A Macroscopic Model for Evaluating the Impact of Emergency Vehicle Signal Preemption on Traffic

by

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(ABSTRACT)

In the past, the study of Emergency Vehicle (EV) signal preemption has been mostly done using field studies. None of the simulation models that are currently commercially available have the capability to model the presence of EVs and simulate the traffic dynamics of the vehicles surrounding them. This study presents a macroscopic traffic model for examining the effect of signal preemption for EVs on traffic control measures, roadway capacity, and delays incurred to the vehicles on the side streets. The model is based on the cell transmission model, which is consistent with the hydrodynamic theory of traffic flow. A special component, in the form of a moving bottleneck that handles the traffic dynamics associated with the presence of EVs, was developed in the model. Several test scenarios were constructed to demonstrate the capabilities of the model for studying the impact of signal preemption on an arterial with multiple intersections under various traffic demand levels and varying frequencies of the arrival of EVs. Performance measures, such as average vehicle delay, maximum delay, and standard deviation of delay to traffic on all approaches, were obtained. An additional advantage of the model, apart from the capability to model EVs, is that the state-space equations used in the model can be easily incorporated into a mathematical programming problem. By coupling with a desired objective function, the model can be solved analytically. Optimal solutions can be generated to obtain insights into the development of traffic control strategies in the presence of EVs.

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1 INTRODUCTION

1.1 Need for Signal Preemption

Transportation system management (TSM) strategies have evolved over the years because of the significant increase in travel demand in urban areas, the lack of additional land to expand the transportation system and the increase in construction costs. These factors have led to the search for methods to improve the level of service of the existing facilities with small investment costs. It is obvious that the efficiency of the existing system can be improved much better if the management strategies are aimed at mass transit systems rather than individual motorists. The reason for this being that the person throughput as well as the fuel efficiency of the system will increase much more if a transit vehicle, carrying many more persons, is given priority in such strategies rather than the single occupancy automobiles. Thus, in recent years, the emphasis of urban traffic management policies has been shifting from the freedom of movement of individual motorists towards the fair allocation of limited network capacity to an ever-increasing number of road users and towards improving the level of service of the mass transit system.

One of the major reasons for the inefficiency of the current urban transportation system is the delay experienced by high occupancy transit vehicles at signalized intersections. It was estimated that stopped delay at intersections comprises of about 20% of the overall transit vehicle delays *(1)*. With the rapid development of microprocessors and communication technologies, efforts have been devoted to developing traffic-responsive signal control methods to meet the ever-increasing traffic demand. Because conventional fixed time signal control design methods are based on the use of historic data, they cannot fully accommodate time-dependent flows. Actuated signal control systems have been developed to meet such transient demand situations. When demands vary and can be monitored in real time, actuated/demand-responsive signal control strategies have the potential to perform better than fixed-time control strategies, by employing the use of automatic vehicle detection technologies. Such detector-based technologies have been extended to identify particular vehicle types, like transit, and give priority to these vehicles over the rest of the traffic, to improve their performance and profitability. Such transit-oriented prioritized traffic operation at signalized intersections is achieved using Signal Priority techniques.

Signal priority is the technique of changing or maintaining a traffic signal display in order to reduce the amount of stopped delay for targeted vehicles, like buses or emergency vehicles. This is usually achieved by providing continuous green phases to these vehicles whenever they approach an intersection.

In order to improve the attractiveness of transit to the public in general, buses need to run on schedule as far as possible. Uncertainties resulting from variations in passenger loading and unloading at bus stops make the exact prediction of bus arrival times at intersections extremely difficult. The location of bus stops (near side as well as far side) also affects the ability of buses to travel through the intersection in an uninterrupted manner. Hence, real time detection of transit vehicles is necessary to provide continuous green phases to the transit vehicles. The priority technology includes instrumented buses, loop detectors, sensing devices, and a real-time traffic control system that can detect an approaching bus, predict its arrival time at the intersection and communicate the information to the signal control for necessary action. The objective of such priority strategies is to increase the perceived advantage of transit relative to the single occupancy vehicles and therefore divert users from the private automobile to the transit system. Such objectives are particularly important in light of greater energy and environmental efficiency of the transit system.

Signal priority technology is used not only for transit vehicles but also for other special vehicles like fire engines, ambulances, police cars etc. In almost every emergency call-out for the services of such vehicles, dangerous situations arise, especially when crossing intersections and when using opposite lanes too. These situations may lead to serious accidents, if not properly coordinated. In city/urban traffic, such a call-out requires the use of continuous sirens. Such emergency vehicles are usually exempt from the traffic regulations when they are fitted with sirens and flashing lights. But the use of sirens leads to an almost intolerable levels of noise pollution, especially if the frequency of these emergency vehicles is high. However, journey speeds of emergency vehicles have become lower as the traffic density has increased with cross street traffic impeding these journeys. Hence signal-setting strategies, to give priority to emergency vehicles, have become necessary to give unimpeded passage to these vehicles at signalized intersections and to stop all cross-street and opposing traffic. Signal priority techniques are termed as signal preemption techniques, when addressed with respect to emergency vehicles. These preemption techniques are thereby intended to:

- Save journey time: Due to unimpeded passage of the emergency vehicle, higher speeds through traffic are attainable. Thus, the necessary assistance can be provided more quickly.
- Increase safety: By stopping crossing and opposing traffic on the route of the emergency vehicle, the number of potential conflicts can be reduced and hence traffic safety can be improved.
- Reduce the level of noise pollution: By giving free passage to emergency vehicles and closing the route to opposing and crossing traffic, the use to sirens can be reduced. Hence the environmental disamenity, in particular near fire stations, hospitals and similar service facilities can be reduced considerably, especially during the night.
- Reduce traffic flow interruptions: Due to fewer conflicts between the emergency vehicle and the traffic in general, the number of uncoordinated interferences in traffic flow patterns can be reduced.

Due to such advantageous nature of signal preemption strategies in providing solutions to the growing traffic demand problem, they are implemented at a lot of intersections and embedded into the commercially available signal control software.

1.2 Priority vs. Preemption

Signal preemption strategies can be implemented in a couple of different ways, depending upon the situation and the severity of traffic volumes involved. In literature, two terms are found to be in use to describe this transit/emergency vehicle oriented signal-setting strategies. They are called signal priority and signal preemption. Usually, signal preemption is the term used to describe the signal-setting strategies, when emergency vehicles like fire engines, ambulances, police cars etc., are involved. In these cases, the emergency vehicle is given a green phase upon its arrival at the intersection, to pass through the intersection uninterrupted, in each and every case such a call-out is made, irrespective of the conditions on the cross street and its impact on the overall traffic. This is necessary because of the nature of the services the emergency vehicles deliver to the public and they have to get a green phase irrespective of the overall conditions.

Signal priority is the term used to describe the case when a transit vehicle is the subject of such a strategy. Every call for a green phase by a transit vehicle is evaluated for its impact on the cross street traffic delays and the overall intersection efficiency and only those calls, which meet the requirements, are given priority. Hence, in a signal priority scheme, it is not necessary that all the transit vehicles will get a green phase upon their arrival at the intersection.

But in this report, both the terms are applied to mean the same thing in all situations. Also whenever it is mentioned as transit vehicle or emergency vehicle, it refers to both categories of vehicles. Hence in this report, the objective is to study the impact of providing signal preemption or priority to transit and emergency vehicles on general traffic.

1.3 Goals, Objectives and Scope of Work

The goals of this report are manifold. They are as follows.

- Describe a macroscopic traffic model and its implementation using the cell transmission model.
- Demonstrate the behavior of the cell transmission model under various traffic conditions and compare its accuracy with standard results.
- Discuss the advantages and shortcomings of the model with respect to its assumptions, limitations and scope.
- Discuss signal preemption for emergency vehicles, its need, various strategies and its general impact on the rest of the traffic.
- Model the presence of an emergency vehicle on the roadway segment using the cell transmission model and demonstrate its capability to model the corresponding traffic dynamics.
- Model different scenarios involving the arrival of the emergency vehicle from different approaches and at various frequency levels.
- Evaluate the impact of providing signal preemption to the emergency vehicles on the main street as well as the cross street traffic.
- Test the sensitivity of the results to changes in the parameters of the model, when modeling the presence of emergency vehicle.

The primary objective of this study is to demonstrate the capabilities of the macroscopic cell transmission model to simulate emergency vehicle traffic dynamics and evaluate some of its impacts on the traffic. Though the analysis described in this study centers around emergency vehicles only, the model considered in this study might be easily extended to study signal priority systems for transit operations.

1.4 Organization of the Report

This thesis report is organized into 5 chapters including this introductory chapter.

Following this chapter, chapter 2 describes the macroscopic traffic model and discusses the various modeling methodologies and issues in this model. It also demonstrates the model behavior by the use of some illustrative examples and also discusses some of its limitations. Finally it demonstrates the capability of the model to simulate the traffic dynamics involved with the presence of an emergency vehicle.

Chapter 3 introduces the concept of signal preemption and discusses some of the work done in this area through some literature review. It discusses the various signal preemption technologies and the strategies that are implemented in the field. It presents the various data needs necessary for its implementation and also discusses the impact of signal preemption on the rest of the traffic.

Chapter 4 outlines the network configuration used for the model and various roadway and traffic characteristics of the network. It describes the various test scenarios, which have been implemented to study the effects of preemption, and tabulates the results obtained.

Chapter 5 presents the conclusions obtained from this study and provides some recommendations for further research.

2 CELL TRANSMISSION MODEL

2.1 Introduction to Macroscopic Model

Traffics simulation models can be either microscopic or macroscopic in nature. Microscopic models assume that the behavior of a single vehicle on the road is a function of the traffic environment surrounding it. Usually microscopic models are based on the car following equations, which determine the reaction of a subject vehicle when presented with the actions of a set of control vehicles ahead of it on the road. Although, the microscopic models keep track of each vehicle's movement, their assumptions are difficult to validate because human behavior in real traffic is difficult to observe and measure. Also the disadvantage of the microscopic model is that it is difficult to capture the "pullover" effect of vehicles, which is the pulling over behavior of vehicles to the side of the road in the presence of an emergency vehicle.

Macroscopic models assume that the aggregate behavior of vehicles, which require fewer parameters for calibration, depends on the traffic conditions in their environment. The underlying theory behind most of these models is the hydrodynamic theory of traffic flow *(2,3)*. The macroscopic model described in this report is based on the cell transmission model *(4)*, which presents an alternative method of predicting traffic behavior for one link by evaluating flow at a finite number of carefully selected intermediate points, including the entrance and the exit. This model is based on a set of finite difference equations that can be shown to be discrete approximations to the differential equations of the hydrodynamic theory for a special form of the equation of the state.

Traditionally, models with analytical and simulation approaches are often developed separately. Simulation models are often used to compare alternative strategies, whereas analytical models are used to develop efficient control strategies. One of the advantages of the underlying macroscopic traffic model adopted in this study is that it combines the features of simulation and analytical models. The state-space equations used in the model can be easily incorporated into an analytical model, such as the one formulated with an LP problem.

2.2 Modeling Traffic Dynamics

The macroscopic traffic model captures the evolution of traffic over a one-way road without any intermediate entrances or exits, so that those vehicles enter at one end and leave at the other end. This model is time-driven, in which current conditions are updated every tick of the simulation second.

2.2.1 Modeling Concepts

The hydrodynamic theory of traffic flow is known to be powerful in capturing the transient behavior of traffic, including the formation, propagation, and dissipation of queues. The central component of the hydrodynamic theory of traffic flow is the classic continuity equation for flow conservation that defines the relationship between flow (*q*) and density (*k*) over time and space in the following form:

$$\frac{\partial k}{\partial t} + \frac{\partial q}{\partial x} = 0 . \qquad (2.1)$$

This equation is usually supplemented by the assumption that traffic flow at location x is a function of traffic density,

$$q=Q(k,x,t). \qquad (2.2)$$

If we assume that the roadway geometry is homogeneous and is time invariant, then the equation can be further simplified as $q=Q(k)$. In the situation when discontinuity arises, such as a sudden reduction in traffic speed when vehicles join queues, the speed of the discontinuity interface that separates two traffic regions can be represented by the shockwave equation in the following form:

$$u = -\frac{q_u - q_d}{k_u - k_d} . \qquad (2.3)$$

where (q_u, k_u) and (q_d, k_d) represent the traffic states upstream and downstream of the interface, respectively. Negativity indicates that the shockwave propagates in the direction opposite to the traffic stream. Equation (2.1) can be solved with the standard solution approach, such as the initial value problem. The solutions are often very tedious to obtain even for a very small network.

2.2.2 Equations and Explanations

The cell transmission model described in this section is a discrete version of the hydrodynamic theory of traffic flow *(4)*. In the cell transmission model, the roadway is partitioned into discrete segments and time into discrete steps. The partition is done in such a way that it takes a single time step (Δt) to traverse one cell at free-flow travel speed. If the free flow speed is taken as 60 kmph and a simulation second of 1 second then the length of a cell is approximately 80 feet. Under light traffic (unsaturated conditions), all vehicles in a cell can be assumed to advance to the next cell with each tick of the clock. It is unnecessary to know where within the cell they are located. Thus, under unsaturated conditions, the system's evolution obeys:

$$n_{i+1}(t+1) = n_i(t) \qquad \text{for } t=0,1,2\ldots. \tag{2.4}$$

where $n_i(t)$ is the number of vehicles in cell i (where i+1 cell is the immediate downstream cell to cell i) at time t. This equation holds true for all traffic flows, unless queuing from a downstream bottleneck slows down traffic. This assumption is valid because for crowded conditions as might arise during the rush hour, queuing at downstream bottlenecks, where flow temporarily exceeds capacity, triggers most of the delays.

Queuing is incorporated into the system by introducing two constants: $N_i(t)$, the maximum number of vehicles that can be present in cell i at time t, and $Q_i(t)$, the maximum number of vehicles that can flow into a cell i when the clock advances from t to t + 1. The first constant is the product of the cell's length and its jam density, and the second one is the product of the maximum capacity of the roadway and the simulation second.

$$\Delta l = V_f * \Delta t \quad (2.5)$$

$$Q_i(t) = q_m * \Delta t \quad (2.6)$$

$$N_i(t) = k_j * \Delta l \quad (2.7)$$

where Δl - Cell length in meters

Δt - Simulation time step in seconds

q_m - Maximum flow or Capacity in veh/hr

k_j - Jam Density in veh/km

By properly defining the flow-density relationship, the differential equations are replaced by a set of difference equations as follows:

$$z_i(t+1) = \min\{n_i(t), Q_i(t), Q_{i+1}(t), \alpha(N_{i+1}(t) - n_{i+1}(t))\} \quad (2.8)$$

$$y_{i+1}(t+1) = z_i(t+1) \quad (2.9)$$

$$n_i(t+1) = n_i(t) - z_i(t+1) + y_i(t+1) \quad (2.10)$$

Where $z_i(t)$ is the number of vehicles leaving cell *i* at time [t,t+1), $y_{i+1}(t)$ is the number of vehicles entering cell *i+1* at time [t,t+1), and $n_i(t)$ the number of vehicles inside cell *i* at time [t,t+1). The model can be proved to be convergent to the continuum model when the discretized time and space elements approach zero.

Equation (2.8) determines the outflow for cell *i*. Equation (2.9) ensures flow conservation at boundaries, such that the inflow to a cell is equal to the outflow from its upstream cell. Equation (2.10) is a state function indicating that the change in the number of vehicles in a cell during a time step is the difference between the inflow and outflow within that time step. The value of α, which is the space constraint parameter, is the ratio of the backward wave speed and the free flow speed. When the downstream area of a cell is a signalized intersection, the capacity for the exit flow is determined by the following equation:

$$Q_i(t) = \begin{cases} Q_i & \text{if the signal light downstream of cell } i \text{ is green} \\ 0 & \text{if the signal light downstream of cell } i \text{ is red.} \end{cases} \quad (2.11)$$

Boundary conditions are specified by means of input and output cells. The output cell, a sink for all exiting traffic, has infinite size and a suitable capacity. Also the input cell has an infinite size and a suitable, desired input capacity. It is interesting to note that the result of the simulation is independent of the order in which the cells are considered at each step. This property arises because of the number of vehicles that enter a cell is unrelated to the number of vehicles that leave it and only current conditions influence the inflow to a particular cell.

It is important to note that the acceleration and the deceleration characteristics of the vehicles cannot be captured realistically in a macroscopic model because of the aggregate nature of the way a vehicle is represented in such models. We assumed that the vehicles have instantaneous acceleration and deceleration characteristics, i.e. the vehicles start or stop instantaneously from their current state when encountered by bottlenecks like signalized intersections or stop lines etc.

2.2.3 Assumptions for Roadway Geometry

Some assumptions were made in this model in order to facilitate a preliminary and approximate analysis of the scenarios and also for demonstrating the usability and the applicability of the model to simulate the traffic dynamics in the presence of emergency vehicles. Cells for the networks considered in this model are assumed to be identical, characterized by the same capacity and the density.

The flow-density relationship assumed in this model is a piecewise linear relation as shown in Figure 2.1 below. The basic relation of traffic flow, which states that the flow is the product of speed and density, still holds in this case. This figure assumes that the relationship is linear over the entire uncongested regime and that traffic at all states within this range has a space-mean speed equal to the free flow speed, which is indicated in Figure 2.2. The congested regime, which is to the right of the uncongested regime, also has a linear shape with a slope equal to the backward wave speed and traffic speed in this regime is a decreasing curve as shown in the speed-flow relationship in Figure 2.2. The speed-density relationship is shown in Figure 2.3. These assumed as well as derived relationships can be easily extended to other general forms.

