

CHAPTER 5

DELAY ESTIMATION FOR OVERSATURATED SIGNALIZED APPROACHES

Delay is an important measure of effectiveness in traffic studies, as it presents the direct cost of fuel consumption and indirect cost of time loss to motorists. Delay, however, is a parameter that is difficult to estimate because it includes the delay associated with decelerating to stop, the stopped delay, and the delay associated with accelerating from a stop. This is particularly true in oversaturated traffic demand conditions, where vehicles continuously decelerate and accelerate. This chapter compares the delay estimates from numerous models for an oversaturated signalized intersection considering uniform and random arrivals. The main purposes of this chapter are: (1) To review the delay estimates from the INTEGRATION microscopic simulation model for oversaturated conditions at isolated signalized intersections; (2) To compare oversaturated delay estimates from the INTEGRATION simulation model with estimates from the analytical models utilized in the HCM, the CCG, theoretical vertical queuing analysis, and theoretical horizontal queuing analysis using shock wave analysis; and (3) To assess the consistency of delay estimates between the various analytical models and the INTEGRATION microscopic traffic simulation approaches for oversaturated conditions.

5.1 INTRODUCTION

The problems associated with vehicular traffic moving through an urban street network are numerous. In particular, as a results of the continuous increase of traffic in central urban areas, traffic queues and delays are often experienced in the vicinity of signalized intersections. The introduction of freeways has also changed the pattern of traffic and has somewhat relieved congestion on surfaces streets; but the signalized intersection continues to be a major problem.

Traffic demands at signalized intersections vary throughout the day and congestion frequently occurs during the morning and afternoon peak periods due to the large number of people simultaneously driving to or from work. The large number of travelers often cause the demand flow on the approaches to signalized intersections to approach, and often exceed, the stop line capacity. When demand exceeds capacity, queuing conditions develop at the intersection. These conditions continue until, at some point in time, demand decreases to a level below capacity allowing the queues to dissipate. When such conditions are present, the intersection is said to be oversaturated or congested. The duration of the congested period is a function of demand at the intersection as well as intersection capacity.

Perhaps the most apparent measure that can be taken to avoid oversaturation is to restrict demand. While this approach has been given serious consideration in traffic management decisions, it must be recognized that such measures may be infeasible. Congestion at signalized intersections can also be prevented by either building new transportation facilities or increasing the capacity of the intersection. However, construction of new facilities is not always feasible in urban areas, where congestion problems are most severe. Furthermore, the addition of new infrastructure does not necessarily result in a complete elimination of the congestion. At the intersection level, capacity can be increased by proper channelization, peak period parking restrictions, prohibition of certain movements during the peak hours, installation of traffic control devices, and other conventional control measures. However, these measures also have certain limitations, and congestion at most signalized intersections during the peak periods is again often unavoidable.

Congestion can further be relieved by proper control of the traffic signals. The traffic signal timing is based on optimization models that are either analytical or simulation based models. While optimization models have been developed and applied successfully to the control of undersaturated fixed-time signalized intersections, relatively little research has been conducted to assess the consistency of delay estimates among them. With the objective of performing such an assessment, this chapter compares the delay estimates from five analytical models to the delay estimates produced by the INTEGRATION microscopic traffic simulation model. The

INTEGRATION model does not use any delay formula, it measures vehicle delay as the vehicle traverses the network, as was described in Chapter 2. Evaluations are made for oversaturated signalized intersections operated in fixed-time considering both uniform and random arrivals. For robustness, the estimation of delay is also conducted for single-lane and two-lane signalized intersection approaches. The importance of validating the delay computations of isolated oversaturated signalized approaches lies in the fact that the INTEGRATION model can evaluate conditions that are beyond the scope of analytical models. Consequently, this validation effort establishes the credibility of the INTEGRATION delay estimates for conditions where analytical solutions are feasible.

5.1.1 SIGNIFICANCE OF DELAY AS A MEASURE OF EFFECTIVENESS

Delay is the primary performance measure used in a number of signal optimization procedures. It is also the primary performance measure in many intersection analysis procedures, such as the HCM. Usually, delay is defined in this context as the average delay incurred by all vehicles arriving at an intersection during the analysis period. In oversaturation, delay includes the delays incurred beyond the end of the analysis period. The complexity of physical design and signal timing must be evaluated against the anticipated operational outcomes defined by the estimation of delay.

On this subject, Rouphail and Akcelik (1992) have explored the issues related to oversaturation models by comparing various delay definitions and delay measurement methods (queuing sampling and path trace). Following this work, Akcelik and Rouphail (1993) have proposed a delay model for signalized intersections that is suitable for variable demand conditions, including highly oversaturated conditions and that could estimate the duration of the oversaturated period. Later, they extended their work to platoon arrivals and stochastic queuing analysis (Akcelik and Rouphail, 1994). In addition, Engelbrecht, *et. al.* (1997) proposed a new delay model for oversaturated signalized intersections. This model differs from the 1994 HCM model in the fact that it is sensitive to the duration of the analysis period and is not restricted to degrees of saturation less than 1.2.

5.1.2 OBJECTIVES AND LAYOUT OF THE CHAPTER

The objectives of this chapter are twofold. First, the chapter describes the assumptions, limitations, and strengths of the different delay computation methods. Second, the chapter demonstrates the consistency and/or inconsistency between the different methods in terms delay estimates at over-saturated fixed-time signalized intersection approaches. The objective of this comparison is to evaluate the accuracy of the INTEGRATION delay estimates for conditions where analytical solutions are feasible.

In order to achieve this goal, the chapter first overviews the various delay models, including vertical queuing analysis, horizontal shock wave analysis, 1994 HCM, 1995 CCG and HCM 2000 delay models for oversaturated fixed-time signalized intersections. This chapter then compares the delay estimates from the previously mentioned models to the delay estimates from six INTEGRATION outputs (Van Aerde, 1998). Finally, the conclusions of the analysis are presented.

5.2 DELAY AT SIGNALIZED INTERSECTIONS

If a link is under-saturated, the queue that forms during the red interval will be completely served each cycle, as is illustrated in the first cycle of Figure 5.1. In this situation, the discharge at saturation flow rate will cease prior to the end of the effective green, such that any subsequent vehicles will pass the stop-line at their arrival rate without being required to stop.

However, if the signal is over-saturated, vehicles will continue to move at saturation flow rate until the end of the effective green. This will result in a residual queue of unserved vehicles to be served in the subsequent cycle. This scenario is illustrated in cycles 4, 5 and 6 in Figure 5.1. In Figure 5.1, cycles 2 and 3 exhibit an intermediate state. In this case, over-saturation occurs during one cycle due to the randomness of vehicle arrivals. However, a drop in demand in the second cycle allow the residual queue to be cleared.

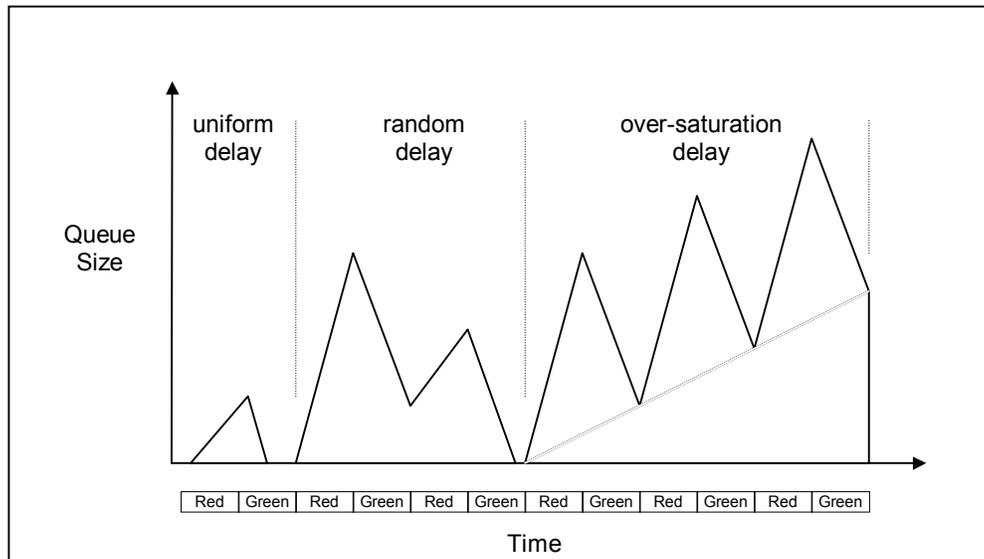


Figure 5.1: Cycles exhibiting uniform, random, and over-saturation delay

In analysis of traffic signals, delay to traffic is estimated as the sum of uniform, random, and overflow delays. Uniform delay accounts for the delay to a traffic stream that arrives uniformly at a signalized approach. Random delay is the additional delay that results from the random fluctuation of arrivals during a cycle length. Finally, overflow delay is the additional delay caused by the overflow of vehicles at the end of the green period. This delay includes the additional delay due to residual queues at the end of a cycle length.

