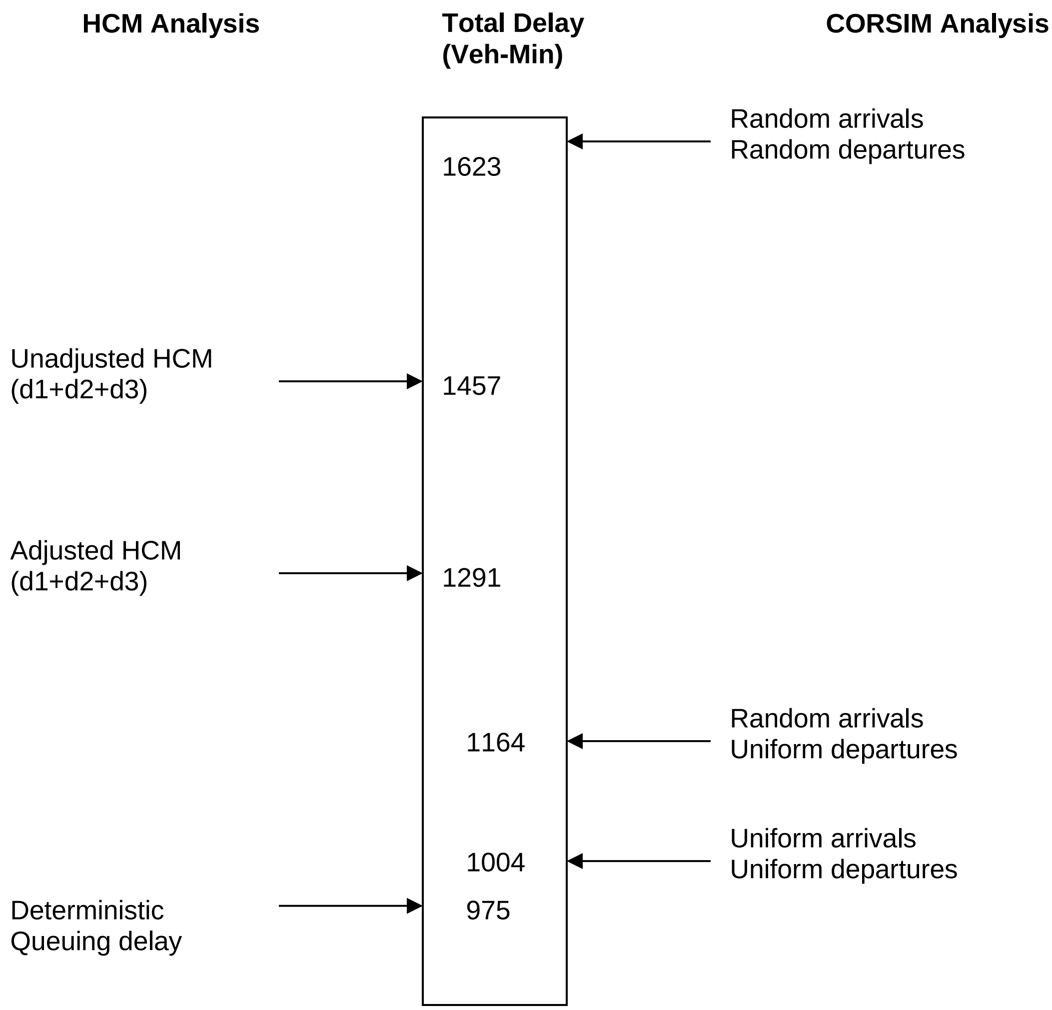



**Figure 7: Comparison of HCM and simulation delay components**

Restoring random arrivals and departures to this example produces some interesting results. The HCM procedure accounts for random arrivals in the $d_2$ term, but it assumes constant departures over the effective green time. In other words each cycle is considered to have the same capacity and to accommodate the same number of vehicles when a queue is present. Maximum compatibility with the HCM assumptions would therefore be achieved by restoring the randomness to the arrivals and retaining the uniform departures. Consistent with expectations, the simulation delay was increased with random arrivals. The value in this case rose to 1164 veh-min.

