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Verifying the Uniqueness of the d1, d2,d3, and d4 Terms for
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VERIFYING THE UNIQUENESS OF THE D1, D2, D3 AND D4 TERMS FOR MODELING THE DELAY OF CLOSELY SPACED SIGNALIZED INTERSECTIONS

By

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ABSTRACT

VERIFYING THE UNIQUENESS OF THE D1, D2, D3 AND D4 TERMS FOR MODELING THE DELAY OF CLOSELY SPACED SIGNALIZED INTERSECTIONS

By

John R. Engle

In congested conditions queues from downstream intersections impact upstream, closely spaced signalized intersections. The interaction of traffic between neighboring intersections must be taken into account, otherwise a portion of the experienced delay will be unaccounted for in oversaturated conditions. To account for the delay resulting from downstream signals, a d4 delay term is introduced to compliment the d1, d2, and d3 delay terms already present in the Highway Capacity Manual. The following research considers the interaction between these four delay terms, while also defending the claim that the experienced control delay can be exclusively represented by one of these four delay terms. Thus by summing the four delay terms, the overall average control delay experienced at a signalized intersection can be more accurately calculated.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 Background

Traffic congestion is the situation in which traffic is forced to travel at a less than reasonable speed as the result of vehicle volumes exceeding the design capacity of the highway. Traffic congestion occurs when the volume of vehicles attempting to use a given highway is greater then the capacity of the roadway. (1)

In the United States and many other countries, highway congestion significantly affects the economy, land use, personal behavior, and the commuting decisions of hundreds of millions of drivers everyday. In a nation such as the United States, where the majority of citizens rely almost exclusively on the automobile for transportation, congestion costs commuters over 4.6 billion hours of delay and $74 billion each year, according to a recent report by the Texas Transportation Institute (2). For one year, this can be as high as $1200 per driver in large metropolitan areas.

Yet despite these costs, congestion has become something that is expected and even tolerated by commuters rather than being viewed as a problem that can be solved. There is significant merit to this view, as governmental budget issues and a sprawling landscape have made the expansion of the highway network impractical in many locations. In recent years, the perspective has switched from a supply side solution of increasing the size of the highway network to alleviate congestion, to an approach of better managing the existing networks to reduce the harmful effects of that congestion (3). New efforts are also underway utilizing demand management to control the time periods where users wish to use the system.

As a point of addressing the issue of congestion, evaluation procedures and engineering methods must be developed to study, analyze, and ultimately address the congestion that is present. Currently very little has been done to address the issue of evaluating delay in congested signalized network conditions, and to develop a procedure or method of how delay can be accurately measured and predicted in a signalized network system.

1.2 Problem Statement and Motivation for Study

New methods of analysis are needed to study delay. Increases in vehicular traffic and the lack of alternative highway choices have resulted in an increase of traffic congestion within the United States. Previously isolated incidents of congestion at one traffic signal have spread to affect entire networks of traffic signals. In many situations, congestion can only be accurately analyzed by studying the entire network of signalized intersections, as the delay from one signalized intersection affects other signalized intersections along the network.

The most prevalent method of evaluating traffic operation and delay is through identifying the level of service (LOS) of a given intersection. The LOS is obtained based on the control delay experienced at a single intersection, as per the current Highway Capacity Manual (HCM 2000) (4). Unfortunately, this method does not account for delays experienced in a given highway network, and can only be used to assess the delay at one location. This does not address the issue of traffic interaction between neighboring intersections. The control delay is calculated in equation 1.2.1. The components in the equation include a progression factor (PF), uniform delay (d1), incremental delay (d2), and initial queue delay (d3).

$$\textit{Control Delay} = PF \; X \; \; d1 + d2 + d3 \qquad (1.2.1)$$

The components taken into consideration in calculating the control delay are based on capacity of approach lanes, green time, and other characteristics that are unique to that intersection. This equation does not consider the effects and delay induced by downstream signalized intersections. In effect, the LOS only considers delay at one intersection, without taking into account the delay that results from congestion at downstream locations along the network. But this congestion is only relevant if the congestion at downstream intersection causes a queue long enough to affect the upstream intersection.

The goal of this research is to build upon earlier work done by Ahmed (5) on the subject of delay interaction from downstream intersections, and to produce a method of determining the control delay at an intersection, while taking into account the interaction from downstream intersections. In doing so, the evaluative measure would no longer be limited to just one intersection, but rather to an entire network as a whole. The dissertation will address the issue of how delay can be evaluated over an entire network, and what procedures are most effective for performing this evaluation.

1.3 Research Objectives

The objectives of this research are to:

1. understand how delays at a given signalized intersection can affect delay at another nearby signalized intersection,
2. account for this delay in developing a procedure to calculate and/or measure delay for signalized intersections while still considering the delay from other nearby signalized intersections, and
3. create a practical procedure of calculating this delay while understanding what factors have significant effects in creating and impacting this delay.

1.4 Research Contribution

The desired contribution of this research is to provide analysis on the delay incurred by a simple network of signalized intersections. Applying theory and results used in this analysis, a model is developed to predict the degree of accuracy in delay calculations for signalized network systems. It is expected that the findings of this research can be used to estimate delay for a signalized intersection, within a developed range of accuracy. In particular, the findings of this document focus on what procedure can be used to predict delay from sampling a set of vehicles on a given network with signalized intersections.

1.5 Dissertation Approach and Layout

Initially, the research begins with a review of earlier work on studies of closely spaced signalized intersection networks, and the concept of intersection delay resulting from the queue at a downstream intersection. Following a comprehensive review of work performed on this subject, as found in chapter 2, the focus of the review shifts in chapter 3 to the study of how delay at one intersection can affect another. More specifically, this focus builds upon basic ideas regarding the d4 concept developed in the doctoral dissertation of Ahmed (5), submitted to Michigan State University. The d4 concept is a delay term that considers delay dot accounted for by the d1, d2, and d3 delay terms in the HCM (4), such as delay from queues originating at a downstream intersection.

The application of the d4 factor, and its implication on network delay, is then discussed in detail in chapter 4 of the dissertation. Chapter 4 also provides the theoretical background on which the dissertation will be based. Chapter 5 contains research on the modeling of simulated vehicle delay, and what procedures can be used to evaluate delay over a highway network. Chapter 6 presents the conclusions and recommendations.

A limitation of this research is that the study only accounts for signalized intersections. The impacts of other delays from sink and source traffic, closed loop networks, and vehicles entering and exiting the system from turning movements at the intersections are beyond the scope of this research. Also, closely spaced traffic signals may be particularly sensitive to left and right turning movements from the cross streets and the road geometry. This aspect was not examined in the analysis.

CHAPTER 2

LITERATURE REVIEW

This chapter contains a review of published research pertaining to the topic of intersection delay and the impact that occurs when congestion affects multiple traffic signals along a given highway network. In general, there is very little material that has been published on this topic. Despite that, the following section provides credit to those individuals who have made significant contributions to this topic, as their research provides the foundation for this dissertation.