Unlike undersaturated conditions, oversaturated conditions are characterized by repetitive accelerations and decelerations on intersection approaches and exits. To show this phenomena, Figures 5.2 and 5.3 illustrate the speed and distance profiles of a vehicle stopping at a traffic signal before accelerating back to its desired speed after the traffic signal turns green. These figures were generated using the INTEGRATION microscopic simulation software and represent simulated traffic conditions with a 1.5 v/c ratio. In these figures, the vehicle enters the intersection approach link after 826 seconds of simulation and starts to decelerate at 932 seconds. At 947 seconds, the vehicle starts to accelerate until it is forced to decelerate again at 961 seconds and come to a complete stop at 979 seconds. The vehicle remains completely stopped for 11 seconds. When the traffic signal turns green the vehicle accelerates and attains its desired speed of 60 km/hr at 1014 seconds. Using the diagram of Figure 5.2, the stopped, acceleration

and deceleration delays of the individual vehicle can be found by computing the difference between the simulated travel time and the free-flow, unconstrained travel time. Knowing that 180 seconds is normally required by a vehicle to travel across the simulated intersection and that it took a total 233 seconds to do so, it can be determined that the vehicle incurred a 53 seconds of delay. As shown in the figure, this delay graphically corresponds to the area between the lines indicating the vehicle's free-flow speed and the line representing the actual speed profile of the vehicle. Similarly, by considering the deceleration, stopped and acceleration portion of the trip, it can be determined that the vehicle incurred 11 seconds of stopped delay and 42 seconds of acceleration/deceleration delay within the 53 seconds of total delay.

As mentioned in the previous chapter, transportation professionals typically define stopped delay as the delay incurred by a vehicle when fully immobilized, while deceleration and acceleration delays are defined as the delay incurred by a moving vehicle when it is either decelerating or accelerating. A similar definition is used in the 1995 Canadian Capacity Guide (CCG) for signalized intersections, which defines stopped delay as any delay incurred by a vehicle traveling at a speed lower than the average pedestrian speed, e.g., less than 5 km/h (ITE, 1995).

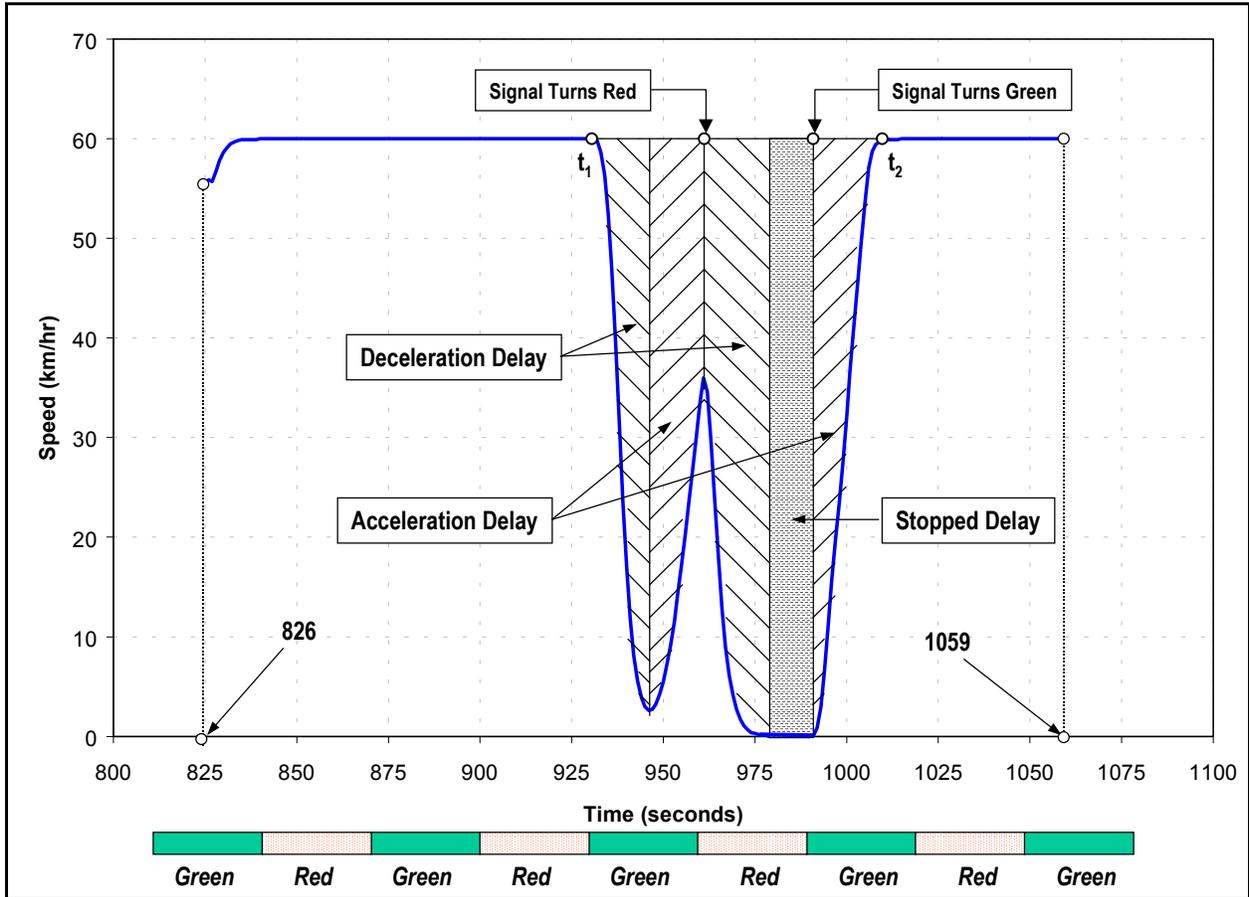


Figure 5.2: Simulated Speed Profile of a Vehicle Crossing a Signalized Intersection

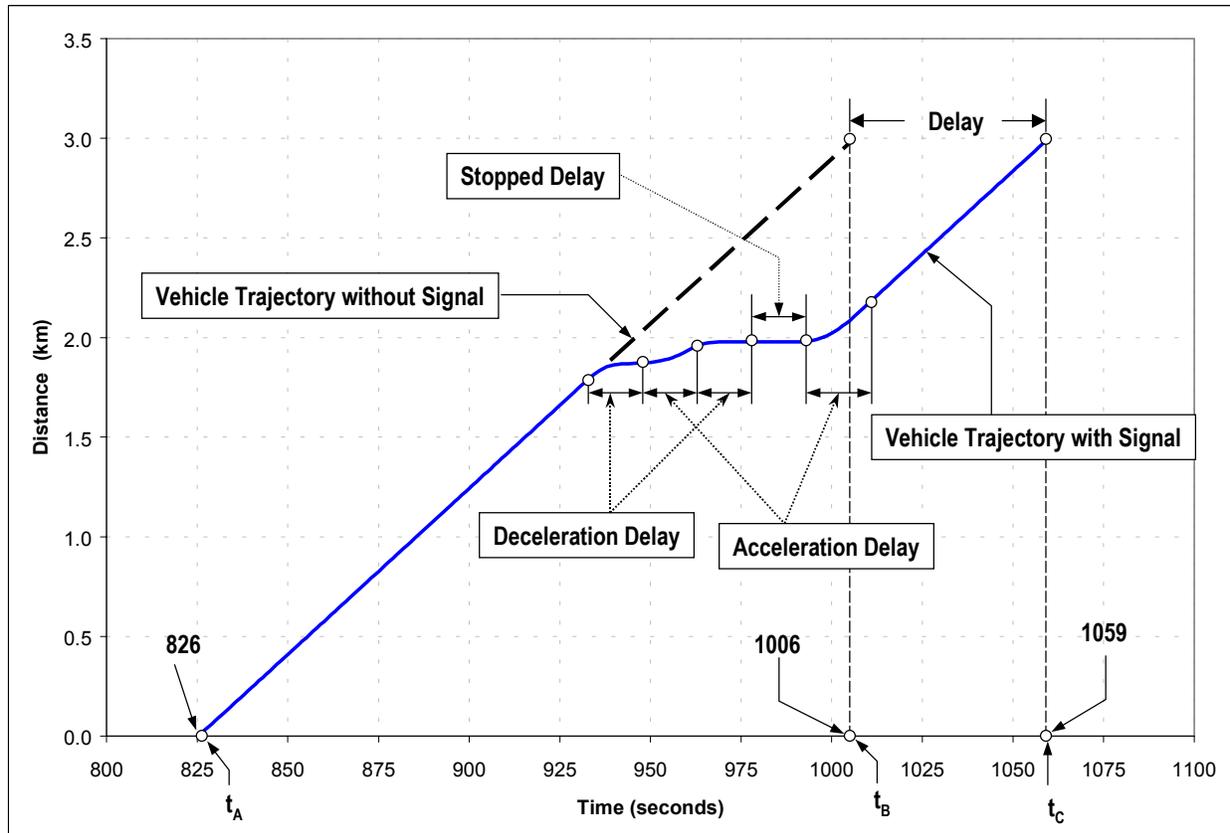


Figure 5.3: Simulated Distance Profile of a Vehicle Crossing a Signalized Intersection

Figures 5.4 and 5.5 illustrate the simulated speed and distance profiles for another vehicle crossing an oversaturated signalized intersection. This vehicle enters the intersection approach link after 1713 seconds of simulation. As soon as this vehicle enters the system, its speed drops to about 7 km/h as a result of an overflowing queue of vehicles that stretches up to 2 km upstream of the intersection. While the vehicle is moving at an extremely low speed, it is incurring acceleration and deceleration delay before coming to a complete stop at 2432 seconds. Once the traffic signal turns green, the vehicle accelerates after a 3-second complete stop and attains its desired speed of 60 km/h at 2471 seconds. In such condition, it is almost impossible to measure the acceleration and deceleration delay exactly by conventional analytical procedures. However, delay can be measured by tracking the speed or distance profiles of an individual vehicle using microscopic traffic simulation. For the vehicle of Figures 5.4 and 5.5, it can be determined that it took this vehicle 2511 seconds to complete its trip while it would take 1893 seconds in the absence of the traffic signal. This results into a total delay of 618 seconds, which

involves deceleration, acceleration, and stopped delay. Also, since it has been determined that the vehicle remained stopped for only 3 seconds, it can be concluded that 615 seconds were deceleration/acceleration delay and only 3 seconds constituted stopped delay.