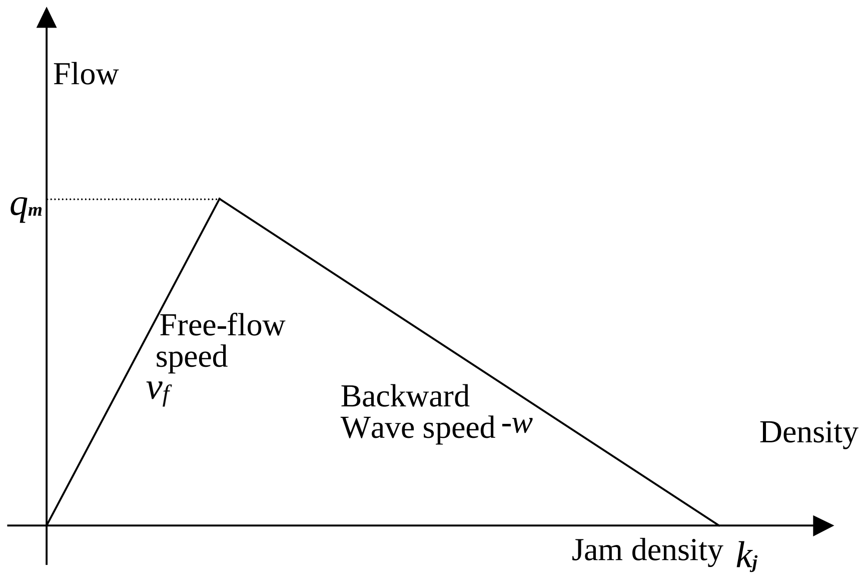


Figure 2.1 Assumed Flow-Density Relationship

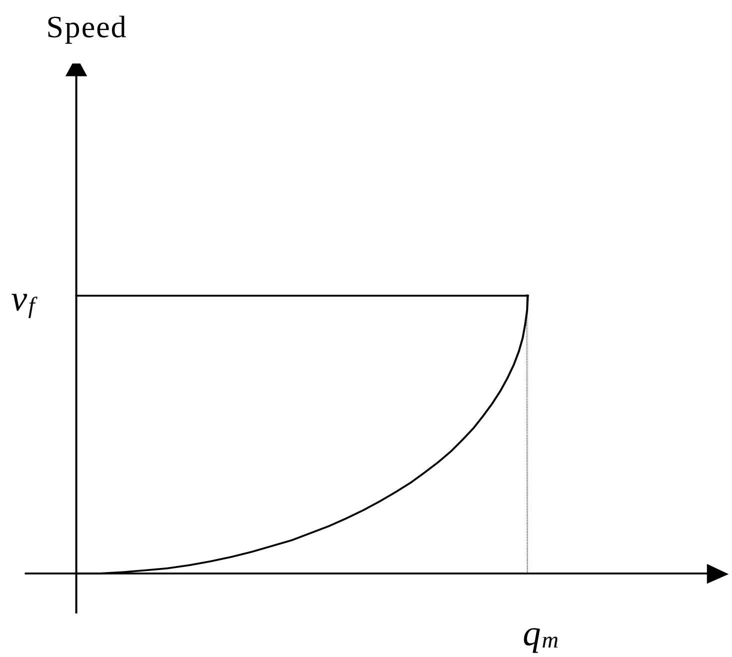


Figure 2.2 Derived Speed-Flow Relationship

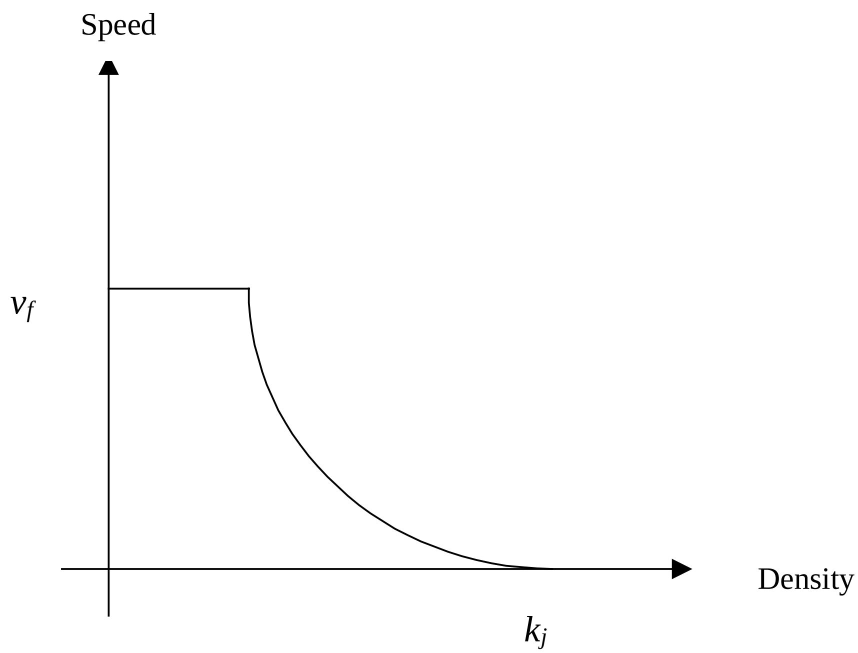


Figure 2.3 Derived Speed-Density Relationship

2.2.4 Assumptions for Traffic Demand Patterns

In this study, we adopt the random arrival process for demand generation, whose headways are exponentially distributed. In other words, this means that the arrivals are simulated as Poisson arrivals. The headway equation used is as follows:

$$h(i) = -h_o * \log(1 - r(i)) \quad (2.11)$$

Where $h(i)$ = headway for one particular vehicle i;

h_o = constant headway for a deterministic arrival, which is the inverse of the volume in seconds; and

$r(i)$ = a real-valued random number uniformly distributed between 0 and 1.

There are a couple of different methods to simulate Poisson distributed random arrivals, at the tick of each second. One method is to take the mean demand volume, convert it to per second volume. This average demand is taken as the parameter for the Poisson distribution. Then using the exponential equation similar to the above headway equation, Poisson distributed random volumes are generated for each simulation second. This process would generate real numbers (or even fractions) for the number of vehicles generated for each simulation second. But this process would generate demand every second and also fractions, which mean that fractions of vehicles are being generated. This process doesn't seem to be an intuitive generation process as the headways between vehicles may not be truly exponential, which is what a true Poisson arrival process should reflect.

Another method of generating Poisson distributed demand is to generate vehicles in such a way that the headway between them is truly exponential. The PDF for this distribution has the following equation, where y (h) is the probability of the occurrence of a headway h.

$$y(h) = (1/h_o) * \exp(-h/h_o) \tag{2.12}$$

From this equation, the cumulative PDF is generated, by integrating the equation. Then using the inverse transformation method, the headway equation (Equation 2.11) is obtained. For different values of r(i), which is uniformly distributed, headway values are generated.

For example, assuming the demand is 900 vph and the demand is loaded for a time period of 3600 seconds, this means the mean headway is 4 seconds and on average 900 vehicles are generated for that particular simulation. So for each vehicle, headway is generated according to the exponential headway equation stated above, with the mean headway of 4 seconds as the parameter for the distribution. Then the arrival times for each vehicle are enumerated from the start of the simulation clock, in seconds. Then, for each second, the demand would be the number of vehicles that are generated in that particular second. This process generates whole numbers for the number of vehicles and also the headway between two consecutive vehicles will be exponentially distributed. It may also happen that there might be more than one vehicle that is generated in one particular simulation second. This case is not a problem, because in the cell transmission model, it doesn't matter where within the simulation second vehicles are generated and transmitted as well as where inside a particular cell is a particular vehicle during one second. This process makes sure that the demand pattern is Poisson in nature and the headways are exponentially distributed.

2.2.5 Delay Calculation Methodology

The most common measures that are employed to evaluate the effect of the implementation of a particular TSM strategy on the transportation system are the overall network delay, the individual link delays, the stopped delays and the queue lengths. In this study, only the individual link delays, their mean values, maximum values and the standard deviation of delays are considered as measures to determine the extent of effect of providing signal preemption to EVs on the rest of the traffic. The link delay calculation methodology adopted in this study is based on the input-output diagram. The calculation methodology is described as follows.

Assuming a particular link has 5 cells, where the vehicles enter the link at point A into cell no. 1 and leave the link at point B from cell no. 5. Hence the free flow travel time (T_{ff}) for each vehicle to traverse the link is 5 seconds. This fictitious link is as shown in Figure 2.2.

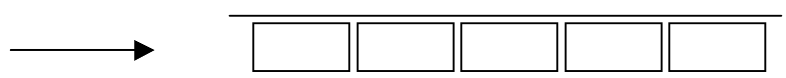


Figure 2.2 Link for the Delay Computation

The cumulative flows of vehicles are plotted at points A and B, as shown in Figure 2.3. It is important to note that the simulation has to be continued until all the vehicles that enter the link at point A leave the link at point B.

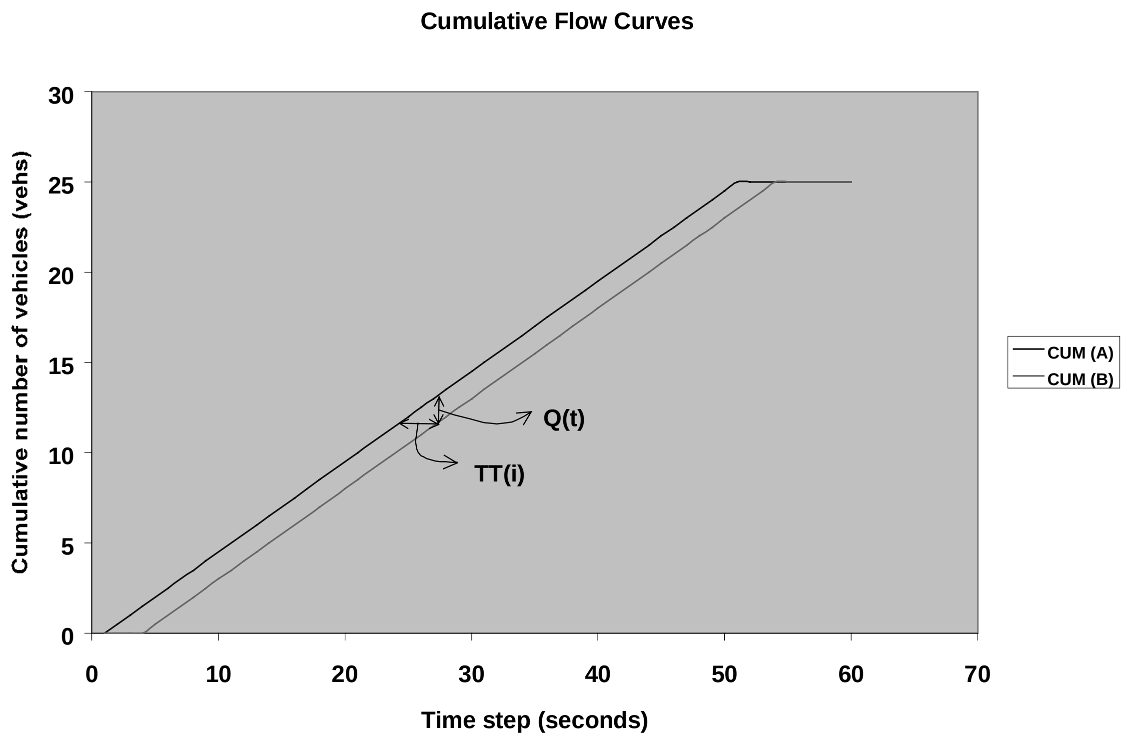


Figure 2.3 Cumulative Flow Curves

From the figure, TT_i is the time taken by the i^{th} vehicle to traverse the link. And Q(t) is the number of vehicles on the link at time step t. Hence the summation of TT_i for all the vehicles gives the total travel time for all the vehicles to traverse the link. If the total number of vehicles that entered the link and then left the link was N, then the average travel time (T_{av}) and the average delay (d_{av}) are given by the following equations.

$$T_{av} = (\sum_{i}^{N} TT_i) / N \qquad (2.13)$$

$$d_{av} = T_{av} - T_{ff} \qquad (2.14)$$

Thus the mean or average delay per link can be computed. Also the maximum delay and the standard deviation of delay can be computed from the individual travel times of the vehicles.

The delays can also be calculated in another way, which is unique to the cell transmission model. Since, under very light traffic conditions, all the vehicles in one particular cell move to the next cell in a single time step, there is no delay under such conditions. But if there is queuing due to bottleneck conditions downstream, then only a fraction of the vehicles move to the next cell in the next time step. This means the vehicles that have been left behind in the previous cell experience a delay of one second, thus giving a total delay of as many vehicle seconds as the number of vehicles left behind in that time step. If this delay is summed over all the cells in the link and also over all the time steps during the simulation, we get the total vehicle delay for all the vehicles for that link. This delay can be calculated from the following formula.

$$d_i(t) = n_i(t-1) - z_i(t) \tag{2.15}$$

$$d_{av} = \sum_t \sum_i d_i(t) \tag{2.16}$$

where d_i (t) is the vehicle delay for cell i at the end of time step t, d_{av} is the total vehicle delay for all the vehicle during the simulation. The rest of the terms mean the same as described earlier in this chapter. These two methodologies for calculating the delays are equivalent and give the same values. In this study the cumulative curves methodology has been adopted to determine the link delays.

2.3 Examples of Model Behavior

The cell transmission model is capable of capturing physical queues. In order to understand the model behavior, a couple of examples were created, which can be used for model verification. The results obtained from the model can be compared with standard analytical techniques to assess the accuracy of the model.

2.3.1 Single Isolated Intersection

In this case, a single isolated and signalized intersection of two one-way, single lane streets is modeled. Both the streets are considered normal arterials with an uninterrupted capacity of 1800 veh/hr and a jam density of 180 veh/km.

The traffic stream characteristics of this isolated intersection are the free flow speed is **60 kmph**, the maximum flow rate or the capacity is **1800 vph** (0.5 vehicles per time step considering one second time steps), the jam density is **180 vpkm** (3 vehicles per cell). The backward wave speed W is 12 kmph, thus giving the value of **α as 0.2**. The simulation time step is taken as **1 second** and from the relationship between free flow speed, time step and cell length, the cell length is obtained as approximately **17 meters**. The isolated intersection has equal demand from both the approaches. The demand can be either deterministic or random, following the Poisson arrival process described earlier. The signal system is a two phase, fixed cycle signal system. Delay curves were generated for these cases, for volume levels from 100 veh/hr to 900 veh/hr, which is the capacity of the signalized arterial.

For comparison purposes, delay curves for the same volume levels were also generated using the standard Highway Capacity Manual 2000 equations. HCM gives the delay equations for an isolated intersection for each approach based on the effective green time, the effective red time and the cycle lengths for any volume level for each approach. The equations are as follows.

$$w1 = \frac{r^2}{2 * C * (1 - q / q_{\max})} \tag{2.17}$$

$$w2 = \frac{0.5 * \rho^2}{(1 - \rho) * q / 3600} \tag{2.18}$$

$$w3 = -0.65 * \left(\frac{C}{(q / 3600)^2} \right)^{0.33} * \rho^{(2 + 2 * g / C)} \tag{2.19}$$

$$w = w1 + w2 + w3 \tag{2.20}$$

where w1 is the delay component taking into account the deterministic delay, w2 is the component, which takes into effect the stochastic delay, and w3 is the component, which takes into effect the random delay. w is the total delay. The other terms are as follows.

r = effective red time in seconds

g = effective green time in seconds

q = volume level in vph

q_{max} = Maximum flow rate or the capacity in vph

$$\rho = \frac{(q / q_{\max})}{(g / C)}$$

2.3.1.1 Delay Curves for Deterministic Arrivals

The demand on both the approaches is equal and deterministic, i.e. the vehicles arrive at a constant headway from both the approaches. Figure 2.4 shows the comparison of the delay curves from the simulation with that from the HCM equations.

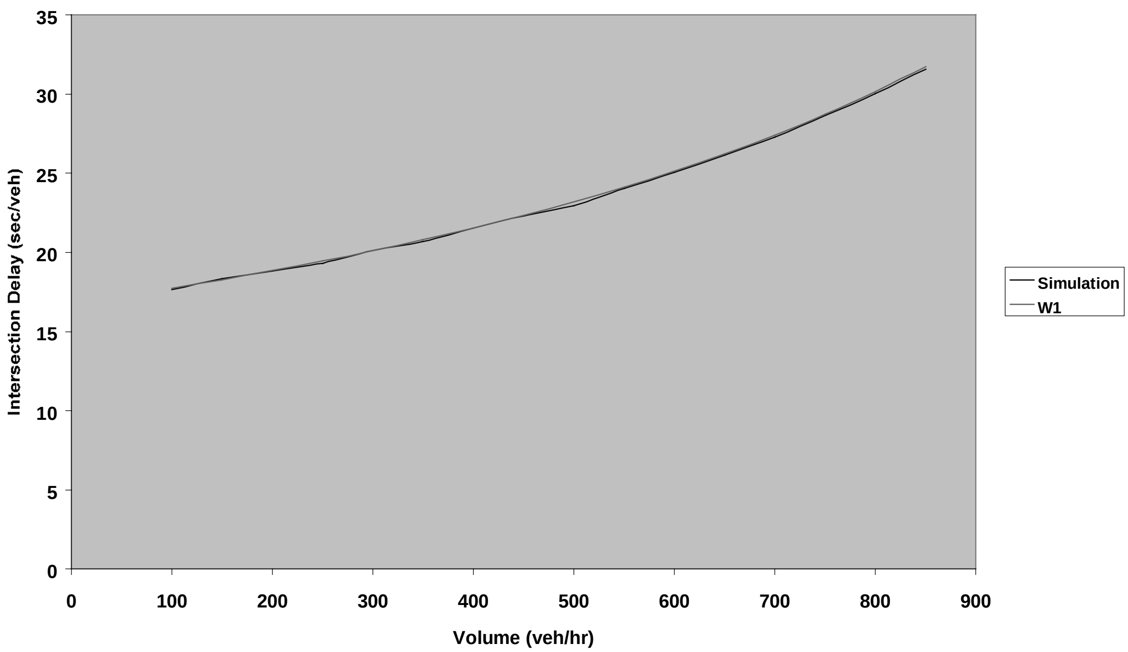


Figure 2.4 Delay Curves for Deterministic Arrivals

The delay curves from the simulation and from the deterministic portion of the HCM equations match very well, as can be seen from Figure 2.4, over the entire unsaturated range. Actually the HCM delay curve values depend on the lost time that is assumed in the calculation of the effective green times for each approach and also the simulation delay curve depends on the saturation flow during the amber phase of the signal. In this example, a lost time of 1 second was assumed corresponding to a amber phase saturation flow of 50% of the full saturation flow during green phase. From these curves, it can be seen that the macroscopic model produces an almost exact delay curve as the widely accepted HCM delay curve.