The first to significantly research signalized intersection pairs were Rouphail and Akcelik (6). Their work focused mainly on queue lengths occurring at a downstream, signalized intersection. The research investigated the length of the queue arriving at the down stream intersection and how that compared to the space between intersections for traffic volume calculations. The investigation also studied the length that would be needed to allow a vehicle to accelerate to the full design speed, and then safely decelerate to a stop, and the maximum queue length that could form on an approach during an average cycle for the traffic signal.

Rouphail and Akcelik (6) found that, in general, the existing methods of evaluating intersection delay were not suitable for evaluating the effectiveness of paired intersections. They found that queues and other delays may develop, even when the individual intersections are operating effectively. Their work was important in identifying that signalized intersection interaction is an issue that needs further investigation and that the delay is not isolated to an individual signalized intersection.

Prosser and Dunne (7) also studied pairs of closely spaced signalized intersections using a graphical approach. In their analysis, the loss of effective green as the result of queue backup was investigated. The limitation of this analysis was that the blocking effect of queues was only considered in situations where the queue was long enough to consume the entire distance between signalized intersections. In doing so, the delay from shorter queue build-ups is ignored. Still, the research again showed that queuing effects can increase delays at upstream signalized intersections for a given pair of signalized intersections.

More research was performed on closely spaced intersections by Johnson and Akcelik (8). Their research focused on the application of analytical software for analysis. The analysis included several measures of effectiveness revolving around vehicular progression. The programs used in the analysis included TRANSYT-7F (9), PASSER II (10), and SCATES (11). It is important to note that VISSIM (12), which is used in this dissertation, was not used by Johnson and Akcelik (8).

The models published by Abu-Lebdeh and Benekohal (13) created methods of estimating volumes of discharged traffic at an intersection upstream. This was done with and without downstream disturbances. Beyond this, their study also predicted the capacities of oversaturated arterials. This prediction was based both on signal coordination and physical capacities of the intersection approaches. Their work found that a significant amount of the intersection capacity can be lost if the congestion from other intersections is ignored. The main focus of their study was the reduction of intersection capacity.

The most recent publication is a doctoral dissertation by Ahmed (5), modeling delay using a d4 factor. The work by Ahmed (5) provides the foundation for this document, and raised the problem statement this thesis attempts to address. This work details the effect of a d4 factor on the delay of a signalized intersection. Basically, Ahmed's work identified the issue of traffic and delay interaction between closely spaced intersections. Building from this issue, the delay occurring at an upstream signalized intersection resulting from the queue buildup at a downstream signalized intersection is investigated. A detailed summary of the work done by Ahmed (5) is contained in chapter 3.

CHAPTER 3

DELAY AT SIGNALIZED INTERSECTIONS

3.1 Introduction

A transportation highway network consists of a system of intersections along a given corridor or corridors. These intersections act as points of conflicts, where vehicles must interact with each other to effectively move about the system. Traffic signals are an instrument of control for these intersections, attempting to better manage the movement of vehicles through these points of conflict. Network management evaluates the interaction of delay between intersections in order to better understand the delays along a highway network. With growth in congestion, analysis of the delay resulting from the interaction of closely spaced signalized intersections is needed to address issues facing urban highway networks.

The purpose of this chapter is to provide a background on intersection control, with specific focus on the methods used by the Highway Capacity Manual (HCM) (4) for calculating intersection delay. It also contains research supplementing the work of Ahmed (5), with a focus on the interaction of traffic between closely spaced signalized intersections.

3.2. Uninterrupted Flow

Uninterrupted flow is the situation where a vehicle can travel between two points without having to slow down or stop because of traffic control devices. During periods of uninterrupted flow, traffic movement is controlled by vehicle interactions and the geometry of the roadway, without any traffic control devices present. Freeways and unsignalized highways are examples of situations when vehicles can travel with uninterrupted flow.

It should be noted that uninterrupted flow refers to the lack of devices present to regulate flow. For example, rush hour traffic jams caused by the number of vehicles exceeding the capacity of the freeway is still an example of uninterrupted flow, even though vehicles are forced to slow or stop.

3.3 Interrupted Flow

When traffic control devices or other external methods affect the flow of traffic, interrupted flow occurs. Such devices cause vehicles to stop or slow at locations irrespective of the amount of traffic present. Streets with stop and yield signs, and signalized highway networks are all examples of situations where interrupted flow occurs along a given highway. The focus of this dissertation deals with conditions of interrupted flow, and how the interruptions can be better managed to reduce vehicular delay along a highway network.

3.4 Signalized Intersections

For high volume intersections, the most prevalent type of control involves the use of a traffic signal. For a typical intersection of two highways with traffic traveling in both directions there are 12 potential vehicular movements, three from each of the four approach legs. In addition, there can also be up to four pedestrian movements crossing each of the approach legs. A traffic signal attempts to manage these movements in a way that both avoids conflicts, and minimizes the delay experience by vehicles or pedestrians waiting to make these movements.

Stop or yield control can also be used to manage intersections, though this type of control is better suited for low volume intersections. Traffic signals are more adept to managing intersections with high volumes. Unlike stop or yield control which rely entirely on the judgment of the driver, traffic signals can be programmed by engineers in various way to favor a given movement or movements. This is significant because unlike a stop or yield controlled intersection, the assignment of delay rests in the control of an engineer or computer who can assign that delay in a method beneficial to the highway network as a whole.

3.5 Defining Delay

Interruptions in flow occurring at a signalized intersection cause vehicular delay. The HCM (4) defines the delay experienced at a signalized intersection to be the sum of three delay components, found in equation 1.2.1 and repeated below in equation 3.5.1. In this equation, the three components are summed to obtain *D123*, which is the control delay experienced at a signalized intersection.

$$D123 = d1 \times PF + d2 + d3 \qquad \textit{(eqn 3.5.1)}$$

The components are a progression factor (PF), uniform delay (d1), incremental delay (d2), and initial queue delay (d3). These components are defined in detail in the following sections.

3.6 Uniform Delay

The uniform delay is based on the arrival pattern of vehicles to the signalized intersection. A uniform arrival indicates the vehicles arrive at a predictable, constant, and steady rate. A random arrival indicates that there is no cohesiveness in the arrival pattern, and that no predictable assumption can be made. Random arrival refers to vehicles arriving not in a set group, without a predictable pattern, and without any predictable method of arriving.

In reality, the arrival of vehicles to a real intersection is somewhere between random and uniform, usually with platooned arrivals and other isolated arriving vehicles. A more predictable arrival may have less delay (4), as the engineer can factor in when vehicles will arrive and time the signals accordingly. The amount of delay experienced as a result of platooned arrival patterns is found by multiplying the d1 factor and progression factor, as contained in the $d1 \times PF$ aspect of equation 3.5.1. (4)

3.7 Incremental Delay

According the HCM (4), the incremental delay, or overflow delay, is attributed to the situation when the vehicular demand time from a given approach exceeds the green increment given by the traffic signal. In essence, this is the situation when more vehicles arrive at a given signal than can be served by that signal during a given cycle. As a result, not all vehicles can be served and some vehicles are delayed to the next green phase before they can proceed through the intersection. The amount of time delayed as a result of this occurrence is known as the incremental delay, and is the *d2* term in equation 3.5.1

3.8 Initial Queue Delay

The initial queue delay is the delay attributed to a preexisting queue at that intersection only, as defined by the HCM (4). The *d3* delay is simply the amount of time a vehicle waits for the vehicles in front of it to clear, once the lead vehicle has the ability to progress forward. In most situations, this is when the green phase begins, but in congested conditions, queues backed up from downstream intersections may postpone the start of the d3 delay. It is important not to confuse this delay with delays attributed to the intersection operating over capacity, or from delays attributed to queues at other intersections. This delay time, along with delay from *d1* and *d2* can be summed to get the overall delay, as defined in the HCM (4).