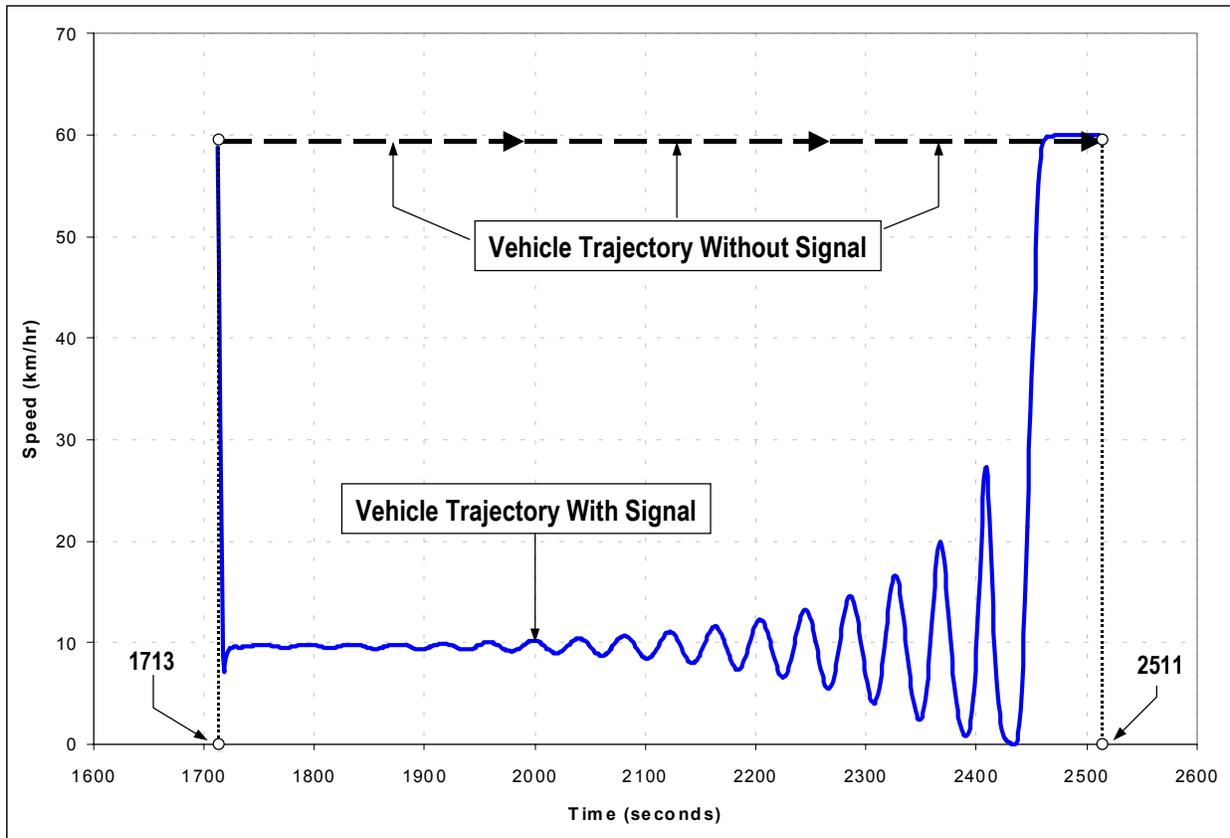


Figure 5.4: Simulated Speed Profile of Vehicle No. 334 in INTEGRATION

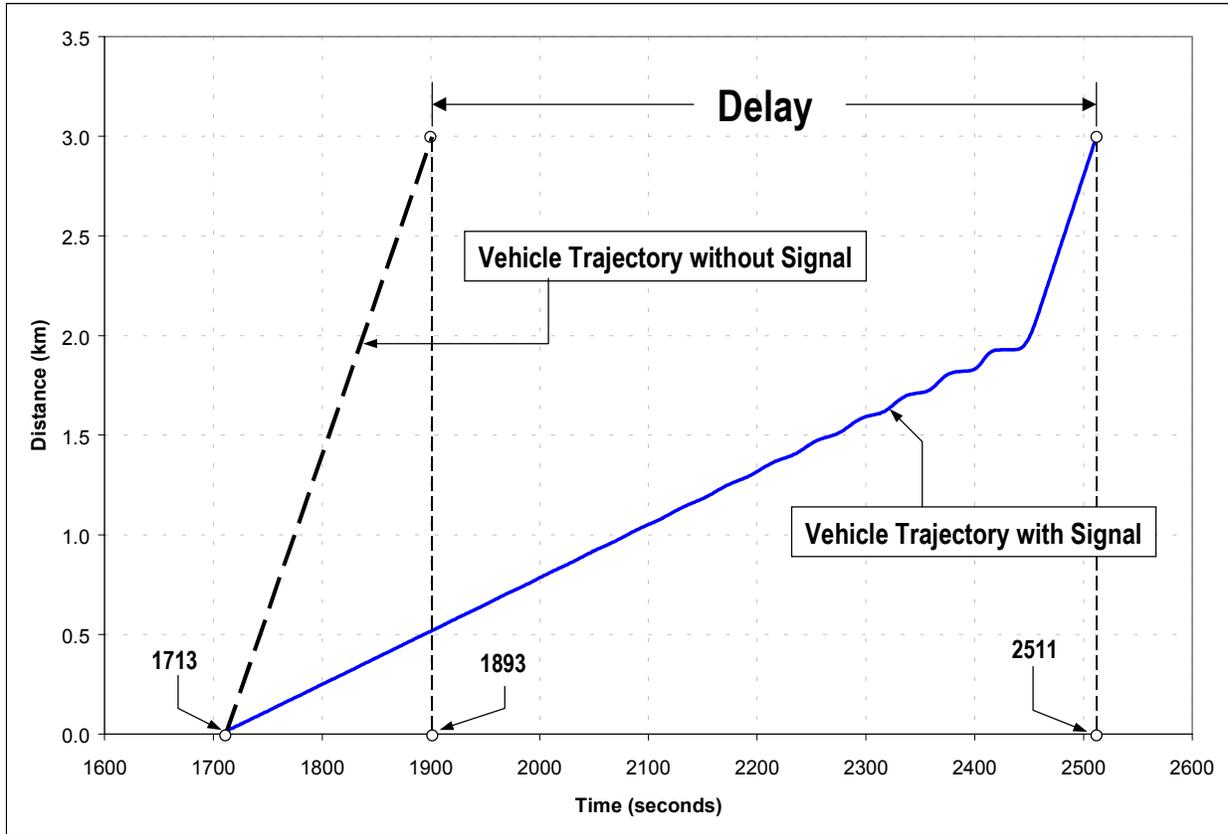


Figure 5.5: Simulated Distance Profile of Vehicle No. 334 in INTEGRATION

Figure 5.6 illustrates the trajectory and a selected speed profile of a series of vehicles arriving at the oversaturated signalized intersection. The figure illustrates that vehicle arrivals during the first cycle length do not experience oversaturation delay. However, as the simulation continues subsequent vehicle arrivals experience significant oversaturation delay with significant partial stops.