2.3.1.2 Delay Curves for Poisson Arrivals

In this case, the demand is equal from both the directions but the arrivals are not deterministic. The arrivals are randomly distributed according to the Poisson distribution. For each volume level, the simulation is repeated 10 times and the mean value for delay is taken for each one of them. This is done so that the randomness in the delay values are eliminated and a smooth curve is obtained. Figure 2.5 shows the comparison of the delay curves from the simulation with that from the HCM equations.

From the delay curves as shown in Figure 2.5, it can be seen that the model produces results which match very well with the standard HCM results, even for random arrival processes. Both the delay curves follow almost exactly the same trend over the entire volume range up to capacity. Due to the random arrival process, one might expect the delay curve from the simulation to show a lot of variance. But as the simulation has been repeated 10 times, such a variation has been smoothened out and a smooth curve has been obtained.

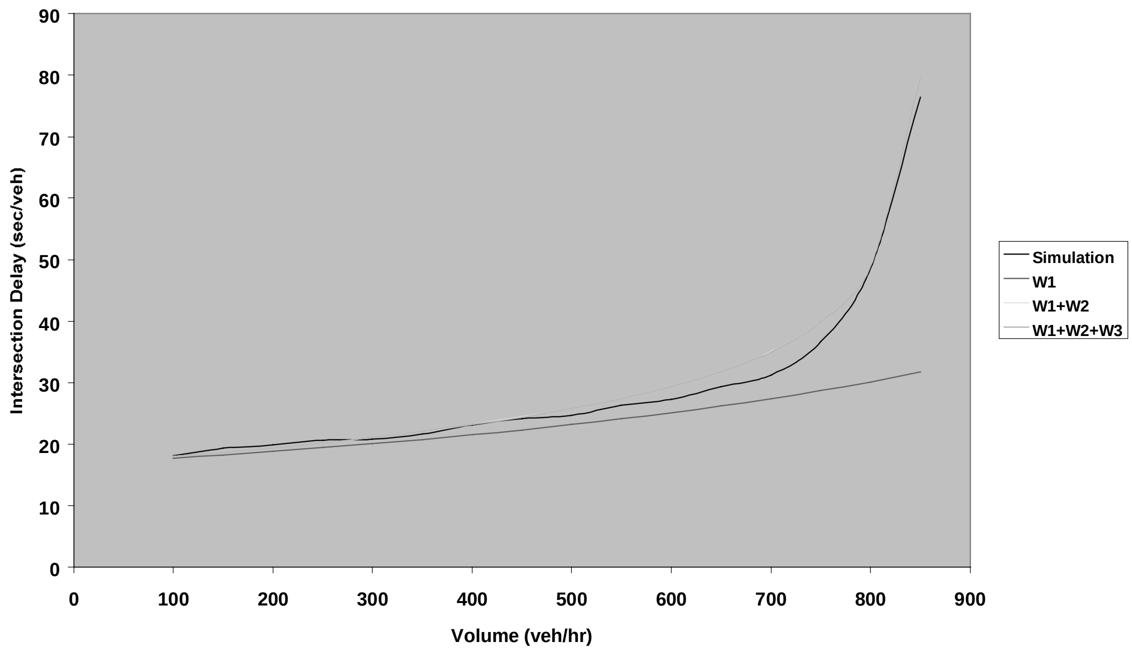


Figure 2.5 Delay Curves for Poisson Arrivals

2.3.1.3 Sensitivity of the Curves to the Number of Repetitions

The demand generated for both approaches follows Poisson distribution. As a result, there is noise in the delay curves. In order to reduce the variability in delay results, the simulation run at each demand level is repeated a number of times and the mean value is taken. Figure 2.6 shows the effect of number of repetitions on the delay curves and its comparison to the HCM delay curve. It can be seen that as the number of repetitions increase, the variation in the curve is reduced and a smoother curve is obtained. But it can be observed that even with only one simulation run, the variance is not substantial and the general trend of the curve is preserved. With 5 repetitions itself a much smoother curve can be produced.

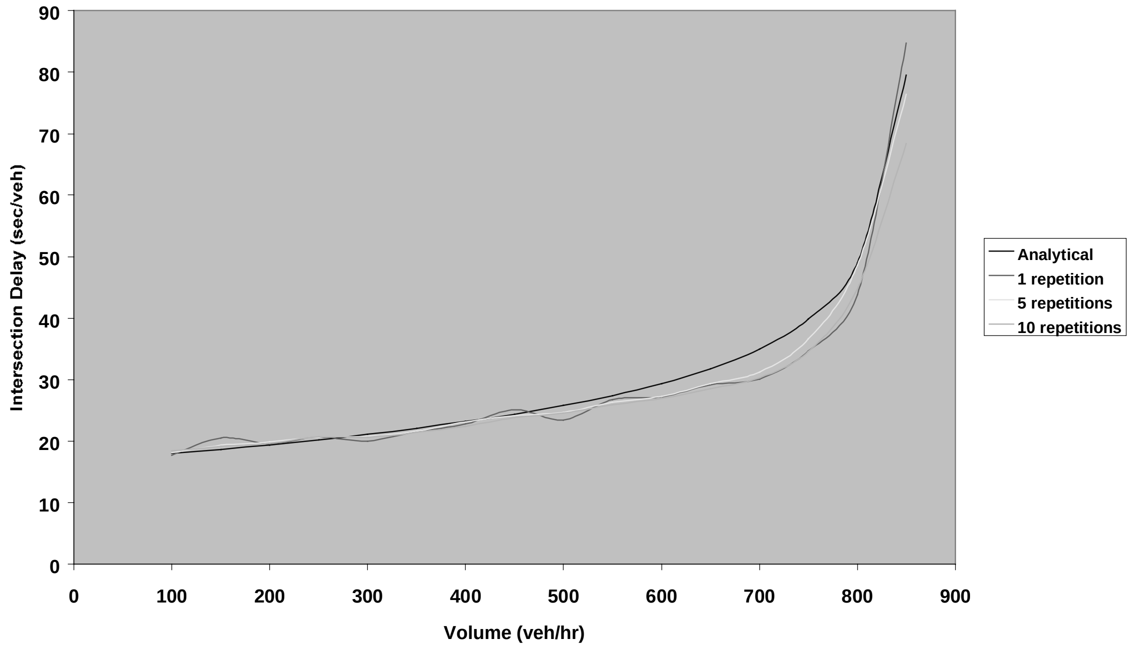


Figure 2.6 Sensitivity of the Delay Curves to the Number of Repetitions

2.3.2 Multiple Intersections

In this case, a main arterial with three side streets is modeled. All the streets in this scenario are also one-way single lane streets. All the traffic stream characteristics are the same as that described for the isolated intersection. The arterial is shown in Figure 2.7.

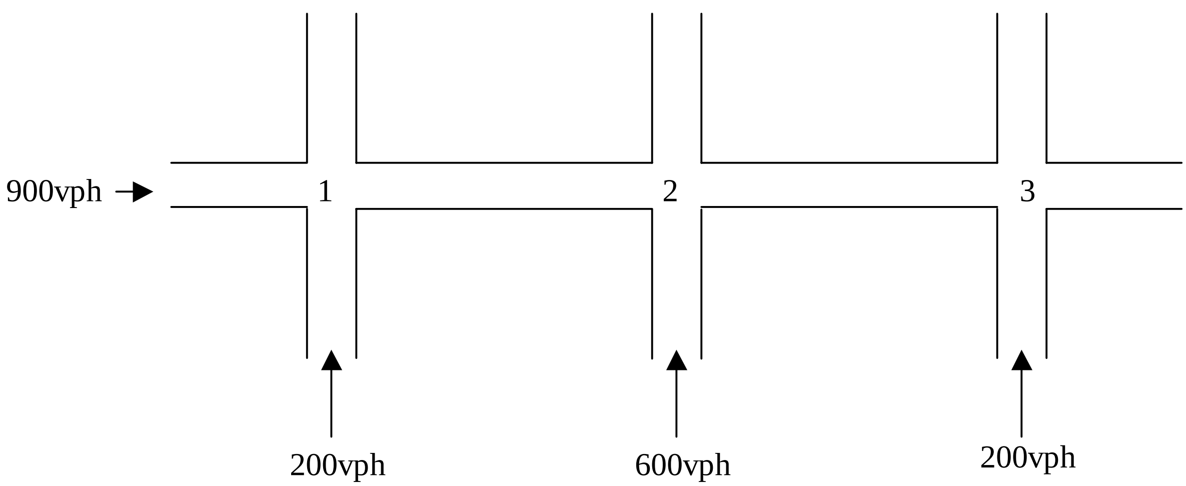


Figure 2.7 Roadway Geometry for the Multiple Intersections Arterial

2.3.2.1 Queue Buildup, Propagation and Dissipation

The first and the third intersection are minor intersections, which means that the volume to capacity ratio on the side streets at these intersections is well below 1. The second intersection is a major intersection, where the volume on the side street is comparable to the main arterial volume. All the arrivals follow Poisson distribution. The signals at the three intersections are coordinated with respect to the offsets between the intersections. Figure 2.8 shows the queue build-up, queue propagation as well as dissipation in the upstream direction on the main arterial due to the flow interruption at each of the signalized intersection.

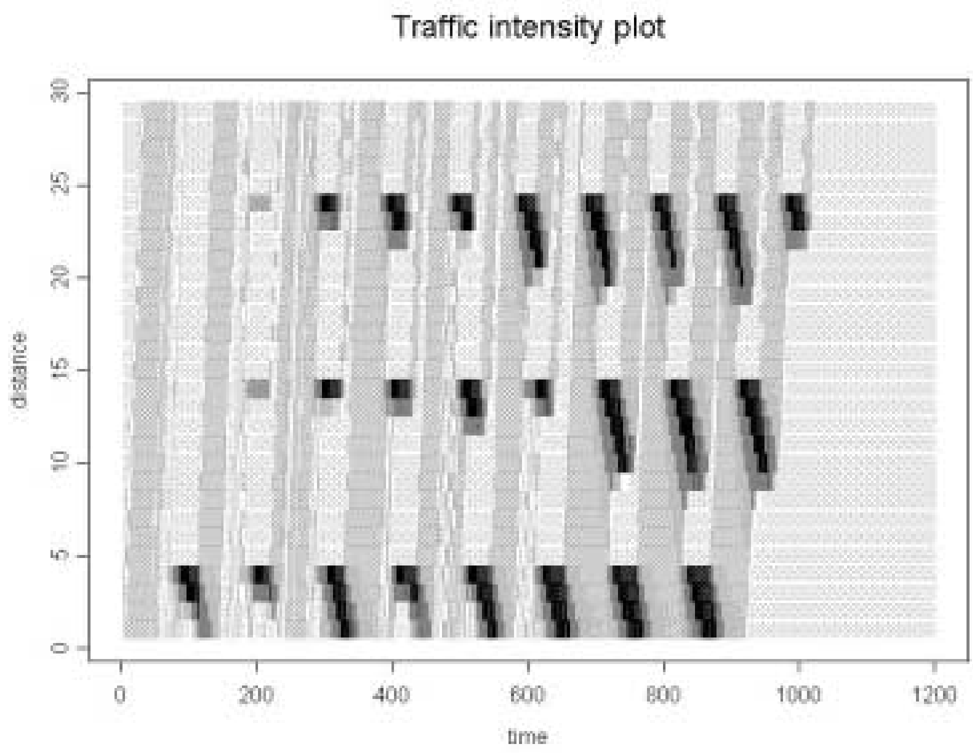


Figure 2.8 Traffic Intensity Plot for the Multiple Intersections Arterial

The areas with darker intensity represent those cells with a high density of vehicles whereas the areas with lighter intensity represent those cells with low density. As there are three signals on the main arterial, it can be seen that there is queuing at these three intersections. The build-up of queue as well as the dissipation of the queue in the upstream direction can be clearly seen from the interfaces between the darker and the lighter areas in the figure. It can also be observed that because the signals have not been designed to perform optimally, there are some periods of time where the entire green phase has not been used for vehicles to pass through. This plot demonstrates that the macroscopic model is capable of capturing one of the important aspects of traffic dynamics, which is queuing.

2.3.3 Arrival Process

As described in Section 2.2.4, demand can be generated either at a constant (deterministic) headway or at a random headway based on the Poisson distribution. But it is to be noted that this demand, either deterministic or random, is introduced only into the first cell at each time step. After that, the traffic progresses into the next cell based on the traffic dynamic equations described earlier. This means that the arrivals that approach the traffic signals may not follow the same distribution that was used for generating the arrivals to the network. But the analytical HCM delay equations described earlier are based on the assumption that the flow that approaches the intersection is random in nature, following the Poisson distribution. This may partially explain the discrepancy between our results and the results from the HCM delay equation. This aspect of the model affects only the queue lengths and the spatial distribution of queues, and only has a minor impact on the individual approach delays and also the overall intersection delays. Hence in this study, we have not concerned ourselves with this aspect of the model, as our objective is to determine the impacts based on overall delay values.

2.3.4 Modeling Temporal Over-capacitated Conditions

The three basic equations of the macroscopic model described earlier imply that the flow conditions are under saturated at all the time i.e., the input volume doesn’t exceed capacity at any time. If the demand exceeds capacity, then there would be no queue dissipation at the intersections and the network would never get cleared of all the vehicles at the end of the simulation time and hence correct delay estimates would not be obtained. Hence it is not possible to load a demand, which is over-capacity for the entire loading period. This would lead to the violation of the conservation of flow at the boundaries.

But if the demand is over capacity for a certain period of time during the simulation, then it is possible to model this situation by temporarily suppressing the capacity constraint in the model equations, in other words temporarily the capacity of all the cells is put to infinity.

2.3.5 Comparison with VISSIM (a microscopic model)

VISSIM is a microscopic traffic simulation model, which was developed by PTV AG, a German-based company. This model has been primarily aimed at analyzing urban arterials and transit operations. For the purpose of comparison of the results obtained from the macroscopic model, a delay curve was generated for a single signalized intersection, which is the same as in Section 2.3.1. Figure 2.9 shows the two curves. These curves show the comparison of the delay curves generated from the macroscopic cell transmission model, from the microscopic VISSIM model and the analytical HCM equations. This shows that there is a very good comparison between the macroscopic model and the HCM equations. The VISSIM model also generates a curve, which follows the trend of the HCM curve but it underestimates the delay, as compared to the HCM values. And at and near capacity, the microscopic model underestimates the delay values. But the relative difference between the delays from each of the three curves is very small compared to the delay values themselves.

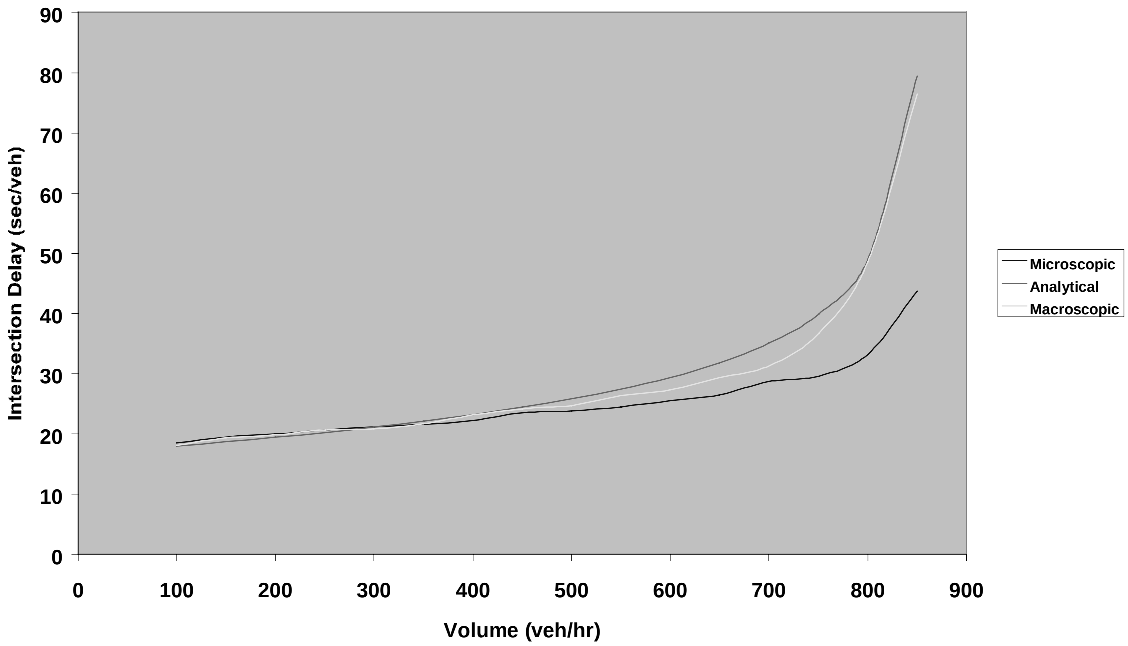


Figure 2.9 Comparison of Delay Curves

2.4 Modeling Emergency Vehicles

Emergency/special vehicles (EVs) are the vehicles, which are given the highest priority on a road. These are vehicles, which are used to provide emergency services to the public. Police cars, ambulances, fire engines etc., are some examples of emergency vehicles. It is required by the traffic law that when these vehicles encounter traffic, the other vehicles are supposed to pull over to the side of the roadway and give way to these emergency vehicles. And when they encounter traffic signals, they are allowed to pass through the intersection without stopping. For this purpose, the cross street traffic is given a red signal by detecting the arrival of the emergency vehicle and also giving green to the street on which the emergency vehicle is traveling. But if the traffic on the cross street is high, then this would mean interrupting a signal cycle to give extra green to the main street and thereby increase delays to the cross street. Also, on the main street, due to the pull over effect there is some additional delay incurred to the main street traffic also. The pull over effect of general traffic in response to the presence of an emergency vehicle is not captured in existing microscopic simulation models. But using the macroscopic model, the effect can be conveniently treated with a capacity reduction factor, which will be described in detail below.