3.9 The d4 Term

In his doctoral thesis, Ahmed (5) described the need for a *d4* term. The *d4* term represents an additional delay that occurs as a result from the congestion occurring at other intersections. This d4 term can be used to account for the delay that occurs when the queues from one closely spaced intersection grows long enough to effect the operation of the other closely spaced intersection. The *d4* term is not included in the Highway Capacity Manual (HCM), and has been created to account for delays that are included in the *d1, d2,* and *d3* terms.

The d4 term is defined as the delay attributed to the "defacto red," or the delay that occurs when a vehicle cannot move through a green light because the queue from a downstream intersection has backed up to the intersection being investigated. As congestion grows, and delays lengthen along signalized networks, it is to be expected that the d4 delay will become more prevalent in congested highway networks. The d4 term is defined in detail in Ahmeds's (5) research. What is important to note for this dissertation, is that the d4 term can have significant effects when studying the delays at closely spaced congested signalized intersections. Thus this delay must be carefully considered when studying the delay at both a single intersection, as well as the delay for an overall highway network.

CHAPTER 4

CALCULATION OF THE DELAY EXPERIENCED BETWEEN CONGESTED SIGNALIZED INTERSECTIONS IN HIGH INTERACTION SITUATIONS

4.1 Introduction

Traffic engineers often coordinate signal timings along a major arterial such that a platoon of vehicles can progress the arterial without having to stop. One method to evaluate the effectiveness of the signal coordination would be to examine the delays experienced along the arterial (14). While the concept of using delay is straight forward, several challenges arise in developing a method of measuring this delay. The issue becomes especially problematic when there is interaction between traffic at neighboring intersections, which is typical of closely-spaced intersections.

When congestion and short spacing between intersections are present, studying delay only at one signalized intersection may result in evaluation and delay calculations that are incomplete. Only by examining the entire network can the full effects of delay be understood when there is high interaction between the intersections. The interaction of traffic between neighboring intersections must be taken into account, otherwise a portion of the experienced delay will be unaccounted for in oversaturated conditions. In certain conditions this consideration could be for just two or three intersections, in other cases it could be for an entire arterial.

4.2 Microscopic and Macroscopic Approaches

Theoretically, the total delay of the arterial could be calculated from both a macroscopic and microscopic approach. Among many things, a macroscopic study considers the interaction between vehicles and intersections in the vehicle stream, in an attempt to understand the system as a whole. A microscopic approach is concerned with the individual vehicles and their individual characteristics. They are each two different methods of studying the system.

A microscopic model tracks the movement of individual vehicles, and the characteristics of these vehicles. A microscopic model is straight forward in delay modeling, and for this reason, was chosen as the method of evaluating delay for this dissertation. The macroscopic model is more concerned with the stream of vehicles, or the interaction of the vehicle group itself. A macroscopic model would be a more difficult and confusing model to evaluate, as the examination of the intricate interactions of the vehicle stream would become very complicated.

Illustrating the difference between a microscopic and macroscopic approach, consider an arterial of signalized intersections. From a macroscopic perspective, the arterial is a highway with signal timings and complex vehicle interactions creating delays that are constantly interacting and changing. From a microscopic perspective, the arterial is merely a highway with x intersections and n vehicles, each having their own individual, and measurable characteristics. The components of the microscopic simulation are easily measurable and easily defined.

4.3 Calculating Delay Microscopically

The HCM (4) uses the formula in equation 4.3.1 to calculate the average delay for a vehicle at an individual intersection. As described in chapter 3, by calculating delay independent of other signalized intersections this "original" equation completely ignores the effect of queues from downstream intersections that affect the operation at an upstream intersection. In the case of congested conditions, the delay at a downstream intersection will cause a queue to form. If the queue becomes long enough, and the intersections are close enough together, the queue from a downstream intersection will reach the upstream intersection and cause additional delays.

By adding the d4 term, discussed in chapter 3, to equation 4.3.1 the equation becomes "modified" accounting for the delays associated with the d4 component. The d4 component represents the additional delay at that subject intersection caused by a queue backup from a downstream intersection. Note that equations 4.3.1 and 4.3.2 calculate the average delay only at one intersection, 'intersection A'. Intersection A can be found in figure 4.3.1.

$$Di\text{-}A\ (original) = d1 \times PF + d2 + d3 = D123 \qquad (eqn\ 4.3.1)$$

$$Di\text{-}A\ (modified) = d1 \times PF + d2 + d3 + d4 = D1234 \qquad (eqn\ 4.3.2)$$

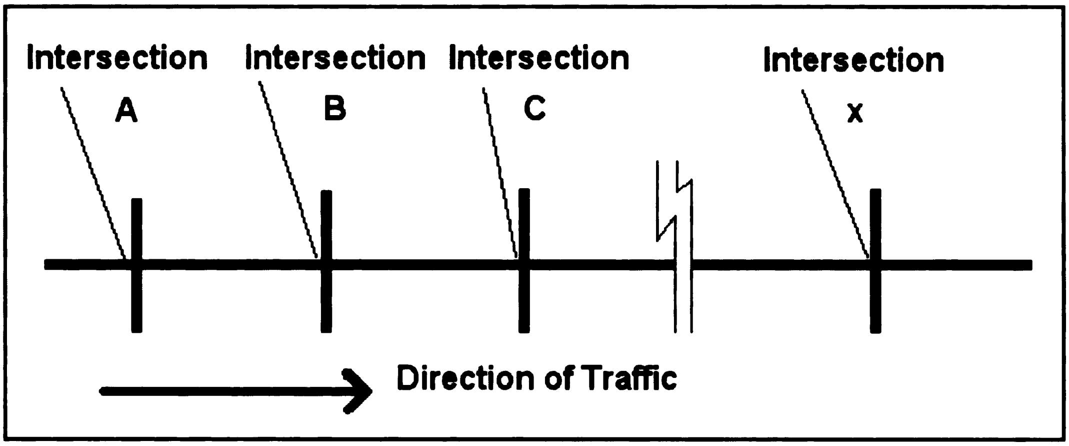

Figure 4.3.1 An arterial of signalized intersections

4.4 Deriving Delay Graphically

The delay experienced by a given vehicle (i) at an intersection (x) can also be found through a graphical model. This delay becomes the input for *Di-x* components in equation 4.3.3. Using a time space diagram, found in figure 4.4.1, a given vehicle *i* approaches Intersection A and incurs delay. Time is displayed along the X-axis, and distance along the Y-axis. For the traffic signal at intersection A, R_A represents the effective red time for northbound traffic, and G_A represents the effective green time for northbound traffic.