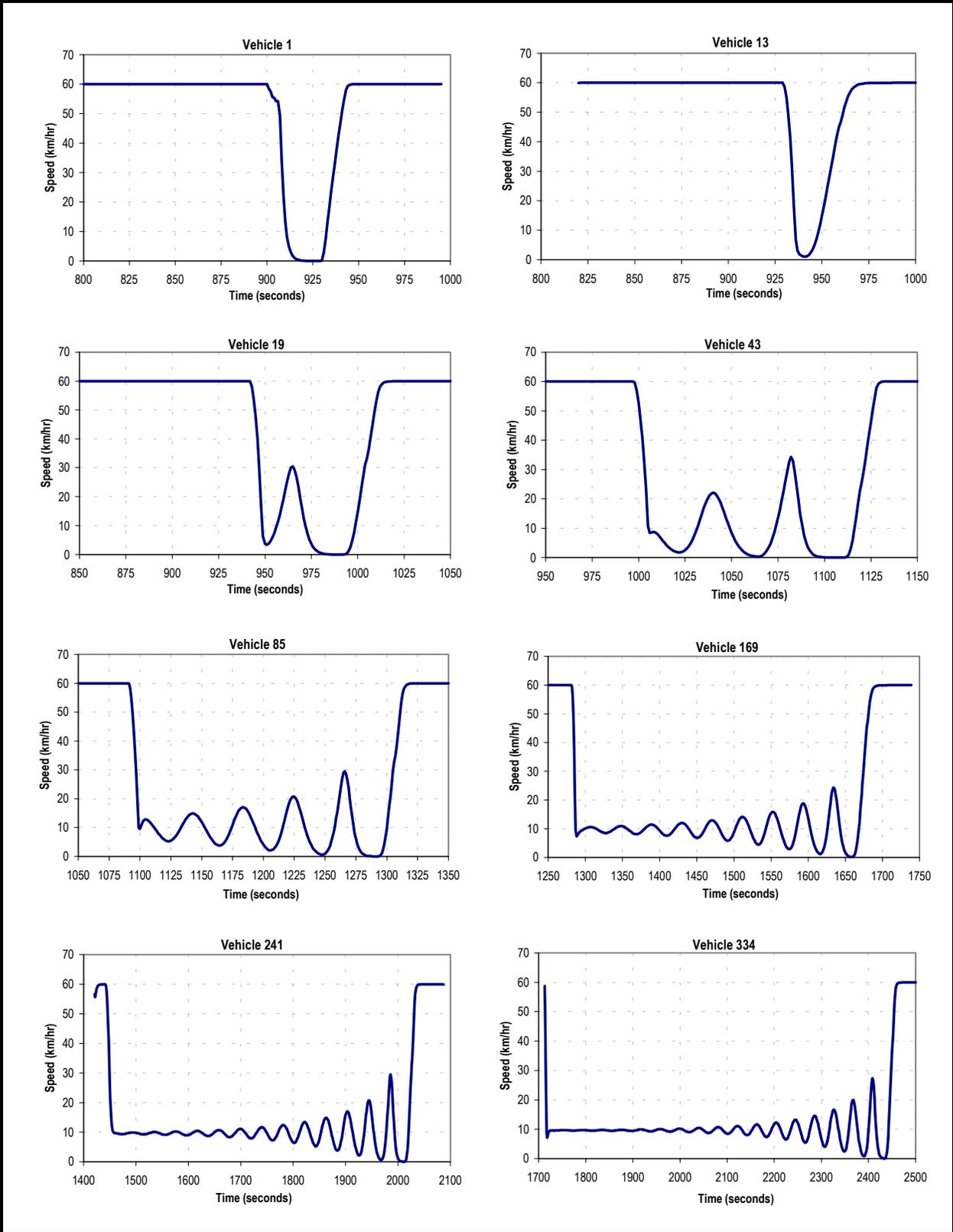


Figure 5.6: Simulated Speed Profile of Selected Vehicles in INTEGRATION

5.3 MICROSCOPIC SIMULATION DELAY MODELS

Traffic simulation models can explicitly measure the delay that a vehicle experiences when traversing a signalized intersection approach without the need for a delay formula, as is the case with the INTEGRATION model. Specifically, the INTEGRATION model explicitly measures the vehicle delays every second as the vehicle travels, thus circumventing the need for an explicit uniform, random and over-saturation delay formula, the delay emerges from the simulation model. Furthermore, by constraining the vehicle deceleration and acceleration capabilities, the INTEGRATION model captures the deceleration and acceleration components of the delay, which is beyond the scope of the current state-of-the-practice analytical approaches.

5.4 VERTICAL QUEUING ANALYSIS DELAY MODELS

Queuing delay estimates can be predicted by deterministic queuing analysis models for undersaturated and oversaturated systems. This is illustrated in Figure 5.7 for a 2-cycle signal operation period. The uniform delay for each cycle is computed as the area of the dark shaded region. This computation was schematically illustrated in Figure 4.9 of Chapter 4. Once the total delay has been calculated, the average delay is computed by dividing the total delay over a defined time interval by the number of arrivals during the same time interval. In the case of oversaturated traffic conditions, the uniform delay comprises the area of the triangle ABC and CEF, while the oversaturation delay comprises the area of the triangle AFG, as illustrated in Figure 5.7. In the diagram, it is first observed that the two areas associated with uniform delays are equal, i.e., uniform delay is equal across cycles. It is evident from Figure 5.7 that the oversaturated delay estimate increases as the analysis time horizontal increases but that, however, the uniform delay remains constant. This leads to the conclusion that delay estimates in oversaturated condition depends on the number of cycles being considered in the analysis.

In the case of oversaturated conditions, the estimates of delay can be found using two area in Figure 5.7, the uniform delay area ABC and the oversaturated area AFG. For this calculation, the uniform delay can be expressed as follows:

$$UD = \frac{r \cdot C \cdot s}{7200} \quad (5.1)$$

where:

- UD = uniform delay (seconds),
- r = effective red interval (seconds),
- C = cycle length (seconds),
- s = saturation flow rate (vehicles/hour).

While delay associated with the oversaturated area AFG can be expressed by Equation 5.2.

$$OSD = \frac{(q - s \cdot \frac{g}{C}) \cdot (N \cdot C)^2}{7200} \quad (5.2)$$

where:

- OSD = oversaturated delay (seconds),
- q = arrival rate (vehicles/hour),
- C = cycle length (seconds),
- N = number of cycle.

Consequently, the total delay over a given time period can be estimated by multiplying the uniform delay by the number of cycles in the period (N) and adding the oversaturation delay estimate. The final total delay can be expressed as follows:

$$D = N \cdot \left(\frac{r \cdot C \cdot s + q \cdot N \cdot C^2 - s \cdot g \cdot N \cdot C}{7200} \right) \quad (5.3)$$

where:

- D = total delay at signalized approach (seconds).

The average delay per vehicle can also be found using the total number of vehicle arriving at the intersection over a defined time interval. This calculation can be done using Equation 5.4.

$$d = \frac{r \cdot C \cdot s + q \cdot N \cdot C^2 - g \cdot s \cdot N \cdot C}{2 \cdot q \cdot g} \quad (5.4)$$

where:

d = average delay per vehicle (seconds).

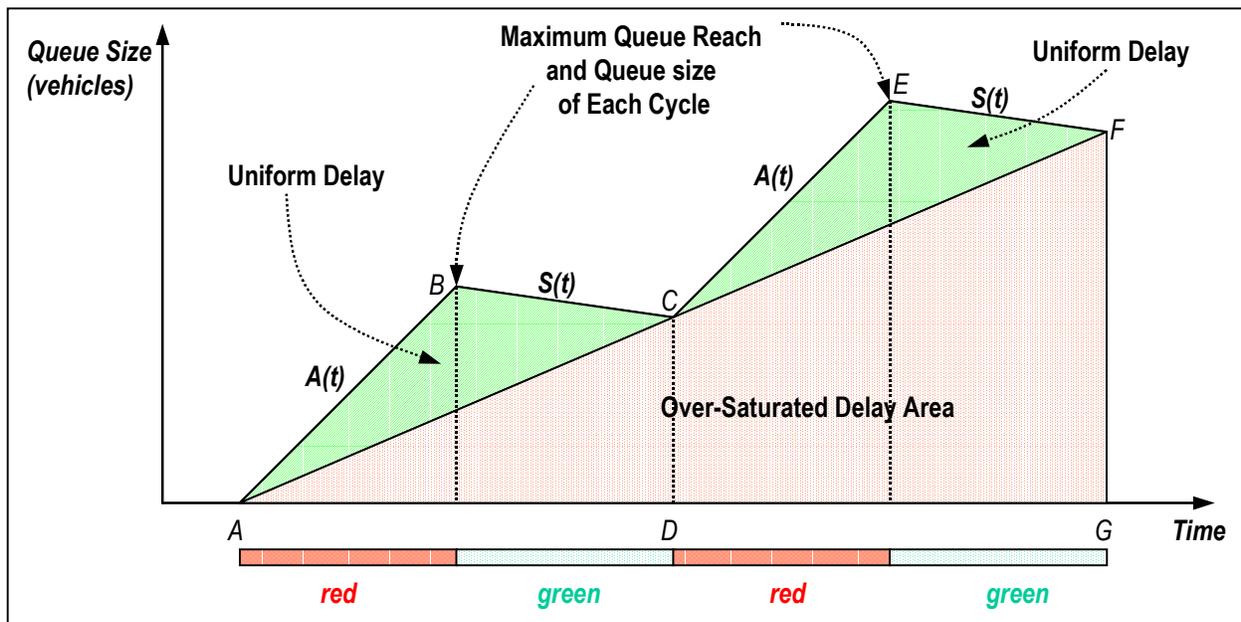


Figure 5.7: Queue Modeling under Deterministic Queuing Analysis

5.5 CAPACITY GUIDE DELAY MODELS

5.5.1 1994 HIGHWAY CAPACITY MANUAL MODEL

The Highway Capacity Manual (HCM) 1994 uses delay as the principal measure of level-of-service at signalized intersections. This delay model is partially based on the traditional Webster model. However, this model is not recommended for use for oversaturated signalized intersections.

The 1994 HCM calculates the average stopped delay per vehicle for a given lane group using Equation 5.5. In this equation, stopped delay is defined as comprising only the delay incurred by a completely immobilized vehicle.

$$d = d_1 \times (CF \text{ or } DF) + d_2 \quad (5.5)$$

where:

d = stopped delay per vehicle (seconds/vehicle),

d_1 = uniform stopped delay (seconds/vehicle),

d_2 = incremental, or random, stopped delay (seconds/vehicle),

DF = delay adjustment factor for quality of progression and control type,

CF = Adjustment factor for control type.

In Equation 5.5, the parameter d_1 , uniform delay, already described in Chapter 4. The parameter d_2 estimates the incremental delay caused by the randomness of vehicle arrivals. This parameter is calculated using Equation 5.6 while this equation is only valid for oversaturated traffic conditions, it may still be utilized with some caution for values of X that do not exceed the minimum of 1.2 or $1/PHF$, where PHF is the peak hour factor. In cases in which the parameter X exceeds 1.0, the delay estimates produced by Equation 5.5 and 5.6 characterize the delay incurred by vehicles arriving during the first 15-minute of the analysis period, as both equations do not account for the cumulative effect of residual queues from previous 15-minute periods.

$$d_2 = 173X^2 \left[(X - 1) + \sqrt{(X - 1)^2 + \frac{m}{c} X} \right] \quad (5.6)$$

where:

X = volume to capacity ratio of lane group,

c = capacity of lane group (vehicles/hour),

m = an incremental delay calibration term representing the effect of arrival type and degree and platooning (assumed to be 16 for random arrival conditions).