2.4.1 Traffic Dynamics of Emergency Vehicles

In the microscopic traffic flow models vehicles are treated as single individual entities. Vehicle dynamics, such as speed, acceleration and deceleration, and lateral movements, are captured in detail by car following theory and gap acceptance functions. When emergency vehicles are present in the traffic stream, other vehicles tend to yield to them in various ways. There is no theory describing this particular maneuver, and is not currently available in any of the existing microscopic traffic flow models. To model accurately how queues would spread in the presence of emergency vehicles is a non-trivial task, involving behavior of individual drivers that we know little about.

Instead of developing very detailed approaches to capturing this behavior, this problem is dealt with in a macroscopic way. The behavior of traffic in the presence of an emergency vehicle is handled implicitly in the macroscopic model. One should recognize that in essence, the passage of an emergency vehicle corresponds to a temporary reduction in roadway capacity when other vehicles yield to the emergency vehicle. Based on this observation, two assumptions for the movement of the emergency vehicle were made: 1) the emergency vehicle travels at a speed independent of the prevailing traffic stream; and 2) the emergency vehicle behaves like a moving bottleneck which incurs a capacity reduction along its path of travel. The first assumption can be relaxed to include the slow-down of the emergency vehicle in the presence of a high volume of traffic locally. In reality, such temporary slow-down may occur from time to time. However, one would expect that the drivers of emergency vehicles would constantly adjust their speeds if they were delayed at a certain location of the network. It is reasonable to assume that, on average, the speed of an emergency vehicle is the free flow speed. For the second assumption, since the actual level of capacity reduction corresponding to the passage of the emergency vehicle is not known, we use an open parameter described below, which can be calibrated once more data become available through repeated experiments. The parameter would enable us to determine if capacity reduction resulting from emergency vehicles is a dominant factor to the overall delay using a sensitivity analysis.

The fact that the presence of emergency vehicles would temporarily reduce the capacity is captured by the following constraint to the outflow of a cell, *i:*

$$z_i(t) \leq \delta(t) Q_i(t) \tag{2.21}$$

where $\delta(t) \in [0,1]$. $\delta(t)$ is a decision variable, which captures the responsiveness of the traffic stream in the presence of an emergency vehicle. A very responsive traffic stream could be modeled by a full capacity reduction in which we choose $\delta = 0$, indicating that vehicles near the emergency vehicle come to a full stop when they yield to the emergency vehicle. Partial responsiveness, meaning that some drivers are cooperative whereas others are not, is associated with a partial capacity reduction in which the value of δ is chosen to be less than 1, depending on the level of responsiveness. The value of δ is chosen to be close to 0 if the traffic stream is more responsive, and close to 1 if the traffic stream is less responsive.

2.4.2 Multiple Cell Capacity Reduction

The underlying assumption for the previous formulation is that the influence area of the emergency vehicle is only over a single cell at each time step. But the actual situation on the road is that the effect of an approaching EV may span across a much longer length of the roadway segment ahead of the EV. Hence the capacity conditions of the road are affected over longer lengths. In order to evaluate the effect of this capacity reduction parameter over a longer length of the road segment, it can be extended to reduce the capacity over more cells, i.e. 2 or more cells, and the effect examined. This is done by introducing a window for the influence area and assuming a value of 0 for $\delta(t)$, for all the cells in this area at each time step. But the issue of how many cells the capacity is affected is a matter of further research. Also due to the acceleration and deceleration characteristics of the vehicles, the influence zone might even exist upstream of the EV, i.e. behind the EV after it has passed a certain point on the road. But for simplicity sake, in this model, the influence area is assumed to be on either side of the EV, i.e. both in front and at the back, and is equal in length. The following equation describes the multiple cell capacity reduction factors.

$$z_j(t) \leq \delta(t) * Q_j(t) \qquad \delta(t) \in [0,1] \qquad (2.22)$$

For j = i-n/2, i-(n/2-1)…… i-1, i, i+1…….i+(n/2+1), i+n/2

where i is the cell in which the EV is present in the time step t, and n is the number of cells effected i.e. influence zone.

2.5 Limitations of the Model

The reason for employing a macroscopic traffic model for this study is manifold. The logic of the model is a proven and widely published material and is completely transparent for the purposes of cross checking. It is based on a set of state-space equations, which can be formulated as an analytical LP problem. As it was shown in the previous section, it is very easy to simulate the pullover effect of the general traffic in the presence of an EV by introducing a capacity reduction factor. And also larger areas of influence of the EVs can be analyzed using the multiple cell capacity reduction concept. And finally by developing our own model gives the flexibility of obtaining the desired outputs from the model and restricts the output range to the analysis domain.

But there are certain limitations to the model as it has been employed in this study to be considered as a complete traffic simulation model. It is assumed that there are no turning movements, lane changes, lane merges, and intermediate entrances and exits and also the acceleration and deceleration characteristics of the vehicles have been ignored. But it is very easy to extend the model to include all these aspects of traffic behavior. The model is not intended to be a detailed simulation of the vehicle dynamics but is intended to be an evaluation tool for analyzing signal preemption for EVs.

3 SIGNAL PREEMPTION

3.1 Introduction

Delays to transit vehicles at signalized intersections comprise about 20% of the average bus trip time *(1)*. Unlike automobiles, transit vehicles cannot be platooned through controlled intersections because of the large variance in the distribution of travel time between different runs. This variation arises due to the fact that there is a large variation in the dwell time of the buses at the bus stops for loading and unloading passengers, which is a random variable. For emergency and public utility service vehicles like fire engines, ambulances, police cars etc., there would be major, in some cases fatal, delays at the intersections due to queuing of vehicles at signalized intersections.

Hence preemption strategies are designed to provide priority to transit/EVs over the general traffic for urban travel. Preemption is essentially a preferential treatment device for transit/EVs to ensure continuous green phases at successive signalized intersections on urban arterials, thereby reducing the travel time and improving overall speed. The technology includes instrumented vehicles, transmitters, loop detectors and a real time control system for estimating the arrival times at the intersection and triggering the signal preemption.

The detector technology detects the presence of a transit/EV at a pre-specified distance from the stop line at the intersection and transmits the message to the control system, which then determines the best course of action to be implemented so that the signal is green when the transit/EV arrives at the intersection and passes through without having to stop there.

There are two variations of responses that are implemented when a transit/EV is detected. One method is to provide additional green to the approach having the transit/EV, irrespective of the extent of disruption that might be caused to the overall intersection traffic, including the cross streets. This is done at intersections where the cross street traffic demand levels are much lower than the main street demand levels. The other method is to evaluate the impact of providing extra green to the approach having the transit/EV, using certain measures of effectiveness, and then taking a decision based on the impact level. This is done if the cross street traffic has a demand, which is comparable to the main arterial demand levels. Usually the response, where the disruption is not taken into account before providing extra green, is called the signal preemption. Signal preemption is generally given to EVs, which have to be given extra green, as they cannot be stopped. The other type of response, where extra green is given based on some impact measures, is called signal priority. Signal priority is generally applied to transit vehicles, which need not necessarily receive extra green. Only those transit vehicles, which meet a certain criteria, are given extra green.

3.2 Literature Review

Over the past three decades, the study of signal priority treatment for transit has received lots of attention. In the early days, the focus of the study was primarily on providing preemption to vehicles such as ambulances, police cars, fire engines etc. In later years, the concept was extended to providing priority to buses in order to maximize the total number of people, instead of vehicles, to pass an intersection. The concepts of priority treatment and preemption treatment are somewhat different. In priority treatment, the decision of whether to provide priority to transit depends on the trade-off between the bus passenger delay and the vehicle driver delay. Previous studies on signal preemption strategies can be broadly divided into three categories: experimental or field studies, modeling or simulation studies and analytical models.

Wilbur Smith and Associates and the Bureau of Traffic Research, Los Angeles Department of Traffic *(5)* conducted the earliest bus preemption experiment reported in 1967. This was a field study that first indicated the significant effect of signal preemption on reduction of bus travel times. An experiment was undertaken in 1972 at Leicester to study the preemption effects on bus delay reductions by introducing selective vehicle detection equipment *(6)*. This experiment showed that this equipment could be very useful in selective detection of transit vehicles, reducing bus delays, and improving schedule adherence. A field study was conducted in 1977 on the Northwest Seventh Avenue in Miami to study the effect of different priority treatments on traffic in general *(7)*. This study demonstrated that priority could be given with little or no effect on the general traffic stream and indeed positive benefits can accrue to automobile traffic as well.

In 1983, a study on the effects of implementing a bus preemption strategy on an arterial corridor in Richmond, Virginia was conducted using the Urban Traffic Control System/Bus Priority System microscopic traffic simulation model *(8)*. A benefit-cost analysis of the strategies used found that preemption was not justified to the network under consideration. A dynamic traffic control software package called SCATS (Sydney Coordinated Adaptive Traffic System) was implemented in the Melbourne metropolitan area to study various preemption strategies *(9)*. The study concluded that there were about 10% reduction in transit travel times and also significant improvements for other road users, both along and across the transit routes.

A real-time signal control procedure that considers transit interference and priority was proposed and tested using a simulated application to a critical intersection in Toronto’s Queen Street corridor using real time data *(10)*. This was a rule-based procedure, which generated a number of short-term alternative real-time phase sequences for various levels of transit priority, based on a number of decision rules. This test indicated the potential reduction in average delay compared to fixed time operations. NETSIM and TRANSYT-7F were used to study preemption effects on the Washtenaw Avenue corridor in Ann Arbor, Michigan in 1996 *(11)*. This study indicated that preemption disrupts traffic progression and thus increases the overall traffic delay. Real time traffic signal optimization software called SPPORT (Signal Priority Procedure for Optimization in Real Time) was developed in 1998 *(12)*. It was a rule-based priority model, which generated signal timings to minimize a certain objective function in which transit vehicles were weighted, as deemed appropriate in relation to other traffic.

Some of the analytical models that were developed over the years to study and evaluate priority effects included models by Jacobson and Sheffi *(13)*, Heydecker *(14)*, Khasnabis, Reddy and Chaudary *(15)*, Cisco and Khasnabis *(16)*, Sunkari *et al* (*17*), Chang *et al.* (*18*).

Literature on signal preemption for EVs, however, is very limited. Some work in this area has been done in Europe. In 1980, a demonstration was done in Northampton England where a priority system called EVADE was implemented for giving priority to fire engines *(19)*. This was shown to be a success when considered in the context of increasing the reliability of fire appliance attendances and has achieved a 10% reduction in journey time under certain operating conditions. Positive experiences also resulted from giving priority to fire engines on certain routes in Liverpool, England *(20)*. In 1984, a field study was done to examine the technical feasibility and anticipated improvements of signal program interventions in Winnenden, Germany *(21)*.

A recent study conducted by Bullock *et al.* (*22*) analyzed the impact of EV traffic signal preemption across three coordinated intersections on Route 7 (Leesburg Pike near Landsdowne), Virginia. Their study shows that the impact of signal preemption for the EVs on the general traffic is very small. In their studies, CORSIM, a microscopic traffic simulation model of network and freeway traffic operations, was modified to handle EVs. The simulator was interfaced with real-time controllers and detectors to collect real-time vehicle arrival and signal phasing data. The traffic dynamics associated with the presence of EVs, however, are not captured in the simulation model. As a consequence, EVs would join the queue when traffic is congested. It is not clear if the results are biased because of this unrealistic feature. At the present time, only a few release versions of commercially available traffic simulation models are documented with the capabilities for signal preemption analysis. Paramics, a microscopic traffic simulation model developed by Quadstone in England, claims that it has the feature that supports the analysis of bus priority measures. Another traffic flow model, VISSIM, developed in Germany, is also capable of handling priority treatments. The methodology of using VISSIM to assess the impact of transit signal priority is described in Dale (*23*). Neither of these two models has the feature to handle the queue-spread effect when EVs are present. Moreover, microscopic models usually require very detailed input data, which are not easy to acquire in most cases.

3.3 Preemption Logic and Strategies

Signal priority/preemption is a method of providing preferential treatment to transit/EVs at traffic signals by altering the signal timing plans in a manner that would benefit these vehicles. In general, signal priority treatments have been broadly categorized into passive priority and active priority treatments.

3.3.1 Passive Priority

Passive priority is achieved by biasing signal timings in favor of transit vehicles on certain routes, taking into account the general operating characteristics of transit vehicles and average traffic conditions on these routes. In passive priority, predetermined signal timing plans are used to provide benefits to the transit operations. But this treatment doesn't necessarily require the presence of a transit vehicle to be active. This form of priority is usually based on historical measurements of traffic flows and observations of the arrivals of the transit vehicles and the signals are preprogrammed to accommodate these vehicles, regardless of whether the transit vehicle arrives in that particular cycle or not in which the priority is given. Since these methods are based on average conditions, a green phase is granted to an approach even without the transit vehicle being present in that cycle. This leads to an increase in the vehicle delay for the general traffic. But these passive priority treatments are seen as low cost methods aimed at improving the transit operations and these methods work well where transit vehicles operate on exclusive right of way like bus lanes. Some forms of passive priority treatments are as follows.

- Adjustment of cycle lengths

  Reducing cycle lengths can provide benefits to transit vehicles by reducing the delay.

- Splitting phases

  Splitting the priority phase movement into multiple phases and repeating it within a cycle can reduce transit delays without necessarily reducing the cycle lengths.

- Green time bias

  Providing for longer green time phases to the bus streets will generally reduce the congestion on the bus-street thereby reducing transit delays.

- Phasing design biased towards transit

  Inclusion of special phases to assist transit vehicles will significantly reduce delays.

- Area-wide timing plans

  Area-wide timing plans providing priority treatments to transit vehicles through preferential progression, which can be accomplished by designing the signal offsets in a coordinated signal system using bus travel times, will significantly reduce transit delays.

3.3.2 Active Priority

Passive priority techniques rely on the differences between the average behavior of the transit vehicles and other vehicular traffic. But the fact is that the transit vehicle movement is closely bound to the flow of other traffic. There are few routes where the buses operate on exclusive right-of-way. Usually they have to share the road with other traffic. Hence active priority is very essential. In active priority treatments, priority is given only when the transit vehicle is actually present and detected. Some techniques of providing active priority are as follows.

- Phase or green extension

  When a bus is approaching an intersection at the end of a normal green phase, the green phase is held for some more time beyond its normal setting to allow the bus to pass through without stopping. This extension is usually limited to a particular maximum value.

- Phase recall or phase early start or red truncation

  An early start priority is used when the bus arrives at the intersection during the last stage of a red phase. In such cases, priority is given by starting the green phase early and truncating all other non-bus phases. This is usually constrained by a minimum green time for the phase that is to be prematurely terminated.

- Phase skipping or suppression

  To facilitate the provision of bus priority phase, one or more non-priority phases with low demand may be omitted from the normal phase sequence.

- Window stretching

  This is priority treatment that combines both green extension and red truncation at the same time. This facilitates the transfer of time between early start and extension.

- Special phase or Red interruption

  When the bus arrives in the early part of a red phase, a short green phase is injected into the normal phase sequence while all other phases are stopped for this period.

- Compensation

  This is done to compensate for the time lost (skipped or cut) from the other non-bus phases in the next cycle to limit the adverse effects that priority has caused to the non-priority traffic.

Among the active priority treatments described above, the ones most commonly used are the green extension, red truncation and window stretching. A lot of times, priority is granted based on whether or not the transit vehicle deserves priority. The eligibility of a priority call is evaluated based on certain conditions before priority is granted.

Priority treatments are also categorized as unconditional and conditional treatments. Unconditional priority is the provision of priority each time a priority call is made, after all other vehicular and pedestrian safety-required intervals are satisfied. But this form of priority is disruptive to the general traffic, as the frequency of calls is high and also the signal co-ordination is disrupted very frequently. This is only used for EV preemption of signals. Conditional priority attempts to limit the undesirable effects caused by unconditional priority through selective consideration of various factors. These factors include schedule adherence, bus occupancy levels, cross-street queue lengths, current traffic conditions, time since last call, effect on coordination etc. If a transit vehicle gives a call for priority and also satisfies all the constraints for eligibility, then it is given priority. If it doesn't meet the eligibility criteria, then it has to follow the rest of the traffic through the intersection, as this treatment aims to improve the overall efficiency of the intersection.

3.4 Effect of Preemption on Cross Street Traffic

Some of the advantages of providing signal preemption are to reduce the transit delay at intersections, improve transit operations reliability in the form of schedule adherence and improve transit attractiveness to the public. Also the increased green time to the main street helps to partially reduce the delays to the general traffic on this approach.

But providing preemption has adverse effect on the cross street traffic which is faced with frequent signal cycle interruptions in the form of green time truncations. Especially if the traffic flows on the cross streets are high, or comparable to the main street traffic, then additional queues are built up and there are longer delays to the cross street traffic. If unconditional preemption is given, then it might adversely affect the entire intersection and not only the cross street traffic because if a transit vehicle with low occupancy is given preemption, then it increases the vehicle delay and also the person delay too.

Signal preemption also effects the traffic progression on a multiple intersection roadway by disrupting the signal coordination, especially if the transit vehicle arrivals are high on that corridor and frequent preemption calls are necessary. This can be avoided by providing selective signal preemption to the transit vehicles, which deserve to be given preemption, based on certain pre-specified criteria.