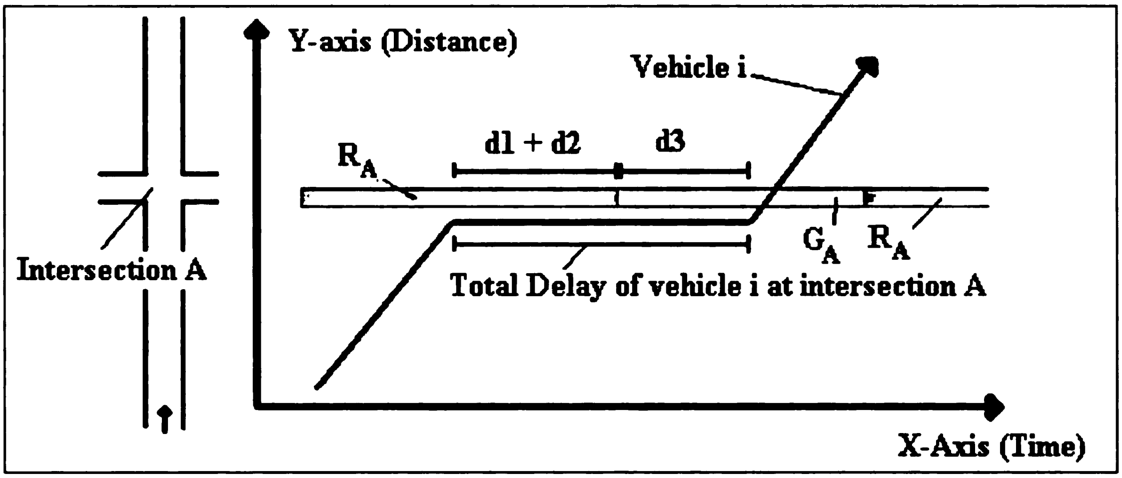

Figure 4.4.1 Delay of vehicle *i* at intersection A.

Figure 4.4.1 shows a time-space diagram of the progression of vehicle i through intersection A. In figure 4.4.1, vehicle i experiences a d1 and d2 delay when arriving during a red phase, and a d3 while waiting for a queue (not visible in this figure) of vehicles in front to dissolve. The Highway Capacity Manual (HCM) (4) refers to the sum of d1, d2, and d3 as the control delay. This is the portion of delay attributed to the presence of red at that given intersection and the lack of uniform traffic arrival patterns. This control delay was calculated in equation 4.3.1, and is repeated below. Please note that figure 4.4.1 ignores the delays from queues of downstream intersections, and thus ignores any d4 component of delay.

$$Di\text{-}A\ (original) = d1 \times PF + d2 + d3 = D123 \qquad (eqn\ 4.3.1)$$

The need for the d4 term is displayed graphically in figure 4.4.2. In this figure, two closely spaced intersections are examined. As illustrated, the queues from Intersection B impact the operation of Intersection A, and thus illustrate the need for the d4 term.

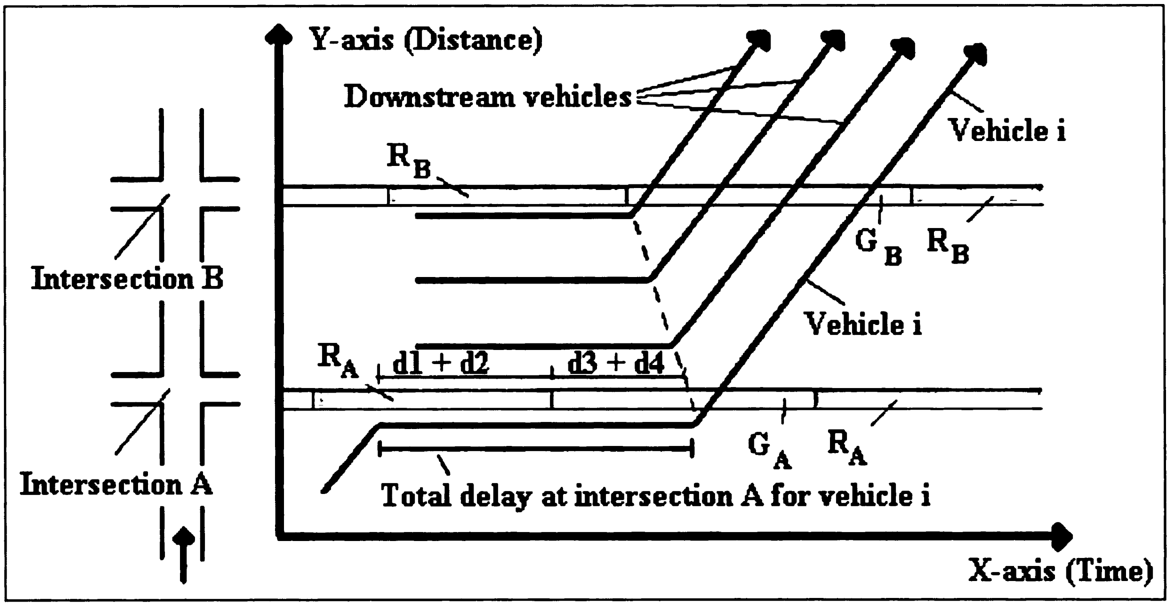

Figure 4.4.2. Delay of vehicle *i* at intersections A and B.

In figure 4.4.2, the delay of other queued vehicles from intersection B cause vehicle i to experience additional delay at intersection A. This extra delay illustrates the need for the d4 term, as delay attributed to backups from other intersections is not included in the d1, d2, or d3 delays. Thus the delays experienced by vehicle i, after the red phase ends, are accounted for under the d3 and d4 delay terms. The challenge is to differentiate which portion of delay is d3, and which portion is d4. Further, the d3 and d4 of figure 4.4.2 at intersection A may even impact the d1, d2, and d3 delays of intersection B. Thus when traffic interacts, it becomes more complex to capture delay using analytical models.

The d3 delay is the delay vehicle i experiences while waiting for the queue at intersection A to dissipate. The d4 delay is the delay incurred waiting for the queue from a downstream intersection (intersection B) to dissipate. The key difference is identifying where the queue originates, and which vehicles are delayed by which queue. A queue beginning at intersection A creates the d3 delay. A queue beginning downstream at intersection B creates a d4 delay. Distinguishing the starting point of the queue that creates the delay allows for the determination of whether the delay is a d3 delay or a d4 delay. Regardless, the queued delay can be *either* d3 or d4, *but not both.*

4.5 Graphically Illustrating d4 Delays in Congested Conditions

In oversaturated conditions, queues delayed at one intersection can have severe effects on upstream intersections. As illustrated in figure 4.5.1, the queue at intersection B is so severe that other vehicles cannot utilize the green time at intersection A. The inability of vehicle i to utilize the green time creates a situation where a 'defacto red' is present. In the example in figure 4.5.1, the delay experienced by vehicle i at intersection A includes the normal d1 and d2 delays, plus a d4 delay during the entirety of the green phase, known as a 'defacto red' period. Because the d4 delay occurs for the entirety of the green phase for this particular timing arrangement, vehicle i also experiences another d1 and d2 delay before being able to finally proceed. Thus to calculate the overall control delay experienced by vehicle i at intersection A both d1 terms, both d2, the d3 term and the d4 term must all be summed. Adding all values, the delay occurring at that intersection is accurately calculated. This is the total delay for vehicle i at intersection A.