5.5.2 1995 CANADIAN CAPACITY GUIDE MODEL

The 1995 Canadian Capacity Guide computes the total delay at an intersection using Equations 5.7 (ITE, 1995).

$$d = d_1 \cdot k_f + d_2 \quad (5.7)$$

where:

- d = average overall delay per vehicle (seconds/passenger car units),
- d_1 = uniform delay (seconds/passenger car units),
- d_2 = incremental, or random, delay (seconds/passenger car units),
- k_f = adjustment factor for the effect of the quality of progression in coordinated systems.

The incremental delay component in the CCG take into account both random and continuous traffic overflows. In this model, the expression for d_2 is shown in Equation 5.8.

$$d_2 = 15t_e \left[(X - 1) + \sqrt{(X - 1)^2 + \frac{240X}{ct_e}} \right] \quad (5.8)$$

where:

- X = degree of saturation,
- c = capacity of lane group (passenger car units/hour),
- t_e = evaluation time (minutes).

It should be noted that the oversaturation delay component is computed as the area under the oversaturation triangle, as described earlier.

5.5.3 HIGHWAY CAPACITY MANUAL 2000 MODEL

In the HCM 2000, the average delay per vehicle for a lane group is given by Equations 5.9 (TRB, 1998), which was previously described in Chapter 2.

$$d = d_1 \times PF + d_2 + d_3 \quad (5.9)$$

where:

- d = average overall delay per vehicle (seconds/vehicles),
- d_1 = uniform delay (seconds/vehicles),
- d_2 = incremental, or random, delay (seconds/vehicles),
- d_3 = residual demand delay to account for over-saturation queues that may have existed before the analysis period (seconds/vehicles),
- PF = adjustment factor for the effect of the quality of progression in coordinated systems.

In oversaturated conditions, the parameter d_2 in Equation 5.9 estimates the incremental delay due to nonuniform arrivals and temporary cycle failures (random delay) as well as the delay caused by sustained periods of oversaturation (oversaturation delay). As indicated by Equation 5.10, this parameter is sensitive to the degree of saturation of the lane group (X), the duration of the analysis period of interest (T), the capacity of the lane group (c), and the type of signal control as reflected by the control parameter (k). In addition, the equation assumes that there is no unmet demand causing residual queues at the start of the analysis period (T). Finally, the incremental delay term is valid for all values of X , including those associated with highly oversaturated lane groups.

$$d_2 = 900T \left[(X - 1) + \sqrt{(X - 1)^2 + \frac{8kIX}{cT}} \right] \quad (5.10)$$

where:

- X = volume to capacity ratio of lane group,
- c = capacity of lane group (vehicles/hour),
- k = incremental delay factor dependent on signal controller setting (0.50 for pretimed signals; vary between 0.04 to 0.50 for actuated controllers),
- I = upstream filtering/metering adjustment factor (1.0 for an isolated intersection),
- T = evaluation time (hours).

5.6 HORIZONTAL SHOCK WAVE DELAY MODELS

In oversaturated traffic conditions, multiple shock waves usually form when the v/c ratio becomes greater than 1.0. In such situation, the formulation of delay estimates is similar to the undersaturated case. However, the calculation of delay estimates in presence of multiple shock waves is more complicated than the single shock wave analysis that was described in Chapter 4.

Delay using shock wave analysis can be estimated by calculating speeds of shock waves using the densities and flow rates of the different regions. Figure 5.8 illustrates the spatial and temporal evolution of a queue in the first two cycles of an oversaturated signalized approach. As mentioned earlier in Chapter 4, the travel time experience by vehicles along the intersection approach can be calculated in this diagram by multiplying the size of each regime by the density of the regime. In Figure 5.8, both the triangle ABC (area 1) and the trapezoid EDFG (area 3 + area 4) have the same density (jam density k_j). Similarly, the trapezoid CBDE (area 2) and GFHJ (area 5 + area 6) have the same density (density of capacity k_d). Assuming the density, k_a , as the approach density to a signalized intersection. Both area ABDE and DFHI have the same travel time, which means that the area ABDE and area DFHI are identical. If the size of area 4 and area 6 is known, estimating of delay is then only a matter of knowing the number of cycles that are comprised within a defined time interval and multiplying it by the travel times in the different regimes.

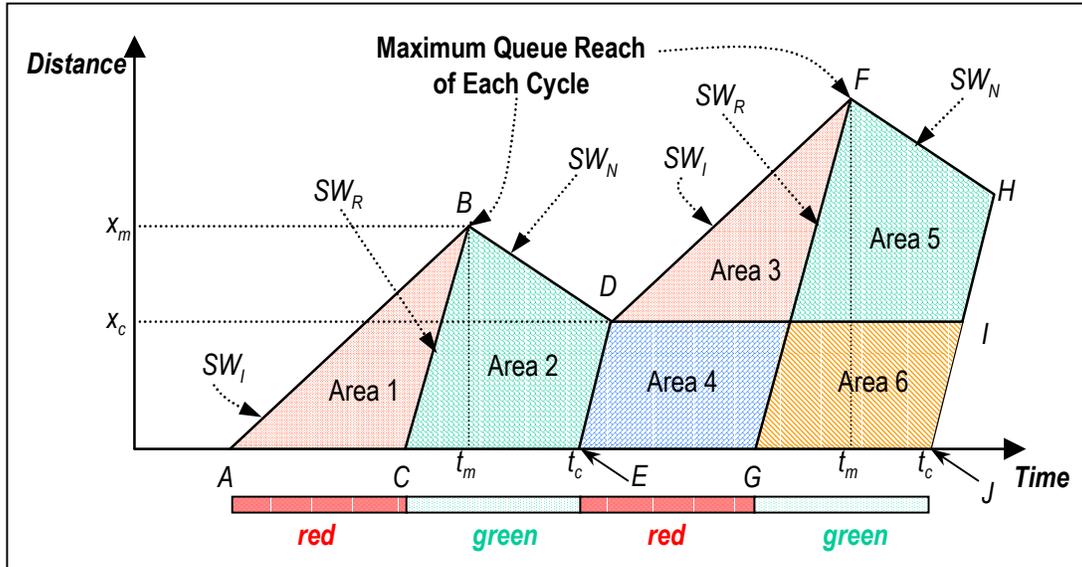


Figure 5.8: Graphical Illustration of Shock Wave Analysis

In Figure 5.8, the speed of the initial shock wave, SW_I , the recovery shock wave, SW_R , and the new shock wave, SW_N , can be determined by calculating the ratio of flow changes over density changes using a flow-density relationship. Using the shock wave speeds, the maximum spatial extent of the queue (x_m) and the time at which the queue extent is maximum (t_m) can be computed to estimate the travel time of vehicles experienced by a signal. The equations for x_m and t_m already described in Chapter 4. The equation of travel time at a signalized approach is computed using Equation 5.11.

$$TTWS = N \cdot \left\{ \frac{r \cdot x_m}{2} \cdot k_j + g \cdot \frac{(x_m + x_c)}{2} \cdot k_d \right\} + \sum_{i=1}^{N-1} i \cdot (r \cdot k_j + g \cdot k_d) \cdot x_c \quad (5.11)$$

where:

$TTWS$ = travel time with signal (seconds),

N = number of cycles,

r = effective red interval (seconds),

g = effective green interval (seconds),

x_m = maximum distance to upstream (kilometers),

x_c = distance to clear queue (kilometers),

$$k_j = \text{jam density (vehicles/kilometers),}$$

$$k_d = \text{discharge density (vehicles/kilometers).}$$

If a traffic signal had not been present, the vehicles traveling through the areas 1, 2, 3, 4, 5 and 6 would still have incurred some travel time. The travel time without a signalized intersection can be computed as the sum of areas, 1 through 6, multiplied by the density which vehicles approach to signalized intersection (k_a), as demonstrated in Equation 5.12.

$$TTWOS = N \cdot k_a \cdot \left\{ \frac{r \cdot x_m}{2} + g \cdot \frac{(x_m + x_c)}{2} \right\} + \sum_{i=1}^{N-1} i \cdot (r + g) \cdot x_c \cdot k_a \quad (5.12)$$

where:

$$TTWOS = \text{travel time without signal (seconds),}$$

$$k_a = \text{approach density (vehicles/kilometers).}$$

The final net delay can be estimated by subtracting the travel time without the traffic signal from the travel time with the traffic signal. When equations 5.11 and 5.12 are combined, the equation of final net delay for the N number of cycles (considered in the analysis period) is expressed by Equation 5.13.

$$D = N \cdot \left\{ \frac{r \cdot x_m}{2} \cdot (k_j - k_a) + g \cdot \frac{(x_m + x_c)}{2} \cdot (k_d - k_a) \right\} + \sum_{i=1}^{N-1} i \cdot \{ r \cdot x_c (k_j - k_a) + g \cdot x_c \cdot (k_d - k_a) \} \quad (5.13)$$

where:

$$D = \text{final net delay (seconds).}$$

From Equation 5.13, the average delay per vehicle can also be found by dividing the final net delay by the total number of vehicle arrivals, which is the arrival rate multiplied by the analysis period.

$$\text{Average Delay per Vehicle} = \frac{\text{Final Net Delay}}{\text{Total Vehicles Arrivals}} \quad (5.14)$$

By combining Equations 5.13 and 5.14, the average delay per vehicle can be expressed by Equation 5.15.

$$d = \left(N \cdot \left\{ \frac{r \cdot x_m}{2} \cdot (k_j - k_a) + g \cdot \frac{(x_m + x_c)}{2} \cdot (k_d - k_a) \right\} + \sum_{i=1}^{N-1} i \cdot \{ r \cdot x_c (k_j - k_a) + g \cdot x_c \cdot (k_d - k_a) \} \right) / (s \cdot g \cdot N) \quad (5.15)$$

where:

d = average delay per vehicle (seconds).