It was somewhat surprising to see the amount of additional delay that resulted from restoring the randomness in the departures. In this case, the delay with random arrivals and departures was increased to 1623 veh-min, which is well above even the unadjusted HCM estimate. The reason for the large increase may be seen in Figure 8, which plots the number of trips processed under three conditions:

- Uniform arrivals and departures, which processed a constant number of trips from run to run.
- Random arrivals with uniform departures, in which the number of trips varied because of the random arrival characteristics. The extra trips resulted in the small increase in delay observed in Figure 7.
- Random arrivals and departures, in which the number of trips was considerably more variable, and generally below the number processed by the uniform departure conditions. The vehicles associated with these trips were left in the system because they exceeded the capacity of the approach.

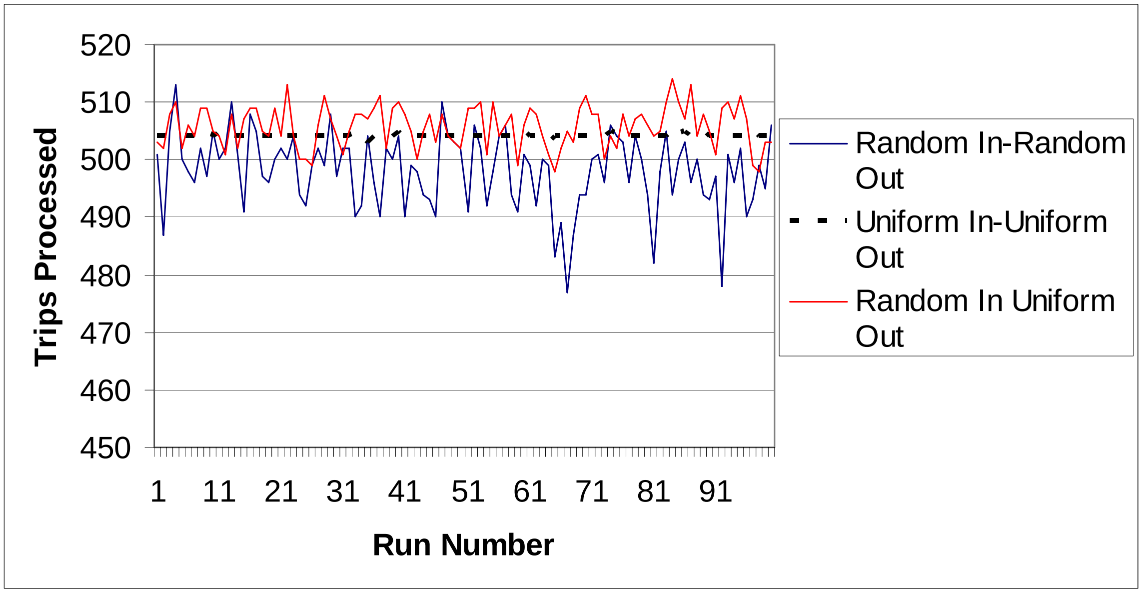



**Figure 8: Variation in estimated delay among runs for three simulated conditions**

## Summary and Conclusions

This paper has compared a microscopic simulation-based approach and a macroscopic analytical approach to oversaturated delay estimation. The conceptual difference between them is seen in the fact that former is a horizontal queue and the latter is a vertical queue. The former considers a queue distributed over distance, while the latter does not.

Summarizing the comparison of multi-period oversaturation by the HCM and simulation, it can be said the HCM overestimates the effect of initial queues, but underestimates the effects of randomness in the cycle to cycle capacity. Neither of these errors presents a great problem for undersaturated conditions. Neglecting the random element of capacity will produce the greatest error at v/c ratios close to 1.0. Simulation offers an arguably more credible modeling of situations such as this, but some care must be used in the interpretation of results in multi period situations with the v/c ratio close to 1.0 over the entire set of periods. While it is recognized that actual field data might provide more convincing arguments, the scope of this study dictated the use of simulation as a surrogate for field data.

A comparison of the control delay obtained from trajectory analysis and that obtained from cumulative arrival/departure curves shows that the cumulative curves omit certain valid portions of the control delay, while including other portions of time that are not delay at all. To guarantee a true measure of control delay, the delay values obtained from these curves must be adjusted by adding in the deceleration delay and the post-stop bar acceleration delay, and by subtracting out the free flow speed portion of both the move-up time and the pre-stop bar acceleration time.

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