As explained, forming an analytical model of delay is extremely difficult due to the complex interaction of the various types of delays. Further, because of the interaction of delays between upstream and downstream intersections, congested condition delay cannot be independently modeled for one just intersection when surrounded by other closely spaced signalized intersections. The interaction of the various d1, d2, d3, and d4 delays for one vehicle queued from a downstream intersection can cancel-out or induce another d1, d2, d3, or d4 delay to occur for a vehicle at an upstream intersection.

The important point to this analysis is that the interaction of delays between vehicles and upstream and downstream intersections is very complicated. There is significant interaction occurring and the various delays cannot be modeled macroscopically. A microscopic approach, looking just at the delays for one vehicle while taking into consideration the queues from other intersections can model the delay that occurs. So while the analysis from a macroscopic perspective is very complicated, the microscopic perspective allows for the control delay to be calculated.

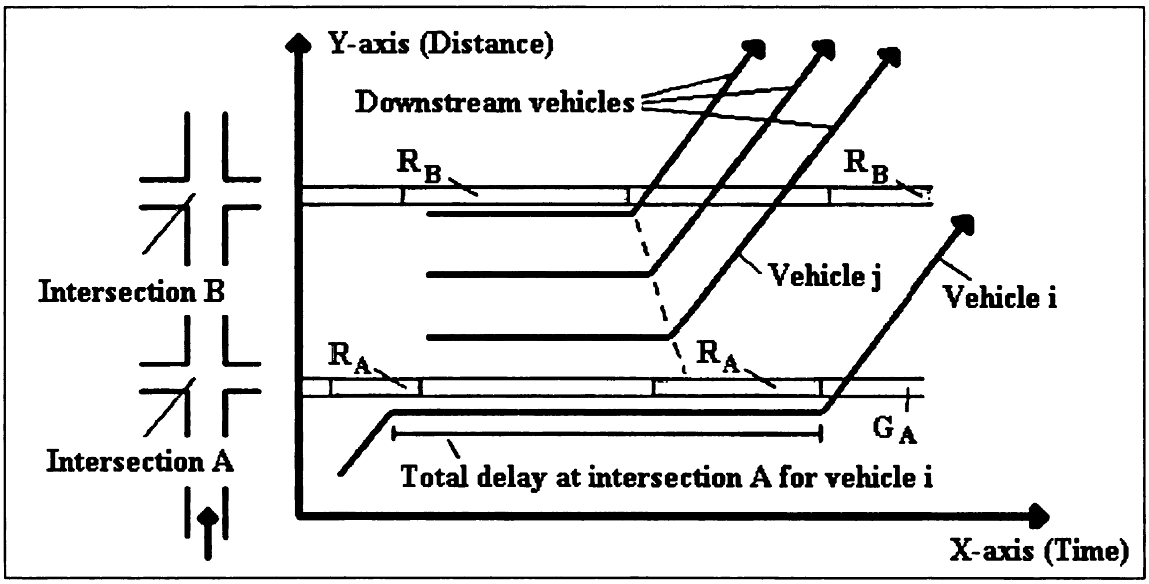

Figure 4.5.1. Delay in congested conditions

In certain situations, such as in figure 4.5.1, with multiple d1, d2, and even multiple d4 delays, the total delay at the at intersection is still merely the sum of all delays experienced at that intersection. Because vehicles are not delayed arbitrarily, their delay must be the result of one of the d1, d2, d3, and d4 components.

As shown, the d3 and d4 terms are exclusive, meaning a delay cannot be 'counted twice.' The term exclusive means that the delay a vehicle is experiencing can be represented by either d1, d2, d3, or d4 but never by two at the same time. Being 'exclusive' means a delayed vehicle cannot be accumulating both d1 and d2 delay simultaneously, for example, even though the two may be related. The Highway Capacity Manual (4) defines that a delay is either exclusively d1 or d2, but not both at the same time.

Finally, because d1 and d2 delays occur during red phases, and because d3 and d4 delays occur during green phases, these delays are also exclusive from each other as well. Thus, all d1, d2, d3, and d4 delays are exclusive, and no delay can be counted twice, (a delay cannot be both a d1 delay and a d2 delay for example). Thus the total delay at any one intersection is simply the sum of the individual and exclusive d1, d2, d3, and d4 values, no matter how many times they repeat. This defends the claim of the modified control delay equation 4.3.2, repeated below, where Di-A is the averaged delay at intersection A for a given vehicle.

$$Di\text{-}A\ (modified) = d1 \times PF + d2 + d3 + d4 = D1234 \qquad (eqn\ 4.3.2)$$

Consider again figure 4.5.1. In the event of two neighboring intersections, the d3 delay of vehicle j at the downstream intersection may cause a d4 delay for vehicle I at the upstream intersection. Regardless that both vehicles experience the same delay for possibly the same duration, two delays are still experienced by two separate vehicles. For instance, if the a 20 second d3 delay for vehicle j at intersection B causes a 20 second d4 delay for vehicle i at intersection A, together vehicles i and j still experience a combined 40 seconds of delay at A and B. So even though the d3 and d4 interact, and even though intersection A and B are separate intersections, everything must be considered together. The two vehicles cannot be considered independently, nor can the two intersections be considered independently.

4.6 Calculating the Overall Delay for Signalized Intersections

As mentioned in section 4.1, delay cannot be calculated for an independent intersection in a congested network of closely spaced intersections. For this reason, the only way delay can effectively be modeled without neglecting the d4 term is to use a model of multiple intersections. This model will then account for the multiple and exclusive d1, d2, d3, and d4 delays experienced by all vehicles along the arterial. Neglecting sink and source traffic, turning movements, and other outside sources of delay, the total delay incurred while crossing the arterial of signalized intersections is simply the sum of all the d1, d2, d3, and d4 components.

It is important to note that the control delay at an intersection is the sum of the d1, d2, d3, and d4 components. However, the complicated interaction of these delays between intersections may prevent the control delay from being independently calculated for closely-spaced signalized intersections operating in congested conditions. If the delays at one intersection cannot be modeled independently, it then become of more value and practicality to calculate delay across an entire arterial of signalized intersections.

In addition to addressing the need of calculating delay across an arterial of intersections, the following paragraphs discuss the calculation of delay for a series of signalized intersections, and for multiple vehicles traveling across that series of intersections. These calculations will be needed in chapter 5 for producing simulated models of signalized intersection in congested conditions.

4.7 Calculating Control Delay For Multiple Vehicles and Signalized Intersections

To calculate the delay experienced by an individual vehicle traveling on an arterial of multiple signalized intersections, a different method than the HCM is needed. Again, figure 4.3.1 illustrates an arterial of x intersections, with vehicles passing signalized intersections A, B, C, ... to signalized intersection x.