5.7 QUALITATIVE MODEL COMPARISON

Specifically, the formation of shock waves upstream a signalized approach using the INTEGRATION model are demonstrated to be consistent with shock wave analysis, as illustrated in Figure 5.9. The first step in the evaluation was to qualitatively compare the formation of shock waves upstream a signalized intersection.

Table 5.1 shows the comparison of the theoretical vertical queuing analysis method and the theoretical horizontal queuing method derived from shock wave analysis. In this table, it can be seen that both the horizontal queuing method and the vertical queuing method for estimating delay produce identical results. These results demonstrate that vertical queuing analysis and horizontal shock wave analysis made invalid conclusions by indicating that the delay estimates are different. It should be noted, however, that the maximum extent of a queue is underestimated using the vertical queuing model given that it ignores the spatial extent of the queue.

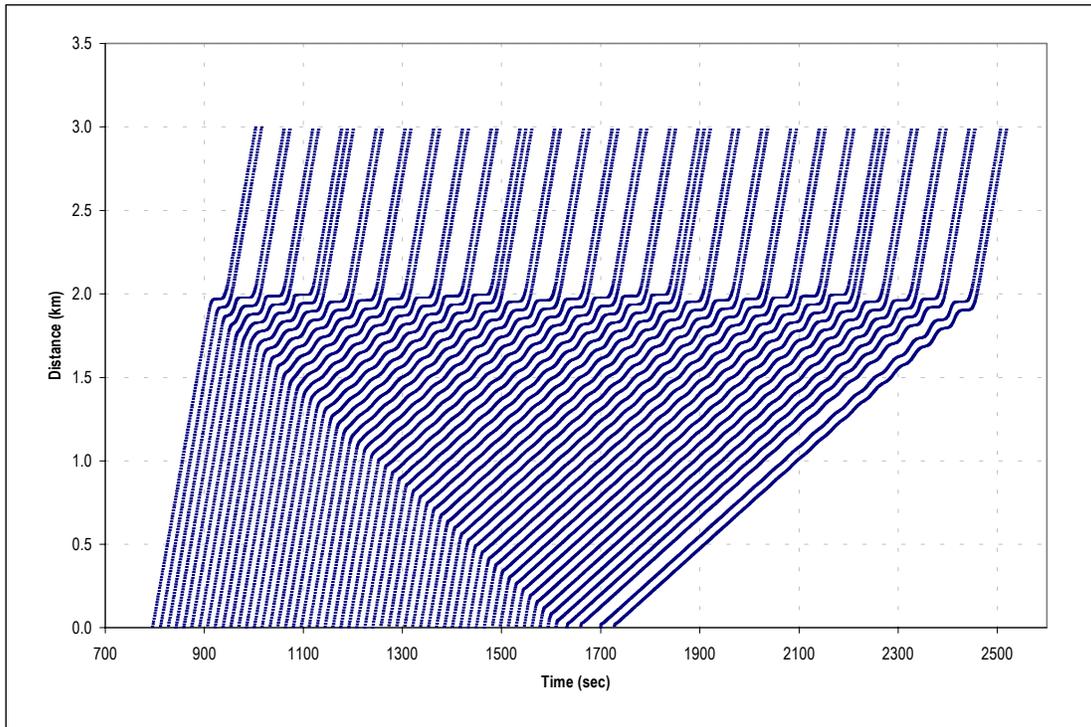


Figure 5.9: Simulated Time-Space Diagram for Traffic Signal Cycles

Table 5.1: Comparison of Vertical and Horizontal Queuing Analysis

Measures of Effectiveness	Vertical Queuing Analysis	Horizontal Shock Wave Analysis
Difficulty to find Delay Estimates	Easy	Difficult
Time to dissipate Queue	Correct	Correct
Maximum Number of Vehicle in Queue	Underestimated	Correct
Maximum Extent of Queue	Underestimated	Correct
Time at which extent is maximum	Incorrect	Correct
Delay Estimation	Correct	Correct

5.8 MODEL COMPARISONS

5.8.1 CONSTRUCTION OF TEST SCENARIOS

In order to evaluate the consistency of delay estimates among the various analytical and simulation approaches in oversaturated conditions, vehicle arrivals were simulated by considering both uniformly and randomly distributed vehicle headways. In the case of random arrivals, vehicle headways were generated using a shifted negative exponential distribution with a minimum headway equal to two seconds (the capacity headway).

In the simulations, the vehicle discharge pattern during the green interval depends on the queue status at the approach. If there is no queue present when a vehicle arrives, then the vehicle can discharge immediately without any delay, otherwise, the vehicle must wait until the queued vehicles ahead of it discharge. The saturation flow rate is assumed to be 1800 vehicles per hour, which corresponds to a discharge headway of two seconds. The simulation starts with no queue present and terminates once the required total number of cycles has been simulated. The evaluation period duration is 15 minutes. The signal timing consists of a cycle time of 60 seconds with both fixed-time effective red and green intervals of 30 seconds. The link consists of a two-kilometer link before signal and an one-kilometer exit link to allow vehicles to accelerate to their final desired speed.

Using the above settings, two sets of five test scenarios were simulated to estimate delays in oversaturated traffic conditions. As was the case for the undersaturated scenarios, the first set of simulation considers uniform arrivals, while the second set adds randomness to the arrival process. For convenience, the scenarios used in this comparison are identical to those described in Chapter 4, except for the v/c ratios, which range from 1.1 to 1.5.

5.8.2 DELAY ESTIMATES FOR UNIFORM VEHICLE ARRIVALS

Table 5.2 and Figure 5.10 provide the results of the delay estimates considering uniform vehicle arrivals. In this case, Equations 5.4 and 5.15 are used to calculate the delays incurred by vehicles using the vertical queue analysis and horizontal shock wave analysis models, respectively. For

three capacity guide models, while only the first term of Equations 5.5, 5.7 and 5.9 were used for the undersaturated analyses, all terms of the three Equations were used in this analysis to take into account both the randomness of vehicle arrivals and the probability of temporary signal cycle oversaturation due to this randomness. the only exception is for the last term of Equation 5.9 in the HCM 2000 model. This term is not used since there is no residual demand delay in this analysis. It should be noted that the overall delays associated with the HCM 1994 model have been obtained by multiplying the stopped delays given by Equation 5.5 by 1.3 to convert the estimated stopped delay into an overall delay estimate.

Along with the above estimates, Table 5.2 and Figure 5.10 show the average overall delay estimates obtained from the INTEGRATION traffic simulation model. It can be observed that all analytical models except for the HCM 1994 provide a very good agreement with the INTEGRATION software under all levels of v/c ratios. When compared with other models, the HCM 1994 delay model predicts higher delays for oversaturated conditions with increasing differences in predictions with increasing degree of saturations. At this point, it should be reminded that the equation of the HCM 1994 model is valid only for v/c ratios of less than 1.0 but may still be used with some caution for v/c ratios of up to 1.2, the generally recognized upper limit of the delay model. When the value of v/c ratio exceeds 1.2, the model becomes invalid, as is evident in Figure 5.10.

As indicated in Figure 5.10, all the analytical delay models discussed in this chapter calculate delays consistent with the INTEGRATION software. It should be reminded that the INTEGRATION software computes delay as the difference between vehicle departure to arrival times without the use of a delay formula. In oversaturated conditions, additional delay is therefore accrued after the end of the analysis period by vehicles that arrive during the analysis period and that remain in queue at the end of that period. All the simulation delay models, reviewed in this chapter, take this fact into account so as to obtain more precise delay measurements.