In the case of EVs, since unconditional preemption has to be provided, it certainly affects the cross street traffic every time. But the arrivals of EVs are not regular and also their frequency is very low, unless the area under consideration is near a hospital, a police station or a fire station. Hence, even though the arrival of EVs disrupts the signal settings and increases the delays to the cross street, the magnitude of delays are most of the times insignificant. Hence EV signal preemption always is beneficial to the intended traffic category and is not very much disruptive to the general traffic.

3.5 Data Needs for Preemption

The implementation of transit/EV signal preemption requires certain additional data to be collected in real time and to be input to the signal controller, for evaluating the system. If unconditional preemption is provided at a particular intersection, for example to emergency vehicles, then apart from the usual traffic data that is collected, only the detector information, in the form of presence or absence of the subject priority vehicle, is to be collected. It is not necessary to collect any other data, as the signal controller has to provide preemption every time the subject priority vehicle is detected.

For providing conditional preemption or priority, certain additional data is to be collected and supplied to the signal controller in real time. This is because every time a subject priority vehicle is detected, the signal controller has to decide whether the vehicle deserves to be given priority, based on certain pre-specified criteria. In this type of priority treatment, which is generally applied to transit operations, the subject vehicle is given priority if it is not affecting the entire intersection operations adversely and also if the total person delay is reduced. In order to make these decisions, the controller needs information on the state of the traffic on all the approaches to the intersection, such as the queue lengths and the delays. Also the controller needs information about the state of the transit operations, like the average occupancy of the transit vehicle, whether the transit vehicle is ahead or behind schedule etc. Based on these information and certain criteria, the signal controller decides whether priority can be given to the subject vehicle or not.

4 TEST SCENARIOS FOR EVS

4.1 Description of the Network

The test scenarios designed in this section are aimed at analyzing the impact of providing signal preemption to EVs on the rest of the traffic. The network consists of an arterial with three intersections as shown in Figure 4.1. Of the three intersections, two are minor ones, and the middle intersection a critical intersection. The main arterial is an eastbound, one-way, single lane road. All the side streets are also one-way, northbound, single-lane roads.

The cell length is determined by the product of the assumed free flow speed and the simulation time step, so that it takes a single time step to traverse a cell at free flow speed. For our simulation runs, the time step is taken as 1 second and the free flow speed is assumed to be 60 kmph. Hence, the cell length is 16.66 meters.

The main arterial is 2000 meters long, which is partitioned into 120 cells. All the three side streets are approximately 166 meters long on either side of the intersection. The two consecutive intersections are spaced 500 meters apart, represented by 30 cells.

The first cell on each roadway segment is a dummy cell with unlimited space that can hold vehicles that are generated but are unable to enter the network because of the capacity or space restraint. Hence the network actually consists of 119 cells on the main arterial going from west to east and 19 cells on each of the side streets going from south to north.

The detectors for EV detection are placed ten cells upstream from each intersection, which is about 166 meters from the stop line. That means that once the EV is detected, it requires ten seconds of time to clear the intersection, since it is assumed to be traveling at the free flow speed.

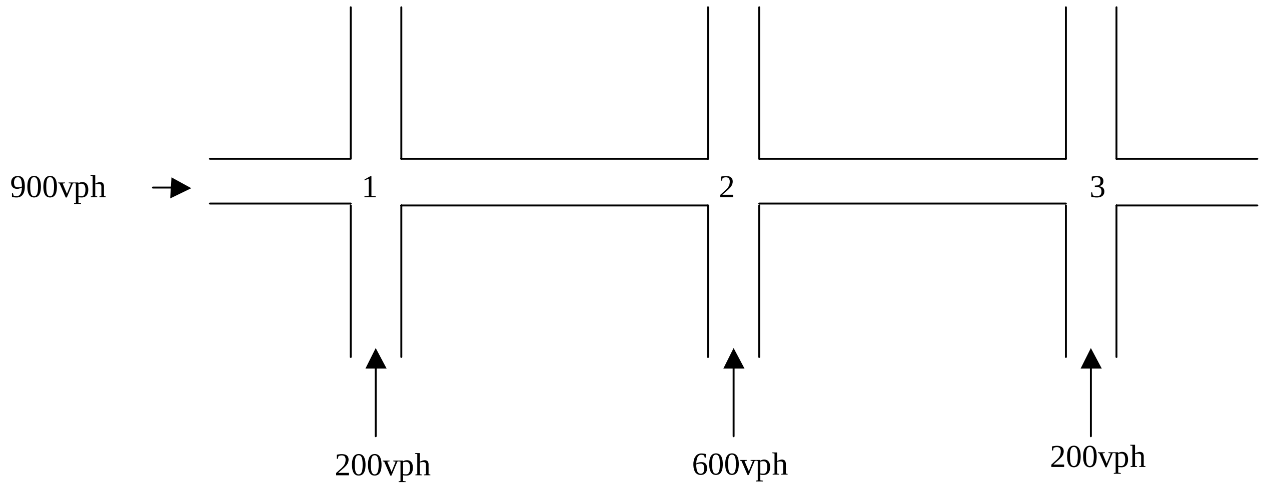


Figure 4.1 Network Profile

4.2 Traffic Stream Characteristics

The traffic stream characteristics on the network have been assumed to follow the simplified flow-density relationship, which was described in Chapter 2. The flow-density regime is assumed to be linear in both the un-congested as well as the congested zones. The capacity of the roadway is 1800 vph and the jam density is 180 vpkm. The free speed is 60 kmph on all the roads.

The discrete equivalent of the capacity is the maximum number of vehicles that can advance from one cell to the next cell at free flow speed in each time step. Hence the discrete capacity, based on a capacity flow of 1800 vph, is 0.5 vehicles per second. The discrete equivalent of jam density is the maximum number of vehicles that can be present in a particular cell at any time step. Hence the discrete jam density, based on a jam density of 180 vpkm, is 3 vehicles in one cell. All the cells in the network are assumed to be homogenous with the same capacity and jam density.

4.3 Demand Characteristics

The demand on the eastbound main arterial is 900 vph. The northbound demands on the side streets at the first and the third intersections, the non-critical intersections, are 200 vph each. The northbound demand at the critical middle intersection is 600 vph.

The vehicle arrivals into the first cell are simulated as Poisson arrivals, i.e. the distribution of headway between the vehicles entering the network is assumed to follow the exponential distribution. The headway equation used is as follows:

$$h(i) = -h_o * \log(1 - r(i)) \qquad (4.1)$$

Where *h(i)* = headway for one particular vehicle *i*;

h_o = constant headway for a deterministic arrival, which is the inverse of the volume in seconds; and

r(i) = a real-valued random number uniformly distributed between 0 and 1.

The random seeds to generate the value of *r(i)* are different for each iteration. The demand generation process follows the process, which was described in Chapter 2, where the exponentially distributed headways are generated first, and then the number of vehicle arrivals within each simulation second is counted. The demand enters the network only through the first cell on each road segment.

4.4 Signal Timing Plans

The signals at all the three intersections have fixed cycle signal timing plans. The signals are coordinated only with respect to the offsets between them, which is the free flow travel time between successive intersections. All three signals are two-phase signals. The green phase for the arterial at the first signal and the third signal is of 75 seconds duration, and the red phase is of 20 seconds duration. At the critical middle intersection, the green phase for the arterial is 55 seconds and the red phase is 40 seconds. There are 5 seconds of amber time in each cycle at all the signals. The co-ordination of the signals is disturbed the first time a preemption call is made and this co-ordination is not recovered after the passage of the EV, i.e. there is no recovery phase in these signals. This is done to make things simpler, as the objective of these scenarios is the demonstration of the behavior of the macroscopic model rather than the development of complex actuated signal systems for EV preemption.

4.5 Preemption Strategies

Since the development of the signal preemption strategies is not the focus of this study, the logic of the signal preemption control strategy is adopted from previous published studies. We consider a simple logic for preemption, which is described below.

The signal preemption strategy that is being used in this model is a variation of active signal priority *(24)*. It is a combination of green extension, red truncation and red interruption, strategies that are commonly used for signal preemption. Since it is assumed that the EV travels at the free flow speed, the time, from the point at which it is detected upstream of the intersection, to when it needs to cross the intersection is the free flow travel time from that point up to the intersection. We assume here that ten seconds are needed to cross the intersection, since the detector is placed ten cells upstream of the intersection. The preemption strategy employed depends on the exact arrival time of the EV at the detector and the state of the traffic signal, at that time step. A total of four cases are considered below. A graphic presentation of these four cases is given in Figure 4.2.

Case (i): Arrival before the last ten seconds of the green phase
If the vehicle comes at the detector and the signal is green for that approach and there is more than ten seconds of green-time left, then there is no need to provide any preemption.

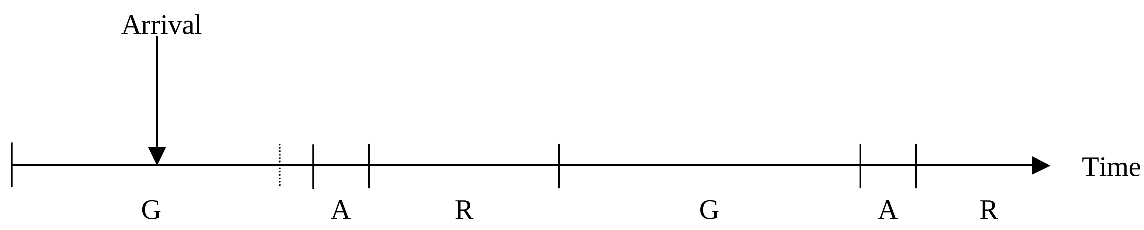
Case (ii): Arrival in the last ten seconds of the green phase
If the vehicle comes in at any time in the last ten seconds of the green phase, then the green-time for that phase is extended by ten seconds, irrespective of how much more green time is required for the vehicle to pass.

Case (iii): Arrival during the last ten seconds of the red phase

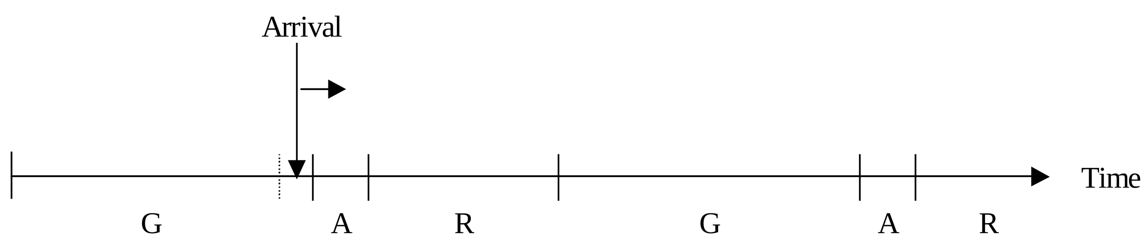
If the vehicle comes in within the last ten seconds of the red phase, then the signal is turned to green; that is, the red phase for the arterial is unilaterally truncated.

Case (iv): Arrival during the early part of the red phase

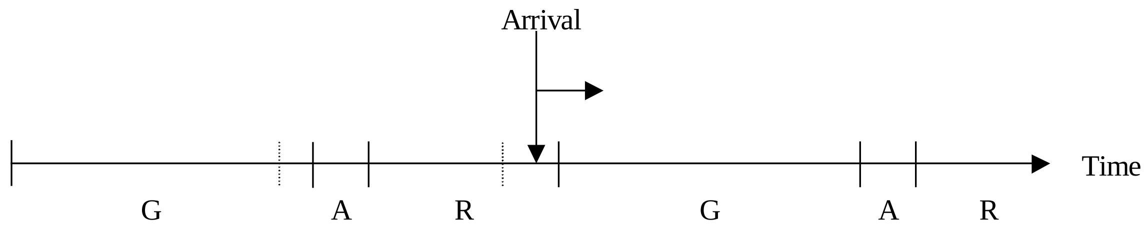
If the vehicle comes in during the early part of the red phase, that is, before the last ten seconds of the red phase, then a small green phase of ten seconds and an amber phase of 5 seconds are injected into the red phase. After the injected amber phase, the red phase is continued from the point at which it was terminated before preemption, but adding the injected time to the red time.



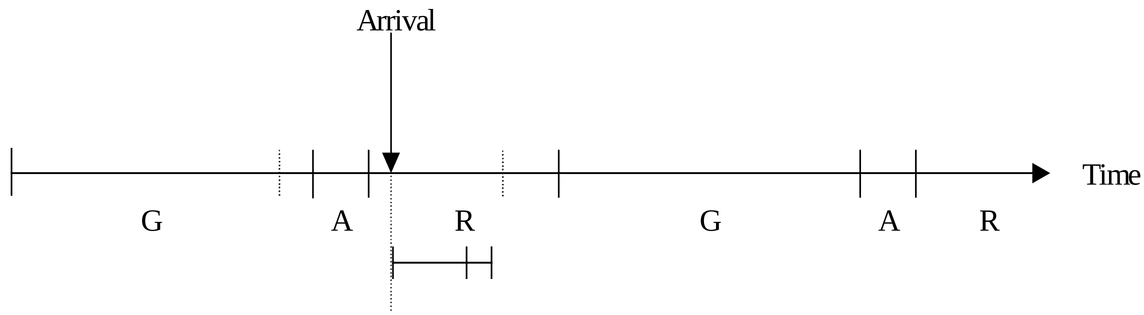
Case (i) arrival before the last ten seconds of the green phase



Case (ii) arrival in the last ten seconds of the green phase



Case (iii) arrival during the last ten seconds of the red phase



Case (iv) arrival before the early part of the red phase

Figure 4.2 Logic of Signal Preemption for EVs

4.6 Test Scenarios

The test scenarios that have been designed in this study to evaluate the impact of signal preemption for EVs on the rest of the traffic in general are described as follows. In all the scenarios, the EVs enter the network at different frequencies. The frequency of arrival of the EV means the number of EVs arriving in one hour. The headway between two consecutive arrivals of the EVs is made random; to ensure that there is no synchronization between the arrival times of the EVs at the intersection and the signal state at that time step. The probability that the signal state is green (red), when the EV arrives at the intersection, is roughly equal to the green (red) time over the cycle length. This would also make sure that the number of preemption calls monotonically increase with increase in frequency. The frequency level is varied from 1 veh/hr to 10 veh/hr.

4.6.1 Test Scenario 1 – EVs from the Main Arterial

In this scenario, the EVs come from the west end of the main arterial. The rest of the traffic arrivals are simulated as Poisson arrivals. For each frequency, the simulation is repeated 30 times, so that the randomness in the results is reduced as much as possible.

The objective of this scenario is to determine the impact of providing signal preemption to these EVs on the main street traffic as well as the major and minor side streets. The outputs from this scenario are the mean delay, maximum delay and the standard deviation of delay for each approach.

4.6.2 Test Scenario 2 – EVs from the Minor Side Street

The EVs are sent into the network from the first side street, which is a minor side street and has a very low demand when compared to the main street demand. In this scenario too, the general traffic arrivals are simulated as Poisson arrivals. The simulation for each frequency level is repeated 30 times to reduce the random variations.

The objective in this scenario is to determine the impact of providing preemption to the EVs coming in from the minor side street on the main street traffic.

4.6.3 Test Scenario 3 – EVs from Major Side Street

In this scenario, the EVs are introduced into the network from the major side street, which has a demand that is comparable to the main street demand. The general traffic's vehicle arrivals are Poisson distributed and each frequency level is repeated 30 times to reduce random variation.

The objective in this scenario is to determine the impact of providing preemption to the EVs on both the major side street as well as the main street.

4.6.4 Test Scenario 4 – Sensitivity Analysis

In this scenario, the sensitivity of the mean delays on the main street with respect to the capacity reduction factor of a cell is examined. The capacity reduction factor $\delta(t)$ is varied from 0% (No capacity reduction) to 100% (full capacity reduction). The meaning of 0% capacity reduction is that during the simulation, the EV just flies over the rest of the traffic without disturbing the capacity or the density of the cell in which it is present. The only effect of such a case is the interruption in the signal phases when the EV is detected by the detectors at the intersection for preemption. The meaning of 100% capacity reduction is that all the traffic in the cell the EV is present comes to a complete halt as long as the EV is there in that cell. Fifty percent and any other fraction of capacity reduction means that only part of the traffic in that cell responds to the presence of an EV and the rest don't respond.

4.6.5 Test Scenario 5 – Multiple Cell Capacity Reduction

The capacity reduction factor $\delta(t)$ determines the fraction of the capacity of a cell that is affected by the presence of EV in a particular cell. The effect of the presence of an EV on the traffic is generally felt over a longer length of the road than just one cell. Hence taking a value of $\delta(t)$ as 1, the effect of the presence of the EV over more cells is examined. The number of cells over which the effect is felt is varied from 1 cell to 9 cells to determine the impact of the different levels of capacity reduction on the main street delays.

4.7 Results and Findings

This section describes the results obtained from the test scenarios that were described in the previous section. Since the simulation was performed based on random vehicle arrivals, stochastic fluctuations in delays should be expected. In a single run, it is possible that the delay obtained for a lower frequency could be higher than the delay for a higher frequency. The magnitude of the delay incurred due to signal preemption is dependent on the number of actual requests for preemption, which, in turn, is dependent on the state of traffic signal when the EV arrives at a particular intersection and also on the signal cycle lengths and the phase splits used. Hence 30 repetitions were performed for each scenario, to reduce the inherent randomness in the arrivals. Still the stochastic fluctuations should be taken into consideration when interpreting the results, qualitatively.

4.7.1 Test Scenario 1 – EVs from the Main Arterial

The mean delay, the maximum delay and the standard deviation of delay, grouped by link, were the three outputs that were obtained from Test scenario 1. The results are as shown in Figures 4.3 - 4.5. It can be seen that signal preemption has a minor impact on traffic on the main street. In fact, average delay, maximum delay, and standard deviation of delay of the main street exhibit a very slight increase as the frequency of EV arrivals increases. Actually, for the main street, the overall delay should decrease because extra green time is being given to the main street for giving preemption to the EVs. But this decrease could be offset due to the reduction in the capacity of the roadway because of the EV. Hence the slight increase in the delay values is understandable. It is interesting to note that the average delay curve and the standard deviation curve follow a very similar trend.