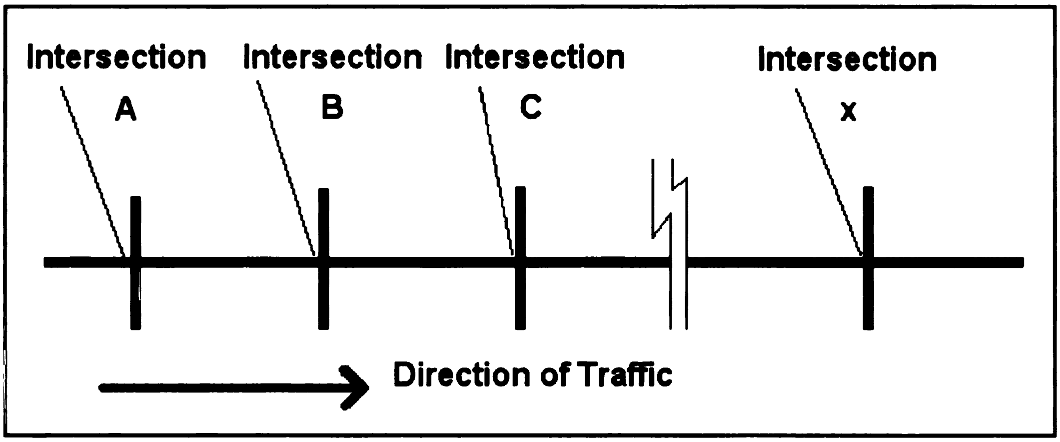

Figure 4.3.1 An arterial of signalized intersections

Considering a vehicle passing through the signalized intersections in Figure 4.3.1, delay may be experienced at some intersections, all intersections, or no intersections. If no delay is experienced at a given signalized intersection, the delay value is simply zero. If delay is experienced, the amount of time spent delayed at the intersection is represented by the Di-x term, where x represents the intersection where the delay occurred.

Examining just the intersections of A and B, if a vehicle were to experience a delay of 20 seconds at intersection A, and 5 seconds at intersection B, then the total amount of time the vehicle spent in delay while traversing intersection A and B would be:

20 seconds (Di-A) + 5 seconds (Di-B) = 25 seconds (Di-total)

Again the Di-A delay, or the 20-second delay, represents the total control delay experienced by vehicle i at intersection A, or the sum of the d1, d2, d3 and d4 delays at this location. In this example, vehicle i spent a total of 25 seconds in delay traveling through intersections A and B. If the vehicle then encountered 10 seconds of delay at intersection C, the total delay experienced for all 3 intersections would be 35 seconds. Thus for one vehicle traveling along arterial of signalized intersections, the total delay experienced is calculated by adding up all the delays experienced across that arterial.

From the perspective of vehicle i traversing the arterial in figure 4.3.1, the total delay experienced traveling from intersection A through intersection x is found by simply summing all delays experienced at each intersection of the arterial. This is represented in equation 4.7.1.

$$Di\text{-}total = Di\text{-}A + Di\text{-}B + Di\text{-}C + \ldots\ Di\text{-}x \qquad (eqn\ 4.7.1)$$

Each vehicle traveling across the arterial in figure 4.3.1 experiences some value of delay, even if that value is zero. For instance, consider the arterial in figure 4.3.1 with only two vehicles (vehicles 1 and 2) traveling from intersection A to x. If vehicle 1 were to experience a total delay of 50 seconds while traversing the arterial, and vehicle 2 were to experience a total delay of 30 seconds, the total delay experienced along the arterial is the total delay experienced by both vehicles. This would be:

50 sec (delay of vehicle l) + 30 sec (delay of vehcile2) = 80 sec (D arterial-total)

Just as the total delay for an individual vehicle can be found by summing all delays experienced along the arterial, so can the total delay of the arterial be found by summing, for all vehicles, the total individual delays experienced by each vehicle while traversing the arterial of signalized intersections. This calculation is presented in Equation 4.7.2, and is the total delay experienced along the arterial.

D arterial-total = D(intersection) total + D(intersection 2) total +

D(intersection 3) total + . . . + D(intersection n) total.

(eqn. 4.7.2)

In Equation 4.7.2, the total delay for the arterial (*D arterial-total)* is the summation of the total individual delays (*Di-total*) experienced by each individual vehicle(*i*), for all *n* vehicles traveling the length of the arterial. In essence, the total delay of the arterial is the summation of the total individual delays (found in equation 4.7.1) for all n vehicles traveling the length of the arterial.

4.8 Conclusions from Chapter 4

A method for calculating the overall delay at a signalized intersection can be developed based on a summary of the ideas presented in Chapter 4. These key concepts are:

- A microscopic model is the most straight-forward and effective approach to modeling delays at a signalized intersection. By studying the individual vehicles, and not the macroscopic trends of the traffic stream, manageable data can be gathered and studied.

- The d1, d2, d3, and d4 terms all interact, and one may influence or create another. Regardless, each delay that occurs is represented only by d1, d2, d3, or d4, and never by two components at the same time. As a result, the control delay at any one intersection is simply the sum of all d1, d2, d3, and d4 delays that occur.

- In congested conditions, the queues from downstream intersections can have a significant effect on the delays at an upstream intersection. For this reason, closely spaced intersections in congested conditions cannot be modeled independently, and that delays must be calculated for multiple intersections.

- Because delays at intersections cannot be modeled independently, it is of more value and practicality to calculate delay across an entire arterial of signalized intersections.

- Finally, the total delay of an arterial is simply the sum of all the total delays of all vehicles traversing the network. The total control delay of each vehicle is also the sum of every d1, d2, d3, and d4 delay that as experienced along the route.

Using the conclusions of chapter 4, a procedure can be developed for calculating and modeling delay for arterials of signalized intersections. Again, simply focusing on one individual intersection ignores the d4 delay. Thus evaluations must be made for arterials of signalized intersection, to properly account for all delays that are occurring.

CHAPTER 5

MODELING DELAY FROM A SAMPLE OF VEHICLES

5.1 Introduction

To calculate the control delay occurring at signalized intersections, the individual delays of each individual vehicle would need to be tabulated and averaged. For practical purposes, the process of collecting and evaluating data for every vehicle at a given location would be difficult, expensive, and impractical, and in certain instances, the location in question has not even been built. Therefore, with some degree of error, a sample set of vehicles can be studied as a reasonable representation of the overall system. Using this representation, the total delay of all vehicles can be approximated using data from a sample set of delays, obtained from vehicles on the arterial.

This chapter discusses the development of a procedure to predict the delay at a signalized intersection, based on a sample set of vehicles from that arterial. The three main objectives of developing this procedure are to:

- *validate* the assertions made in Chapter 4 that the delay at an intersection really is the sum of the d1, d2, d3, and d4 delays for all vehicles traversing the arterial of signalized intersections,
- *develop* a model of predicting delay at an intersection or series of intersections, based on the delay characteristics of vehicles within a given sample, and
- *evaluate* how accurate the model's prediction of delay is compared to total delay that is actually occurring.

As explained in Chapter 4, the delays between closely spaced intersections constantly interact in congested conditions. For this reason, it is not be possible to separate out all delays. A way around this issue is to examine delays for two or three closely spaced intersections. By studying the delay across all the interacting intersections, control delay can be evaluated.