Table 5.2: Overall Delay Estimates under Uniform Arrivals

Delay Model	v/c Ratio				
	1.1	1.2	1.3	1.4	1.5
Vertical Queuing Analysis	60.00	105.00	150.00	195.00	240.00
Horizontal Shock Wave Analysis	60.00	105.00	150.00	195.00	240.00
HCM 1994 Model	68.32	122.92	197.44	292.83	410.77
HCM 2000 Model	76.18	115.72	158.17	201.75	245.85
CCG 1995 Model	76.18	115.72	158.17	201.75	245.85
INTEGRATION File 10	62.42	105.49	151.49	196.18	241.71
INTEGRATION File 11	62.30	105.30	151.49	196.10	241.60
INTEGRATION File 15	62.56	105.68	151.66	196.34	241.85
INTEGRATION File 16	62.57	105.68	151.67	196.35	241.85
INTEGRATION Summary File	62.46	105.57	151.55	196.24	241.74

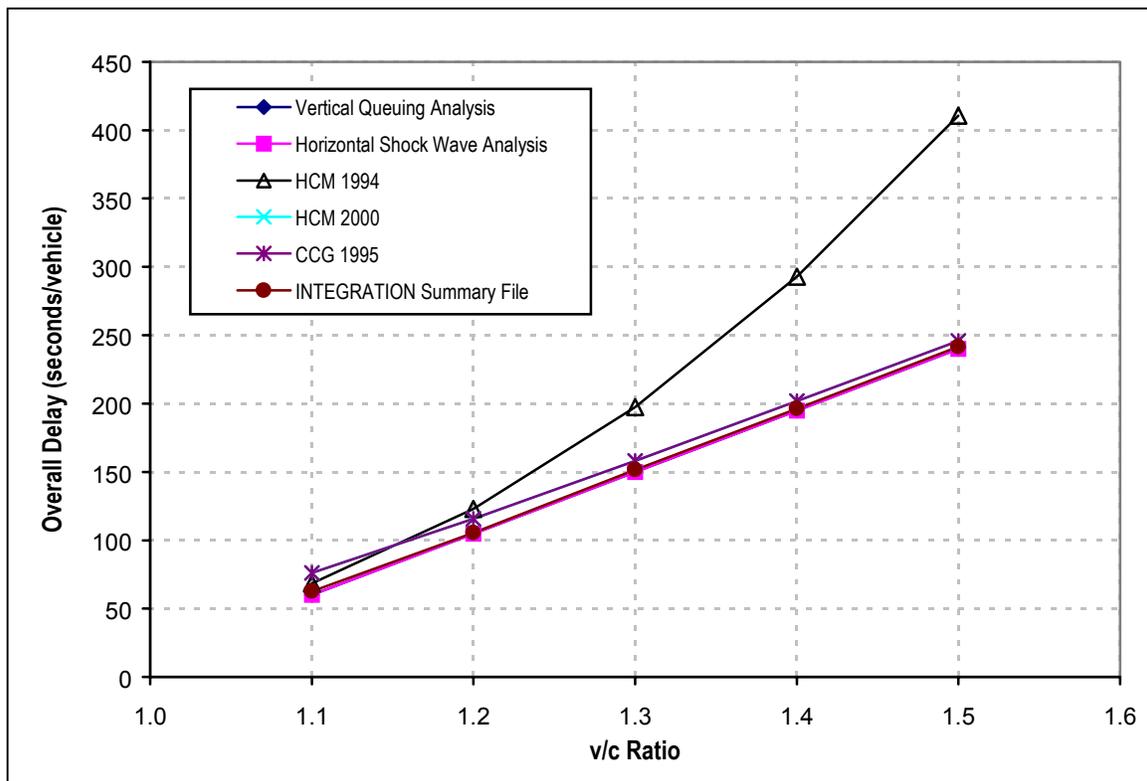


Figure 5.10: Overall Delay Estimates under Uniform Arrivals

5.8.3 COMPARISON OF ACCELERATION AND STOPPED DELAY ESTIMATES

In this section, the ratio of stopped delay to overall delay obtained from each model is analyzed to assess the consistency of all delay models. However, as mentioned in Chapter 4, this comparison is only possible between the INTEGRATION delay model and the CCG 1995 model as the other models provide no means to estimate individual delay components such as deceleration, stopped and acceleration delay.

In INTEGRATION, the deceleration, stopped and acceleration delays can be produced by using the individual second-by-second speed profiles. As an example, consider Figure 5.11, which illustrates the delay obtained under uniform arrivals for a v/c ratio of 1.5. In this figure, by summing the delays incurred by vehicles while they were moving at a speed of less than 5 km/h, the criterion used in the CCG 1995 to define stopped delay, it is found that 52.4 percent of the total simulated delay could be considered as stopped delay. The ratio of stopped delay to overall delay for oversaturated conditions is a bit lower than that for undersaturation conditions since more acceleration delay and deceleration delay result from the constant stop and go pattern that appears when the v/c ratio is greater than 1.0. However, this ratio compares favorably with the 56 percent stopped to overall delay ratio assumed in the CCG 1995 for similar traffic conditions.

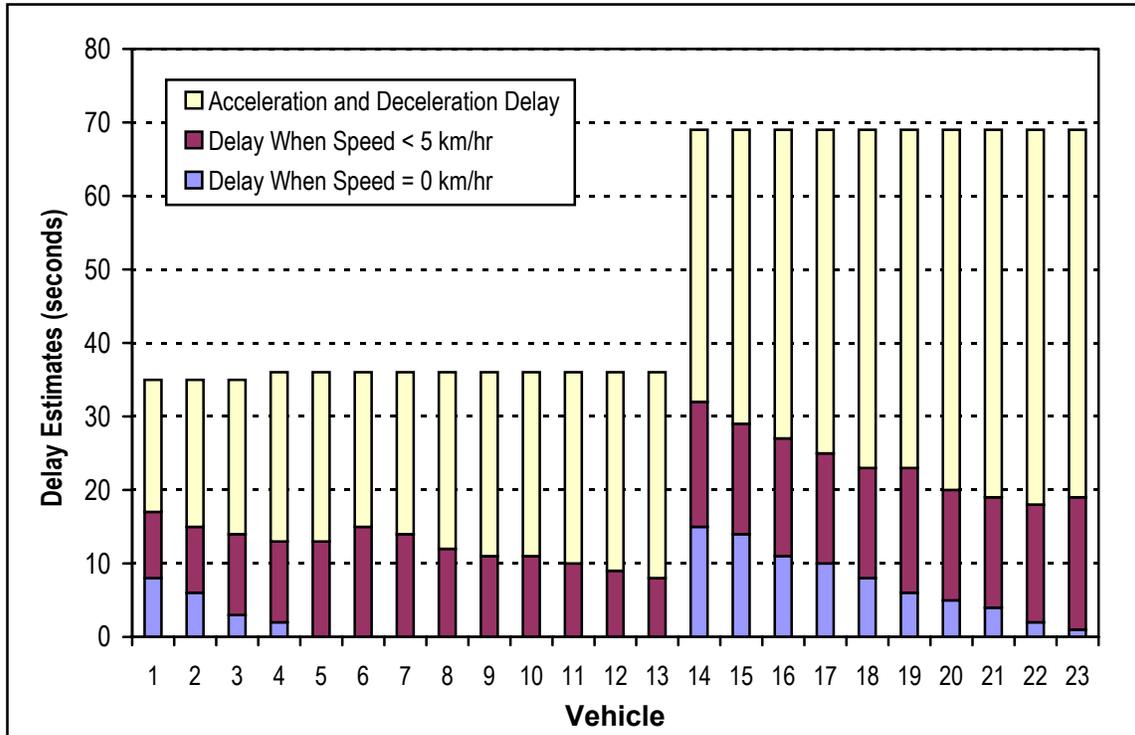


Figure 5.11: Stopped and Overall Delay for Arriving Vehicles in Typical Signal Cycle

5.8.4 DELAYS ESTIMATES FOR RANDOM VEHICLE ARRIVALS

Table 5.3 and Figure 5.12 show the results of the delay estimations using the random arrival scenarios. For this set of scenarios, Equation 5.4 and 5.15 were again used to compute the overall delay predicted by the vertical queuing and horizontal shock wave analysis models. Also, all terms of Equations 5.5, 5.7 and 5.9 were used to measure the overall delays predicted by the three capacity guide models. Similarly to the uniform arrivals, the stopped delay estimates produced by the HCM 1994 delay model were again multiplied by 1.3 to obtain the corresponding overall delay and allow a direct comparison of its delay estimates with other models. In the case of INTEGRATION, the reported delays are the average of ten repetitions using different random number seeds.

The results of Table 5.3 and Figure 5.12 indicate that there is a good agreement between the delay estimates from INTEGRATION and the estimates calculated by the 1995 CCG, the HCM 2000, the vertical queuing analysis and the horizontal shock wave analysis models when these models are applied to the analysis of oversaturated fixed-time signalized intersection. However,

the delay estimates from the HCM 1994 model are found to be very high for v/c ratios approaching 1.5. Again, the HCM 1994 indicates that the delay model is valid only for v/c ratios in the range of 1.0 and 1.2.

Table 5.3: Overall Delay Estimates under Stochastic Arrivals

Delay Model	v/c Ratio				
	1.1	1.2	1.3	1.4	1.5
Vertical Queuing Analysis	60.00	105.00	150.00	195.00	240.00
Horizontal Shock Wave Analysis	60.00	105.00	150.00	195.00	240.00
HCM 1994 Model	68.32	122.92	197.44	292.83	410.77
HCM 2000 Model	76.18	115.72	158.17	201.75	245.85
CCG 1995 Model	76.18	115.72	158.17	201.75	245.85
INTEGRATION File 10	68.24	113.18	157.53	200.51	243.65
INTEGRATION File 11	68.15	113.03	157.43	200.42	243.60
INTEGRATION File 15	68.41	113.32	157.67	200.68	243.82
INTEGRATION File 16	68.41	113.41	157.68	200.67	243.83
INTEGRATION Summary File	69.41	114.59	159.26	202.70	246.49