Both side streets 1 and 3 are minor streets and have similar characteristics in demand and signal timing plans. Since the volumes are very low on these approaches, the presence of EVs would only increase the delay on these two streets by less than 4%. It appears that the EVs have a slightly more significant impact on the side street at the second intersection, which is a critical intersection. The increase in the average delay is about 11% when there are ten EVs present within an hour as compared to one vehicle within an hour. This is understandable because of the higher volumes on the second side street. The maximum delay and the standard deviation of delay also exhibit a similar increase as the frequency of the arrivals of the EV increases, but there are no drastic increases in these values as the frequency of EV arrivals increases

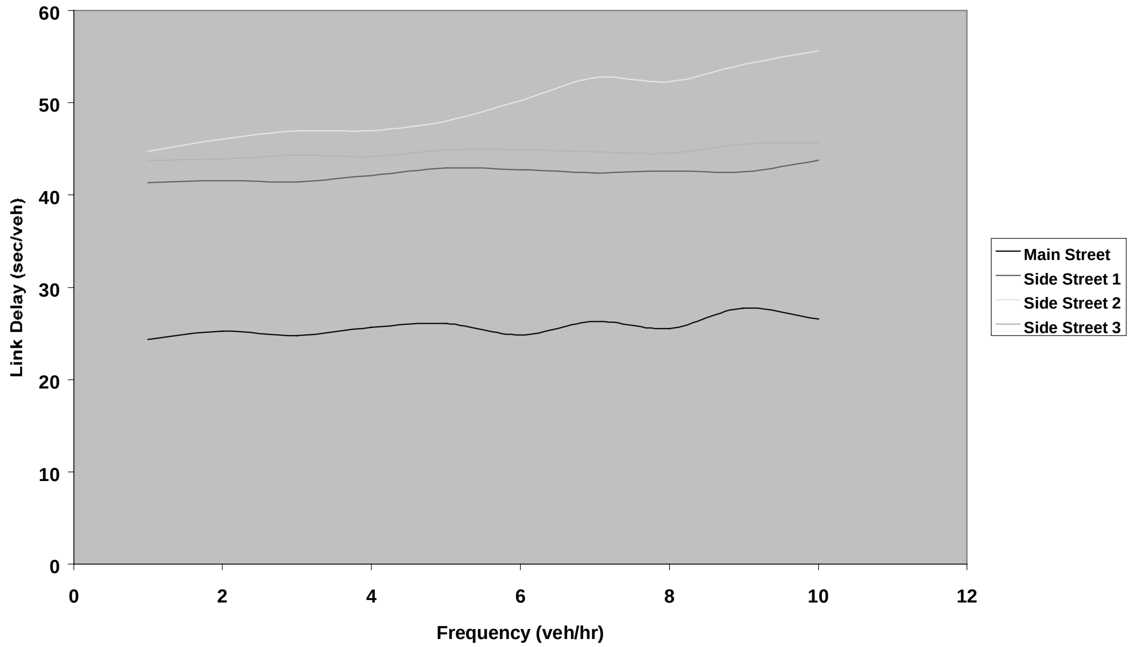


Figure 4.3 Mean Delay Curves for Test Scenario 1

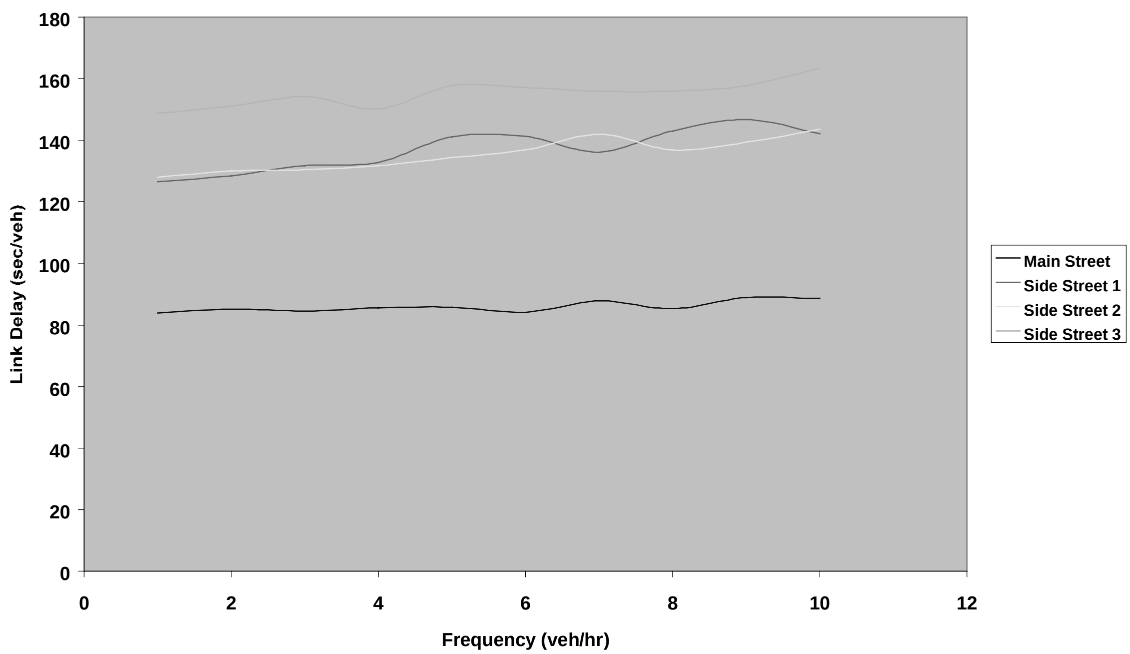


Figure 4.4 Maximum Delay Curves for Test Scenario 1

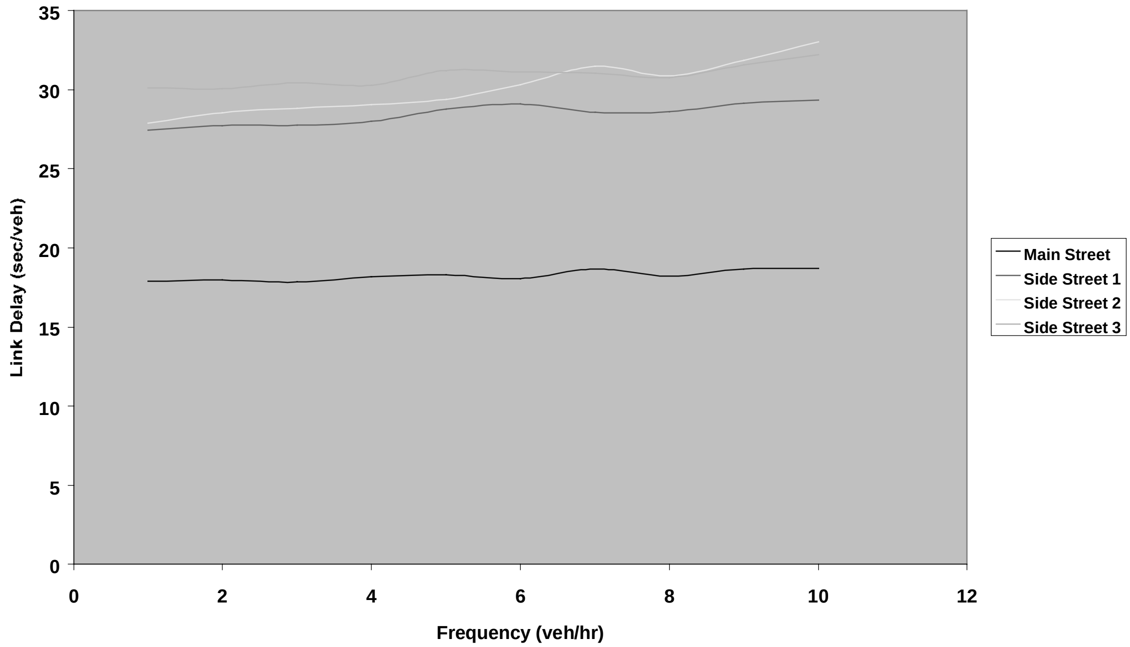


Figure 4.5 Standard Deviation of Delay Curves for Test Scenario 1

4.7.2 Test Scenario 2 – EVs from the Minor Side Street

The results that were obtained from Test scenario 2 are shown in Figures 4.6 - 4.8. The EVs enter the network from the minor side street in this scenario and cross the main street only at the first intersection. Hence preemption calls are given only at the first intersection and the other two intersections are not affected at all. Hence the second and the third side streets are not affected at all due to the presence of the EV and are not shown in these figures.

From Figure 4.6, it can be seen that the mean delay curve for the first side street shows a decrease, which is evident because of the preemption and increased green time. But the decrease itself is very small in magnitude and is about 3% of the average of the mean delay values. Even though there is a capacity reduction due to the presence of an EV on this side street, the increase in the green time due to preemption, offsets the increase in delay due to capacity reduction, on this low volume approach. Hence a decreasing delay curve is observed. The maximum delay and the standard deviation of delay curves also show a slightly decreasing trend for the side street, because of the preemption effects.

The main street shows a slightly more increase in the delay due to the frequent disruptions to the signals for preemption calls. But the magnitude of increase is less than 6% of the average of the mean delay values. From Figure 4.6, it can be seen that the deviation of the delay values from the average of the mean delays is not too significant. It appears that the preemption effect on main street delay is very much marginal, even when the number of preemption calls is very high, i.e., for higher frequencies. The maximum and the standard deviation of delay also follow the same pattern as the mean delay.

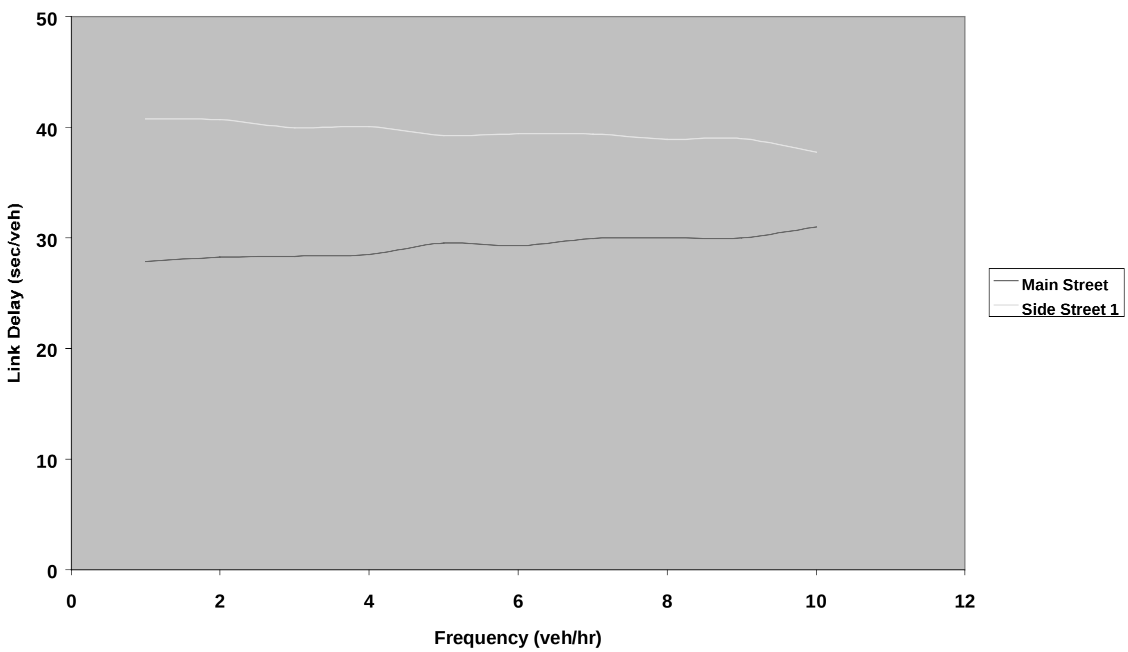


Figure 4.6 Mean Delay Curves for Test Scenario 2

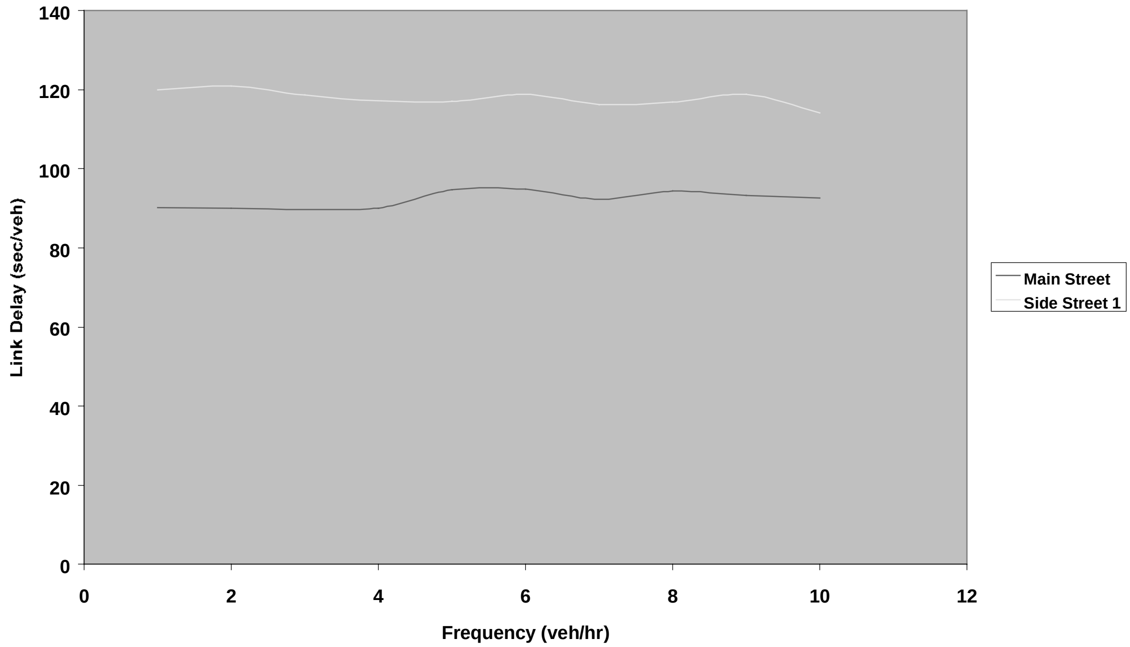


Figure 4.7 Maximum Delay Curves for Test Scenario 2

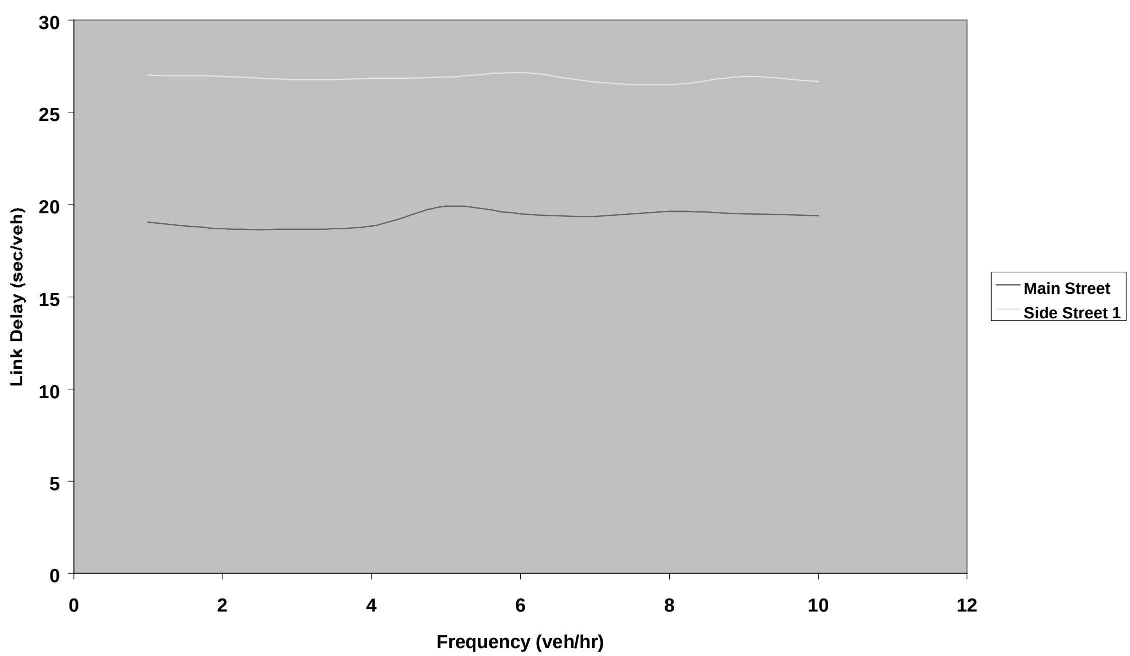


Figure 4.8 Standard Deviation of Delay Curves for Test Scenario 2

4.7.3 Test Scenario 3 – EVs from Major Side Street

The results that were obtained from Test scenario 3 are shown in Figures 4.9 - 4.11. In this scenario, since the EVs enter the network from the major side street and cross the main street at the second intersection, there is no effect on the other two side streets, which are the minor side streets. Hence they are not included in the results.

Since the EVs are on the side street, the delay values for this approach show a decrease as the frequency increases, which is obvious because of the preemption and additional green time. The decrease is approximately about 6% of the average delay and is not very significant in terms of absolute magnitude. The main street shows an increase in delay as the frequency of EVs increases. Also the increase is quite substantial and is of the order of about 40% of the average delay. Also there appears to be a direct correlation between the number of preemption calls and the delay values for both the main street and the side street, which is understandable.