5.2 The Need for a Model to Predict Control Delay at an Intersection

To obtain the needed data for calculating control delay, and without the availability of data from the field, a simulated model was created to obtain the necessary data for evaluation. As mentioned, the process of collecting actual data for every vehicle along a given location would be difficult, expensive, and impractical. Yet to evaluate the procedure of predicting intersection delay based on a sample set of vehicles, data is needed for both the intersection being studied and the surrounding downstream intersections. For this reason, a microscopic simulation model became the practical choice to obtain the necessary data.

VISSIM Traffic Software was used to create a microscopic simulation to model the arterial with signalized intersections. An advantage of VISSIM is its ability to both model traffic flow conditions at signalized intersections, but also take into consideration the interaction of vehicles at closely spaced signalized intersections, in congested conditions. VISSIM also can be used to evaluate the delays of vehicles traveling the simulated intersection or intersections.

5.3 The VISSIM Model

VISSIM is a software package that is used by transportation engineers to evaluate simulated highway conditions at a macroscopic level. VISSIM can take into consideration the interaction of delay between intersections, and account for delays associated with lengthy queues and blocked intersections during conditions of simulated congestion. To ensure the occurrence of delay, the model was designed so that congestion would occur.

To ensure the procedure would not be limited to the simulated design of one model, five different VISSIM models were created. The five simulated models consisted of the following parameters:

- Each of the five models simulated 1000 vehicles traveling across an arterial of 3 signalized intersections. The intersection geometry and lane usage were consistent for all five of the simulated models.
- In all five simulated models, only through movements were simulated, and there were no sink or source traffic inputs that could cause and incur more delay.
- During the initial run, the first 2 minutes of simulation were excluded allowing the system to reach fully congested conditions before data collection began. After the completion of the initial 2 minutes, collection of data began and the simulation continued until 1000 vehicles traversed the system.
- The five models differed in link distances between signals, in signal timing plans and offsets, and in vehicle volume inputs.
- Different random seeds were used for each model, to ensure variation in traffic generation characteristics.
- To further ensure differences in traffic patterns, different vehicle densities were

created. This was done by adjusting the length of time to simulate 1000 vehicles. For example, 1000 vehicle simulated over one hour would have half the density of 1000 vehicles simulated over a half hour.

- Delay was evaluated over the arterial of signalized intersections, and not just at one intersection. As mentioned, the delays between intersections are constantly interacting. Thus to accurately model control delay, the examination needs to be over a system of multiple signalized intersections. In the case of this simulation, 3 intersections were chosen.

The cycle lengths of the three intersections, input volumes, and the duration of simulation for each of the five models are contained in Table 5.3.1.

Table 5.3.1 VISSIM model parameters

Model		1	2	3	4	5
Cycle Lengths	**sec**	60	70	80	90	100
Veh/Hr/Lane Input	**veh/h**	1000	2000	1334	1000	2000
Simulation Length	**min**	60	30	45	60	30

Using the parameters listed, the five VISSIM models were created to simulate an arterial of signalized intersections during congested conditions. Table 5.3.2. contains the output file information obtained from the VISSIM model. In the table, the delays incurred by the 834^{th} vehicle of Simulation 1 are presented. Vehicle 834 was chosen randomly to be a case example. Over the course of the three intersections, VISSIM found that vehicle 834 incurred 134.1 seconds of delay at all three intersections. VISSIM also found the overall delay to be 25,501.70 seconds for the 3-intersection arterial, as experienced in total by all

1000 vehicles. Using data from the VISSIM output files, and shown in table 5.3.2, the following observations were made:

- As shown in table 5.3.2, delay for an arterial can be obtained by summing the delays experienced at each of the signalized intersections, as the sum of delays at intersection 1, 2, and 3 equaled the total delay of the vehicle across the arterial.
- The total delay of an arterial is the sum of the total individual delays for each of the vehicles. Shown in table 5.3.2, the data from the VISSIM output file matched the sum of all control delays for the tabulated 1000 vehicles traversing the arterial of signalized intersections.

Table 5.3.2. VISSIM outputs

	Observed Delay (in seconds) at:				
	Intersection 1	*Intersection 2*	*Intersection 3*	**Sum**	
Vehicle 834:	**45.2**	**38.6**	**50.3**	**134.1**	**(Sec)**
VISSIM Output of Total Delay of Vehicle 834 Across Arterial =				**134.1**	**(Sec)**
VISSIM Calculation for Total Network Delay:			**25,501.70**	**(Sec)**	
Sum of Total Individual Delay for all 1000 Vehicles:			**25,501.70**	**(Sec)**	

5.4 Results of the VISSIM Model

From the 1000 delay samples generated for each of the five models, the delay values of 200 vehicles were randomly chosen. From those 200 delays, an individual delay was randomly chosen and placed into a list, followed by another random draw, followed by another random draw, and then followed again until all 200 delays had been listed in random order. This was performed for all five models, creating five different lists of 200 random delays for each of the five models simulated.

Random Draw and Experienced Delay

In table 5.4.1, the results from one of the five simulations are shown. The delay value represents the total amount of time it took for a simulated vehicle to traverse the simulated 3 intersection system. The first column identifies the *n-th* random draw, between 1 and 1000. The second column, titled experienced delay, describes the total delay experienced by the *n-th* randomly drawn vehicle.

Cumulative Delay

The cumulative delay in the third column is calculated by summing the delay of that random draw, and the delay of any previously drawn values. The cumulative delay is calculated in equation 5.4.1.

Cumulative Delay = Experienced Delay for Random Draw (n) + Experienced Delay for Random Draw (n-1) + ... + Experienced Delay for Random Draw (1).

(eqn. 5.4.1)

Cumulative Average Delay

The cumulative average delay is derived by dividing the cumulative delay by the number of random draws (n) that have occurred. This is shown in equation 5.4.2.

Cumulative Average Delay = Cumulative Delay / Number of Random Draws (n)

(eqn 5.4.2)

Table 5.4.1 Cumulative accuracy

Random Draw	Experienced Delay	Cumulative Delay	Cumulative Average Delay	Accuracy
n	*sec*	*sec*	*sec*	*%*
1	106.60	106.60	106.60	83.60%
2	122.90	229.50	114.75	89.99%
3	127.70	357.20	119.07	93.38%
4	148.80	506.00	126.50	99.21%
5	147.10	653.10	130.62	97.56%
6	109.30	762.40	127.07	99.65%
7	144.30	906.70	129.53	98.42%
8	116.10	1022.80	127.85	99.73%
9	137.50	1160.30	128.92	98.89%
10	142.00	1302.30	130.23	97.87%
20	94.20	2489.10	124.46	97.61%
50	130.00	6324.40	126.49	99.20%
100	105.00	12660.20	126.60	99.29%
200	150.60	25361.90	127.45	99.95%
1000	139.80	25501.70	127.51	100.00%

Accuracy

The cumulative average delay for the 1000th vehicle is equal to what the average delay would be if calculated for all 1000 vehicles. Thus by collecting data on all 1000 vehicles, an average delay could be calculated with 100% accuracy. However, if the average were derived from a sample of only 500 vehicles, there would be some degree of error. The error is reflected in the accuracy.