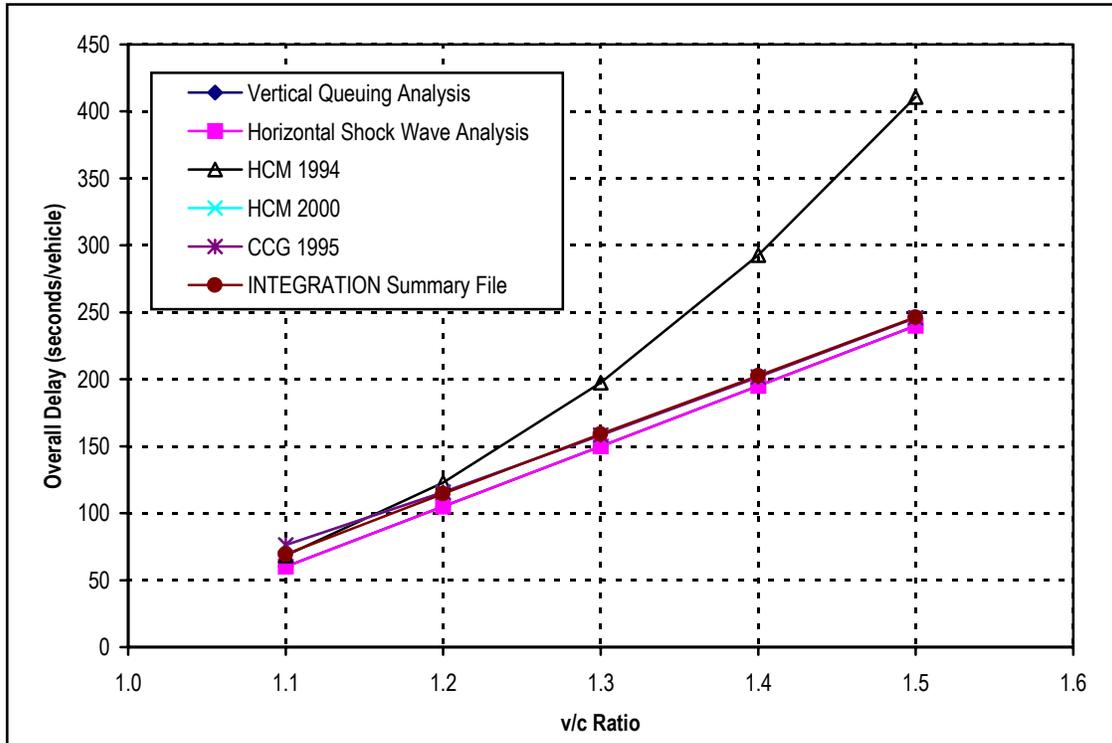


Figure 5.12: Overall Delay Estimates with Stochastic Arrivals

Figures 5.13 and 5.14 finally present the results of all replications conducted with the INTEGRATION curve for both the single-lane and two-lane scenarios. In addition, the HCM 1994, HCM 2000 and 1995 CCG delay curves are shown for comparison purposes. In both cases, it is observed that the INTEGRATION delay estimates correspond almost identically to the analytical delay estimates under all oversaturated v/c ratios. These results clearly indicate once more that there is consistency between the simulated and analytical delay models for oversaturated signalized approaches. Figure 5.14 illustrates overall delay results which conducted the same procedure for two-lane delays for oversaturated conditions.

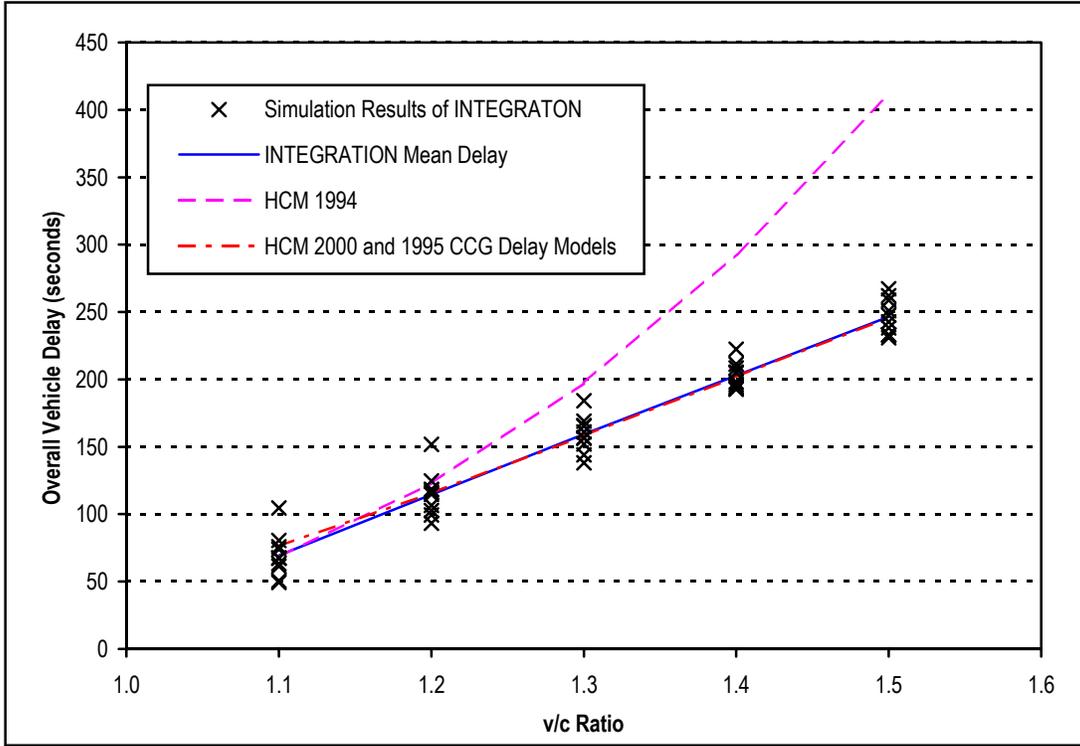


Figure 5.13: Simulated Results of INTEGRATION for Single-Lane

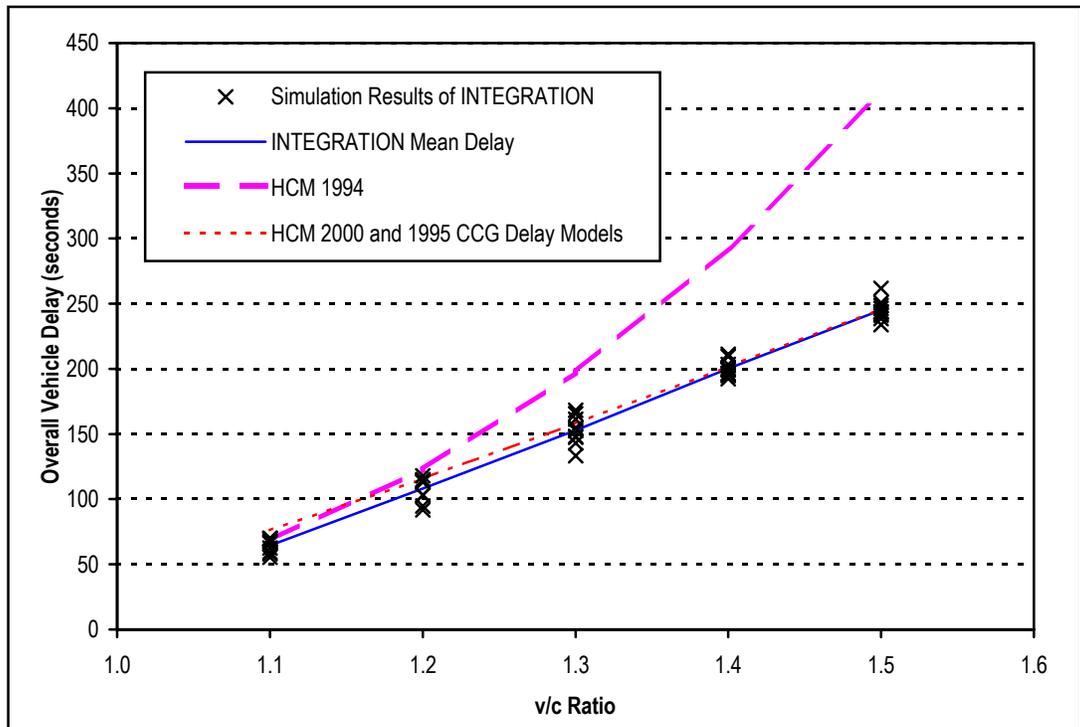


Figure 5.14: Simulated Results of INTEGRATION for Two-Lane

5.9 SUMMARY AND CONCLUSIONS

This chapter compared the delay estimates predicted by analytical and the INTEGRATION simulation models for the case of an oversaturated fixed-time signalized intersection. The models that were compared included a theoretical vertical queuing analysis model, a theoretical shock wave analysis model, the queue-based models that utilized in the HCM 1994, 1995 CCG and HCM 2000, and six delay estimates from the INTEGRATION microscopic traffic simulation software.

In general, it was found that the delay estimated by the existing analytical models are in close agreement with those simulated by the INTEGRATION model under uniform and random arrivals. It was observed under uniform arrival scenarios that all analytical models except for the HCM 1994 provide a very good agreement with the INTEGRATION delay models under all levels of v/c ratios. It was also found under random arrival scenarios that the INTEGRATION model produces slightly higher results and follows the same general trend as the delay estimates from the analytical models. The difference in delay estimates between the analytical models and the simulation results is explained by the sensitivity of delay estimates from microscopic traffic simulation models to assumed traffic arrival patterns. It should be noted that the delay estimates from the HCM 1994 model are not valid when the value of v/c ratio exceeds 1.2.

In conclusion, the study has demonstrated the validity of the INTEGRATION model in computing vehicle delay for oversaturated signalized approaches. While the application of analytical models is feasible for such simplified examples, they are less feasible for real-life applications involving mixed flow and the interaction (spillback) of oversaturation queues. Alternatively, the INTEGRATION model is ideal for the modeling of such real-life applications. The results of this study provide significant credibility to the model for real-life evaluations.