The increase in the main street delay is much more substantial in this case than when the EVs enter the network from the minor side street. This is an expected result. The reason for this is that the signal phase split at this critical intersection is different from that at the minor intersections. The main street has a lower green time at the critical intersection than at the minor intersection. Hence a preemptive interference to the main street at this intersection increases the delay much more than at the minor intersection, which can be observed in Figure 4.9.

The maximum delay curve and the standard deviation delay curve both show the same trend as the mean delay curve.

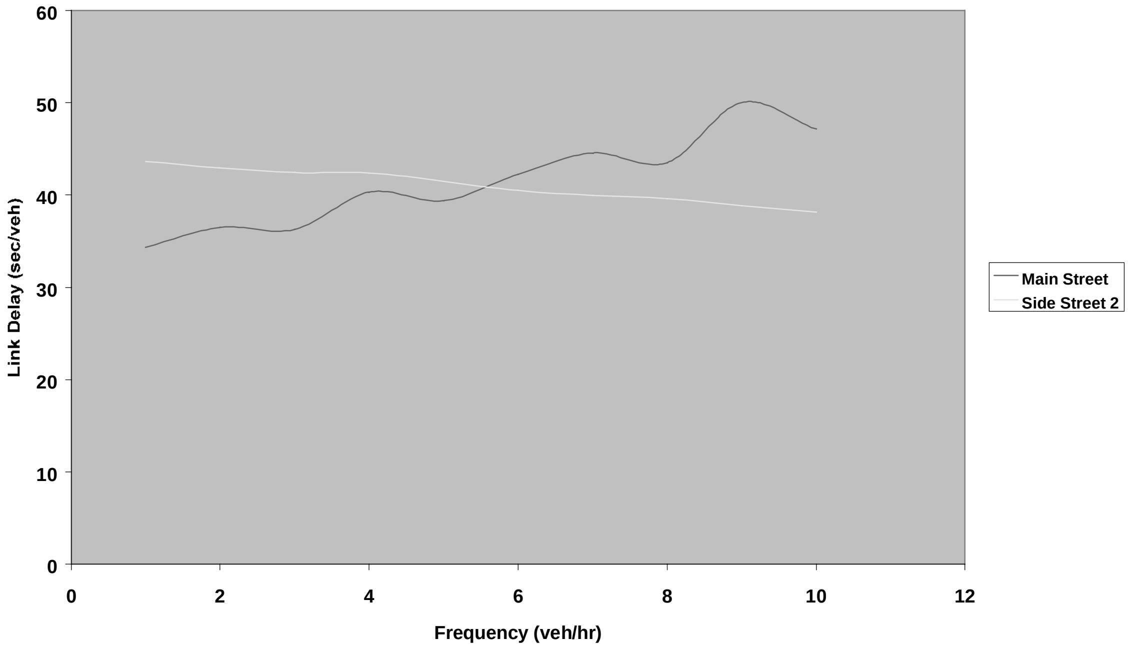


Figure 4.9 Mean Delay Curves for Test Scenario 3

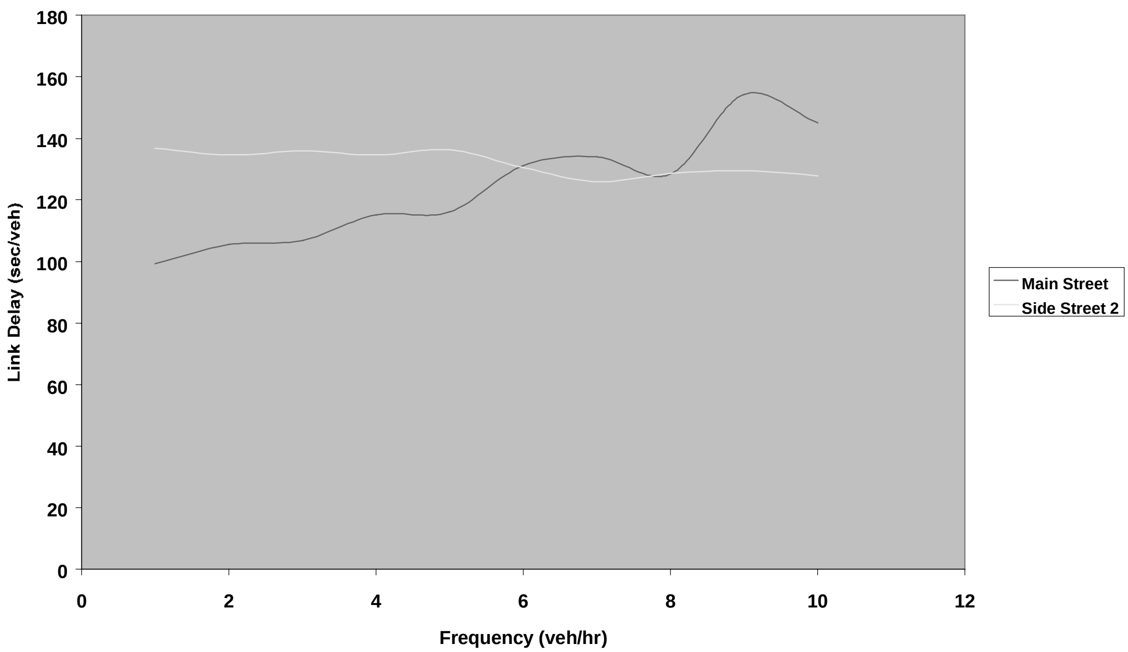


Figure 4.10 Maximum Delay Curves for Test Scenario 3

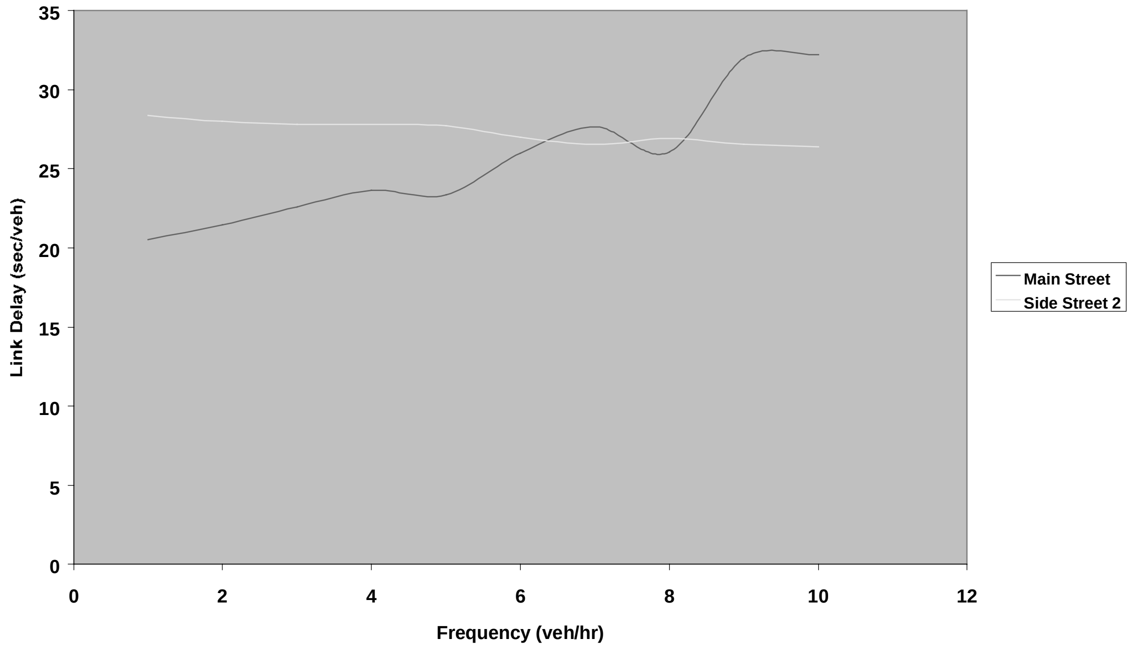


Figure 4.11 Standard Deviation of Delay Curves for Test Scenario 3

4.7.4 Test Scenario 4 – Sensitivity Analysis

The results obtained from Test scenario 4 are shown in Figures 4.12 - 4.15. These are the mean delay values for the main street as well as the side streets. Each curve corresponds to each frequency level of arrival of the EVs. A steady increase in delay is observed within each frequency level as the capacity reduction level increases from 0% to 100%, consistent with one's expectation. But in all cases, the magnitude of increase is very small as the capacity reduction increases.

From the figures, we can observe that the deviation of the curves to the average values is very minor and the maximum difference is less than 5% of the average of the mean delays. This shows that the single cell capacity reduction factor doesn't have a major impact on the delays and the primary reason for the delays is the reduction in green time due to preemption and the resulting additional queuing. The other reason for this might be that the influence of the EV covers more than one cell i.e. the capacity over a longer stretch of the roadway is affected by the presence of the EV.

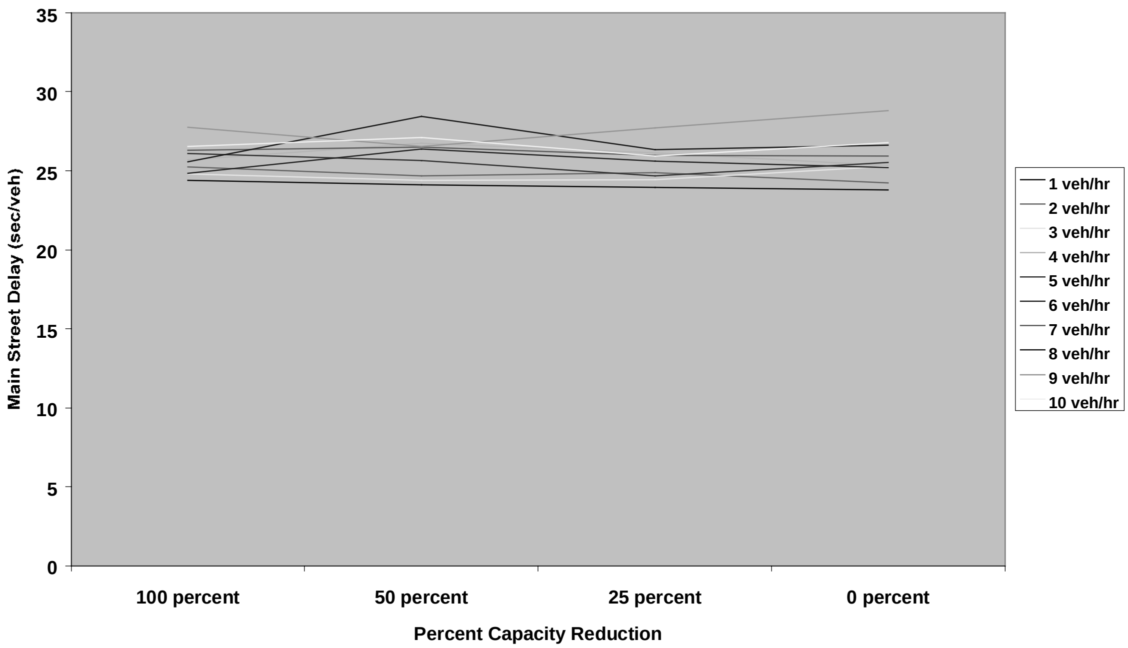


Figure 4.12 Sensitivity Analysis Curves (Main Street)

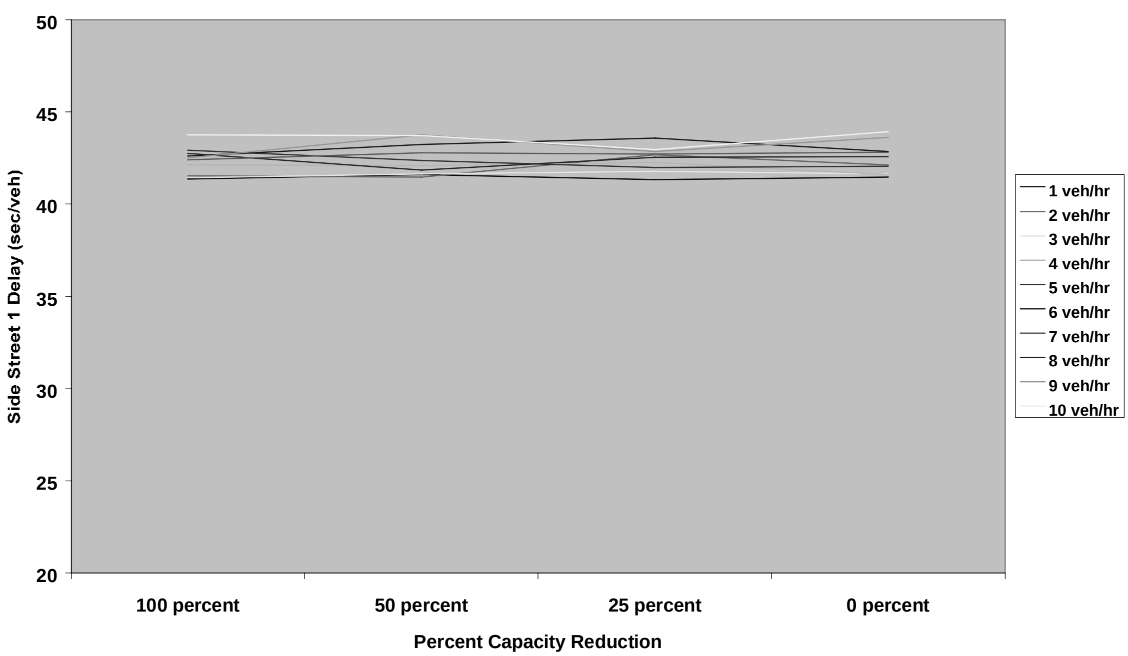


Figure 4.13 Sensitivity Analysis Curves (Side Street 1)

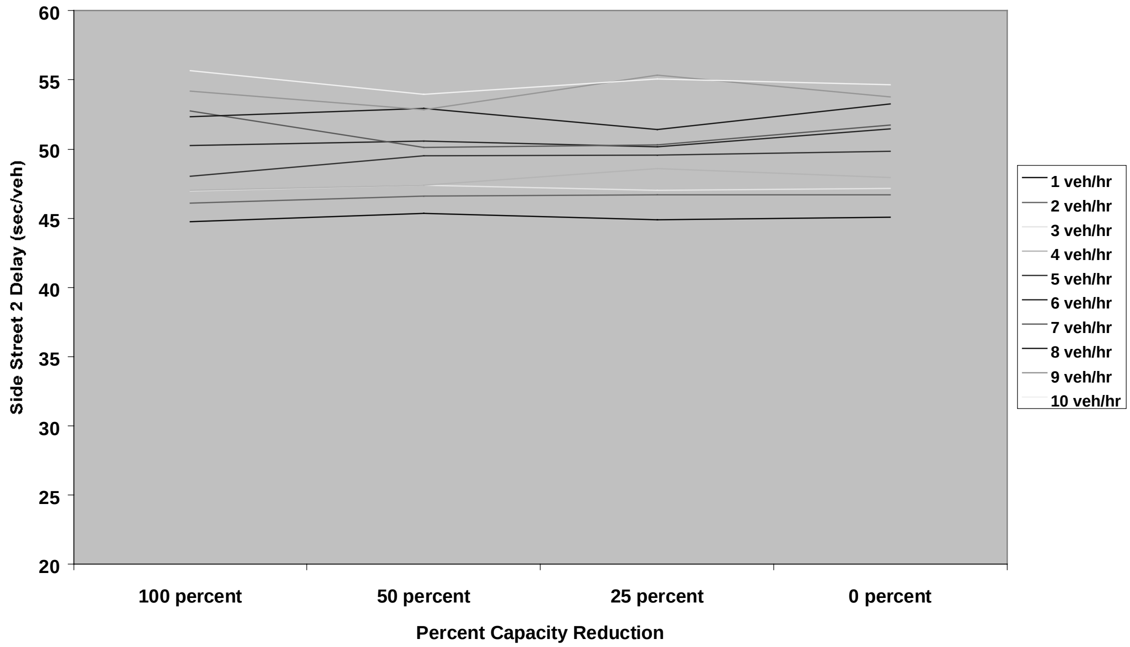


Figure 4.14 Sensitivity Analysis Curves (Side Street 2)

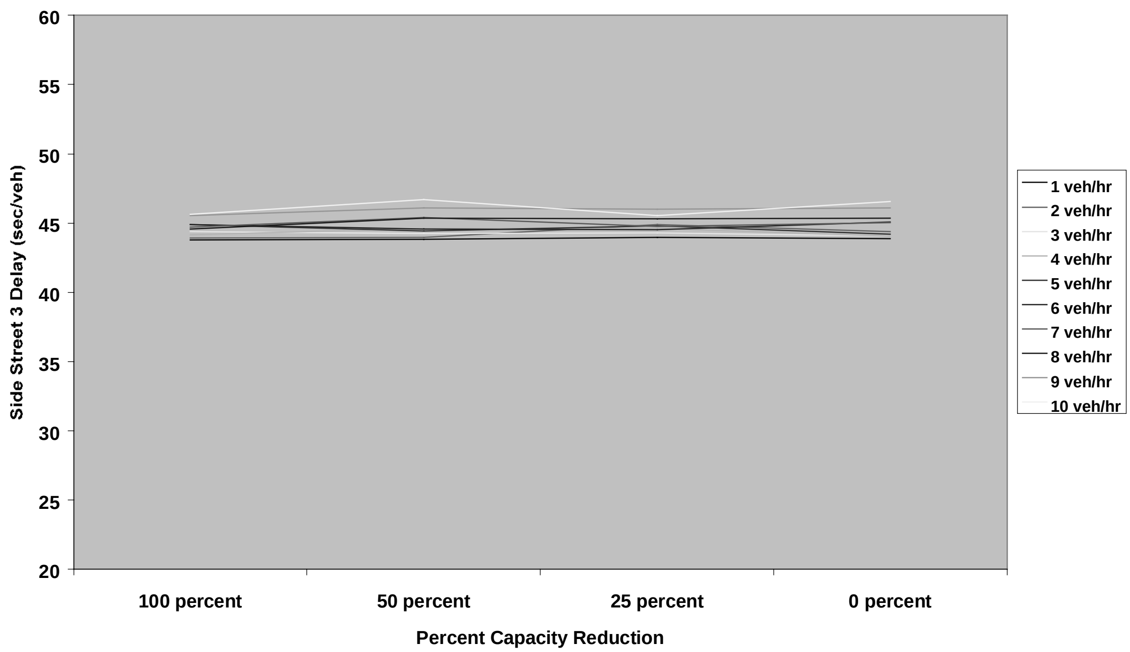


Figure 4.15 Sensitivity Analysis Curves (Side Street 3)

4.7.5 Test Scenario 5 – Multiple Cell Capacity Reduction

The results from Test scenario 5 are shown in Figures 4.16 - 4.18. In the previous scenario, it was assumed that the influence of the EV is felt over a single cell on the roadway. In this scenario, the capacity of the roadway is reduced to zero over multiple cells around the EV, which enters the network on the main street. The simulation is repeated for a capacity reduction of 1 cell, 3 cells, 5 cells, 7 cells and 9 cells, where the influence area is spread equally on either side of the cell in which the EV is present.

The EVs travel only on the main street and the multiple cell capacity reduction for EVs on main street doesn't have any effect on the side streets. This is because whether the capacity reduction is for one cell or multiple cells, the signal interruption period is still the same for the side streets and hence there are no additional delays that are incurred on the side streets due to multiple cell capacity reduction on the main street. So in the results, it was found that it was not necessary to include the delay values for the side streets and only the effects on the main street are shown in the figures. This can be observed and verified from Figure 4.18.

For the main street, as the capacity reduction area for EVs increases from 1 cell to 9 cells, the mean delay increases. The reason for this is that as the capacity of more cells is reduced, more vehicles are affected, resulting in an increase in delay. This increase in the main street delay with respect to the influence area can be observed in Figure 4.19. For each frequency level of EV arrivals, as the capacity reduction is increased from "No Red." to "9 cells", the main street delay values increase. It was also observed that the increase in delay is more when the frequency of EV arrivals is higher. But it can be seen that the magnitude of increase is very small for all frequency levels and the maximum increase is less than 9% of the average of the mean delays.

Figure 4.17 shows the main street delay values as the frequency of EV arrivals increases, for each level of capacity reduction. When there is no capacity reduction, i.e. the base case when there are no EVs present, the delay values are all same, indicated by the straight horizontal line. But as the capacity reduction is increased to 1 cell, when an EV is present, there is a change in the delay values as the frequency increases. The curve for "1 cell" shows that the delay increases very slightly as the frequency increases. But as the capacity reduction is extended over more cells, it influences the delay values more than the green time extension and the delays actually increase much more as the frequency increases. The curve for a capacity reduction of 9 cells shows a much higher increase in the mean delay as the frequency increases than the curve for a capacity reduction of 1 cell. This result is very much intuitive. This shows that there is a trade-off between the amount of benefit derived from the preemption and the assumed influence area of the EV in the model. The true area of influence of the EV can be calibrated once more appropriate data is obtained for a real model.

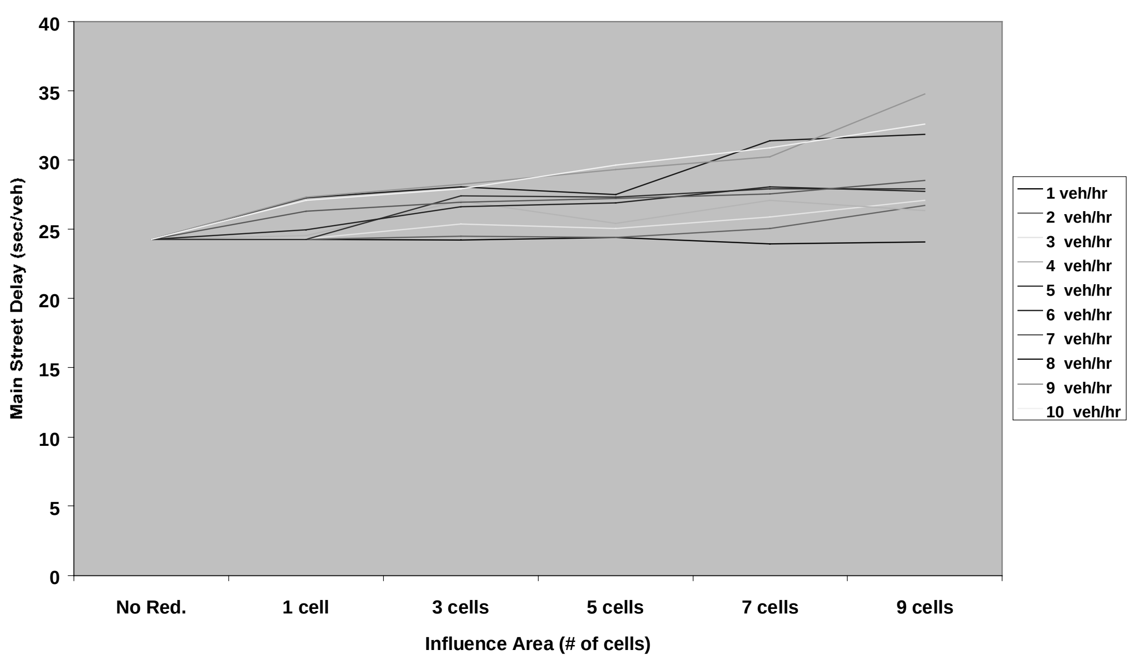


Figure 4.16 Sensitivity of Main Street Delay with respect to Multiple Cell Capacity Reduction

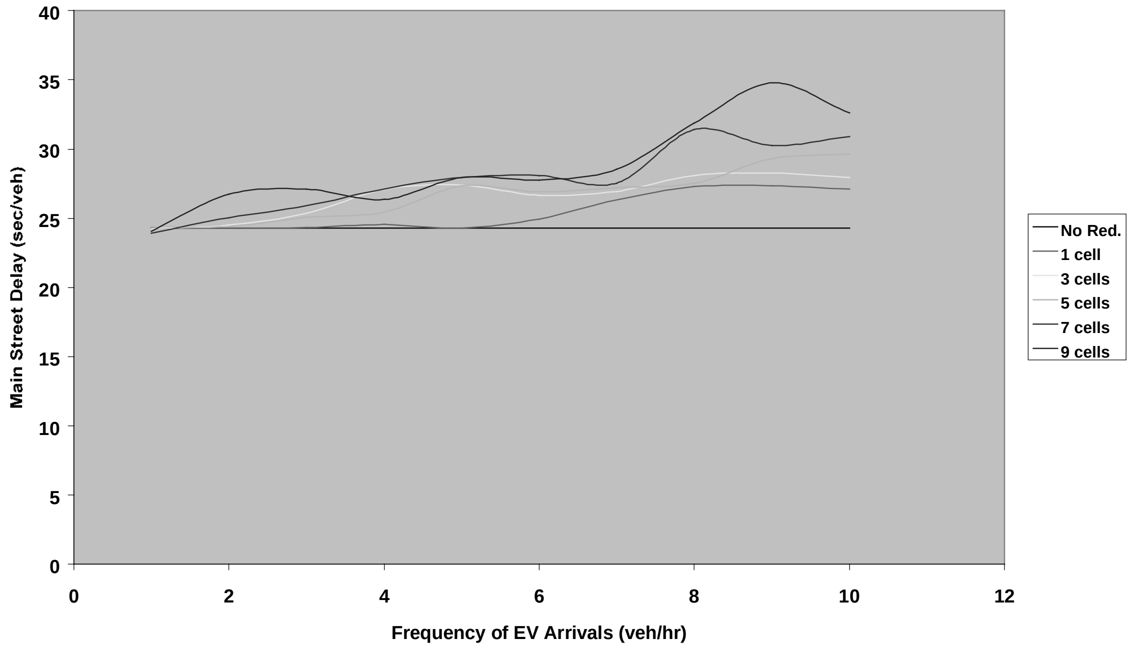


Figure 4.17 Sensitivity of Main Street Delay with respect to Frequency of EV Arrivals

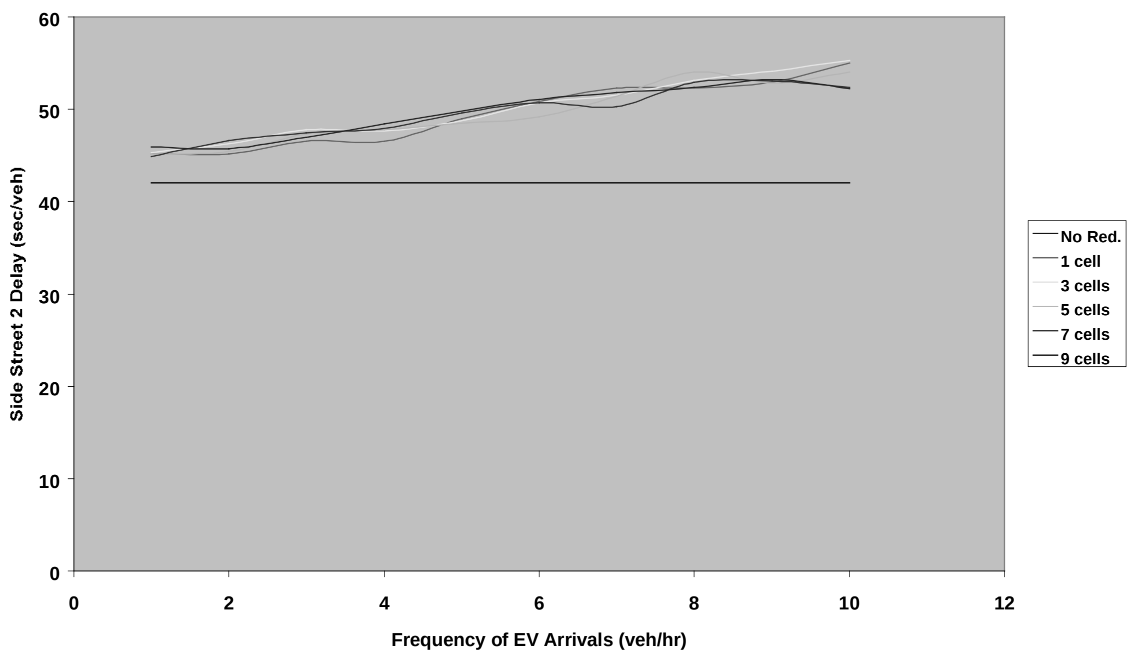


Figure 4.18 Sensitivity of Side Street 2 Mean Delays with respect to Multiple Cell Capacity Reduction

5 CONCLUSIONS

5.1 General Comments

In this study, a macroscopic traffic simulation model, based on the cell transmission model, was described and a couple of examples were demonstrated on the behavior of the model in various scenarios. The macroscopic model is a set of state-space equations, which are consistent with the hydrodynamic theory of traffic flow. This theory is known to be powerful in capturing the transient behavior of traffic, including the formation, propagation, and dissipation of queues. The model described in this study combines the features of both simulation and analytical models to describe the spatial and temporal behavior of traffic on a roadway segment. The focus of this study was on making use of the model to address the issue of evaluation of signal preemption for EVs rather than on developing a comprehensive traffic model. All the assumptions made in this model have been stated and are not restrictive in nature to the intended analysis. This model at this stage can only be used as a first-order approximation for assessing the impact of emergency vehicles on traffic.

A very important feature of the model is that it can be easily modified to model the presence of an EV and simulate the behavior and reaction of the rest of the traffic in the vicinity of the EV. In commercially available microscopic models, it is very difficult to simulate the pullover effect of the general traffic in response to an EV, a moving obstruction in the form of a capacity reduction factor was introduced in the model to mimic that effect. The capacity reduction feature can be used to model either partial or complete responsiveness of the general traffic to the presence of an EV. Also the extent of influence of the EV on the rest of the traffic can also be examined using a multiple cell capacity reduction formulation.

This model was used as the base model for the evaluation of the effect of signal preemption for EVs on the rest of the traffic. Various scenarios were implemented to examine the impacts of providing signal preemption to EVs, which enter the network from different approaches with different volume to capacity ratios. Signal preemption affects the cross street traffic the most, when an EV is present and also disrupts the traffic progression and the signal coordination after every call. In this study, it was assumed that there was no recovery phase in the signal settings to recover the signal coordination, because the objective here was to study the effects in its simplest form and evaluate the impacts in terms of link delays.

5.2 Summary and Conclusions of the Results

Five test scenarios were implemented to evaluate the impacts of EV signal preemption on the general traffic, especially the cross street traffic. Emergency vehicles were introduced into the network at various frequencies, which is the number of EVs per hour, and the headways between consecutive arrivals of the EVs were made completely random. Each simulation run was repeated 30 times so as to dampen the variations in the results due to the random nature of the arrivals of both the EVs and the general traffic and also to be statistically significant. But the base condition, which is the condition with no EV arrivals, for all the scenarios was kept the same so as to be able to compare the results for different scenarios. The signal preemption strategy used in these scenarios was a combination of green extension, red truncation and red interruption. This strategy disrupts the traffic the least among all the different preemption strategies that have been described in chapter 3.

In test scenario 1, where the EVs entered the network from the main street and a single cell capacity reduction for the cell containing EV is assumed, there is a very minor impact to the traffic on the main street because of the extra green time given to that approach, as the frequency of EV arrivals increases. The effect on the minor side streets is also very minor because of the volumes on these links, which are very low. But the increase in delay to the major side street is appreciable and is about 11% of the average of the mean delay. This shows that, as expected, signal preemption, apart from providing advantage to the main street traffic, significantly affects the side streets with higher volume to capacity ratios than the side streets with lower volumes. Also it has been observed that the maximum delay and the standard deviation of the delay follow a similar trend of increase as the mean delay curve and there is no drastic increase in these values as the frequency increases. This shows that, overall, the impact of signal preemption for EVs entering the network from the main street is not really that significant and the increase in delays are not really appreciable.

In test scenario 2, where the EVs enter the network from the minor side street, there was an expected decrease in the minor side street delay on which the EVs are present. Also the main street delay shows an increase as the frequency decreases, but the magnitude of the increase is very minor as compared to the average of the mean delays. The reason for this is the signal phase splits at these intersections favor the main street traffic very much and have a much larger green time for the main street, which compensates for the frequent disruptions.

In the test scenario 3, where the EVs enter the network from the major side street, there is a more significant impact of the preemption on both the main street and the side streets than in the test scenario 2. The side street shows a noticeable decrease in delay as the frequency increases and also the main street shows a more significant increase in the delay than in the earlier test scenario. The reason for this is the signal phase splits. The main street has a much lower green time to cycle length ratio in this scenario than in the previous scenario. Hence as higher volumes are involved at this critical intersection, much longer queues are formed at this intersection due to frequent disruptions and hence delays increase much more appreciably in this test scenario. This result is very much intuitive.

In test scenario 4, the effect of the single cell capacity reduction factor on the main street delays was examined. It was observed that the impact of a full capacity reduction is not much different from the impact of no capacity reduction. This means that the capacity reduction factor for a single cell doesn’t play a significant role in the increase/decrease of the delays for the various approaches. Also this means that the impact of an EV is felt over more than one cell, i.e., over multiple cells around the EV.

In test scenario 5, the effect of multiple cell capacity reduction on the main street delays was examined. It was observed there is not much difference for the side streets due to a multiple cell capacity reduction for the presence of an EV on the main street. But the main street delays increases noticeably when the area of influence of the EV is increased to 9 cells from 1 cell. It was observed that the main street delays actually increase with increase in the impact area as well as the frequency of arrivals of the EVs. But it was observed that the magnitude of increase is very small for all frequency levels and the maximum increase is less than 9% of the average of the mean delays. This shows that there is a trade-off between the amount of benefit derived from the preemption and the assumed influence area of the EV in the model. The true area of influence of the EV can be calibrated once more appropriate data is obtained for a real model.

The results from the five test scenarios were very much on anticipated lines and are intuitive. Even with the assumptions on certain parameters in the basic model, the results, which were explainable with intuitive logic, were obtained. With more data and much more general model, a detailed and accurate analysis of impacts of signal preemption on the general traffic can be carried out.

5.3 Future Scope of Work

Certain assumptions were made in this macroscopic traffic model. A more detailed model, which can model turning movements, lane changes etc., can be developed to carry out a more comprehensive analysis of the signal preemption effects. Also the assumed form of the flow-density relationship can be extended to a more generalized form to reflect the exact behavior of a macroscopic set of vehicles on the roadway.

For the EVs certain assumptions were made with respect to the speed at which they travel and the extent of the effect on the presence of an EV on the roadway. The speed restriction can be removed by having an EV that travels as per the conditions on the roadway instead of the free flowing speed, which means that the EV can slow down in areas of denser traffic and make up for the lost time by speeding up in areas with lighter traffic. This is a much more realistic situation than an EV moving at free flow speed irrespective of the traffic conditions around it. The area of influence of the EV on the roadway is an issue of further research and collecting suitable information from the field and using certain legal restrictions imposed by law pertaining to the behavior of general traffic in the presence of an EV, can calibrate this parameter. Another area of further research is the development and implementation of a recovery phase for the signal systems after an EV has passed the intersection. This would reduce the delays to a certain extent as the signal control system has been optimized for performance now.

In the test scenarios, the v/c ratios for all approaches were kept below 1. In future research, the model can be utilized to study the impact of signal preemption on traffic during the peak hour when the v/c ratio temporarily exceeds 1. Since the model is powerful in capturing the temporal and spatial effects of congestion, it can be utilized to study the disturbance to traffic when queues propagate from one intersection to another. Another area for future research is the development of an analytical model based on this modeling framework using 0-1 integer linear programming. The activity is currently underway. Real-time control strategies can be developed based on the insights obtained from the model. Future study can also be conducted to examine the impact of signal preemption on traffic when signal coordination is disrupted. The design of the recovery phases can be studied with the optimization model.

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