The accuracy refers to how accurate the cumulative average delay is for a sample size of n random draws, when compared to the cumulative average delay value for all 1000 delay samples. As the sample size increases, the accuracy of the cumulative random delay generally approaches 100%. The accuracy represents how close the cumulative average delay at a given random draw is to the overall average delay for all 1000 vehicles traversing the arterial. The formula for calculating the accuracy in Table 5.4.1 is found using Table 5.4.2.

Table 5.4.2 Calculating the accuracy value

Let A =	Cumulative Average Random Delay Value at Random Draw #n		Let B =	Cumulative Average Random Delay Value at Random Draw #1000
If A < B :	Accuracy = [A / B] * 100 %			
If A > B :	Accuracy = [(B - (A - B)) / B] * 100 %			

5.5 Plotting the Simulation Results

Using the method described in Table 5.4.2, the accuracies were calculated for the first 200 randomly drawn delay values in each of the 5 simulations. As expected, when the sample size increased the accuracy approached 100%. Figure 5.5.1 and 5.5.2 plot the accuracy against the sample size.

Using the first 200 random draws, Figure 5.5.1 compares the percent accuracy value, found in the last column of Table 5.5.1, with the amount of random draws. Figure 5.5.2 exhibits the *same plot*, but instead the x-axis is labeled by the sample size, for the first 200 samples. The percent of the sample size is calculated by dividing the number of samples by 1000, the total number of samples.

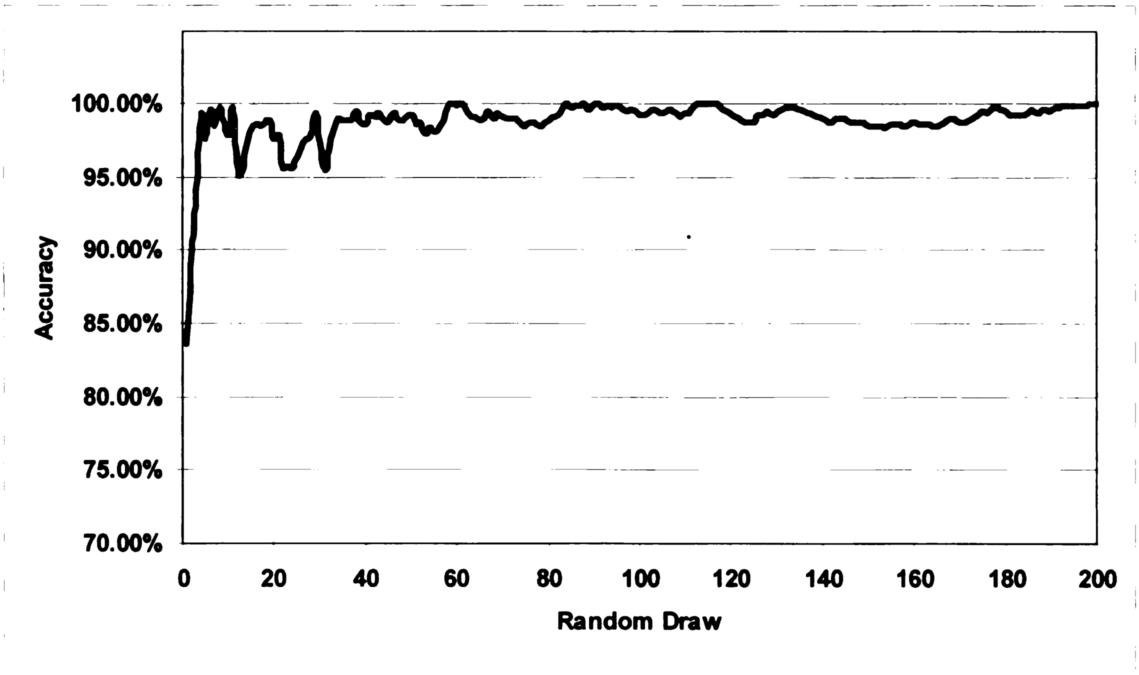

Figure 5.5.1 Accuracy vs. random draw for simulation #1

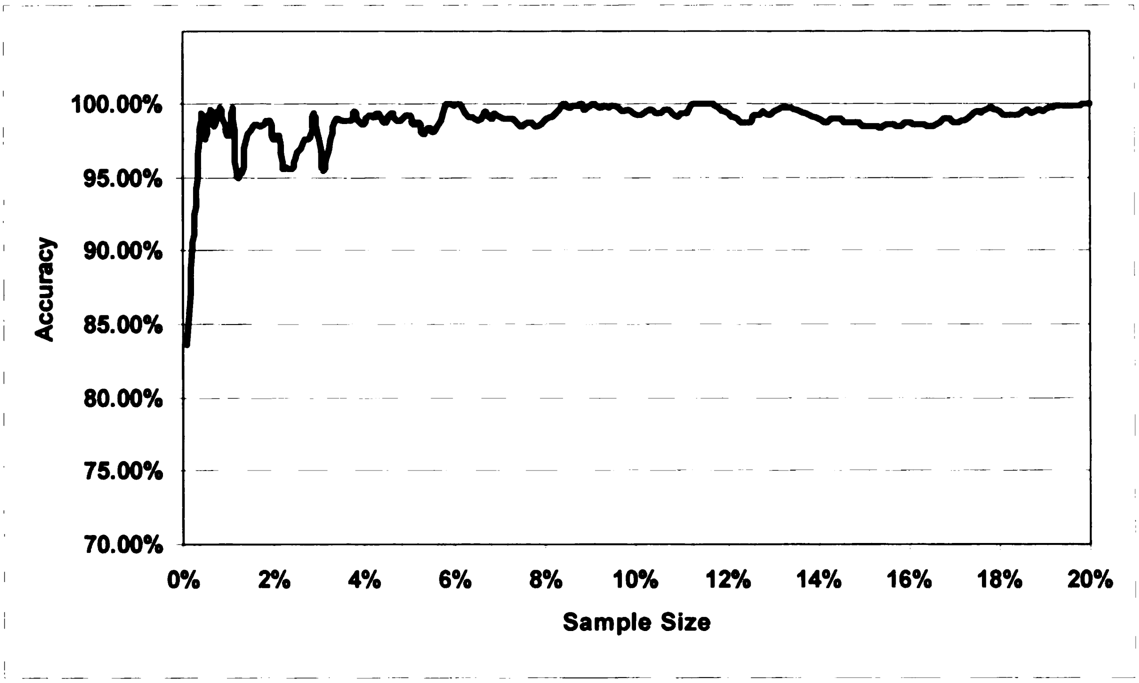

Figure 5.5.2 Accuracy vs. sample size for simulation #`1

A similar plot is generated for each of the other four simulations. These plots are found in Figures 5.5.3 through Figure 5.5.6. Combining the plots for all five simulations, Figure 5.5.7 is developed. An examination of Figure 5.5.7 shows that all 5 simulations exhibited the expected general trend that as the sample size increases so to does the accuracy.

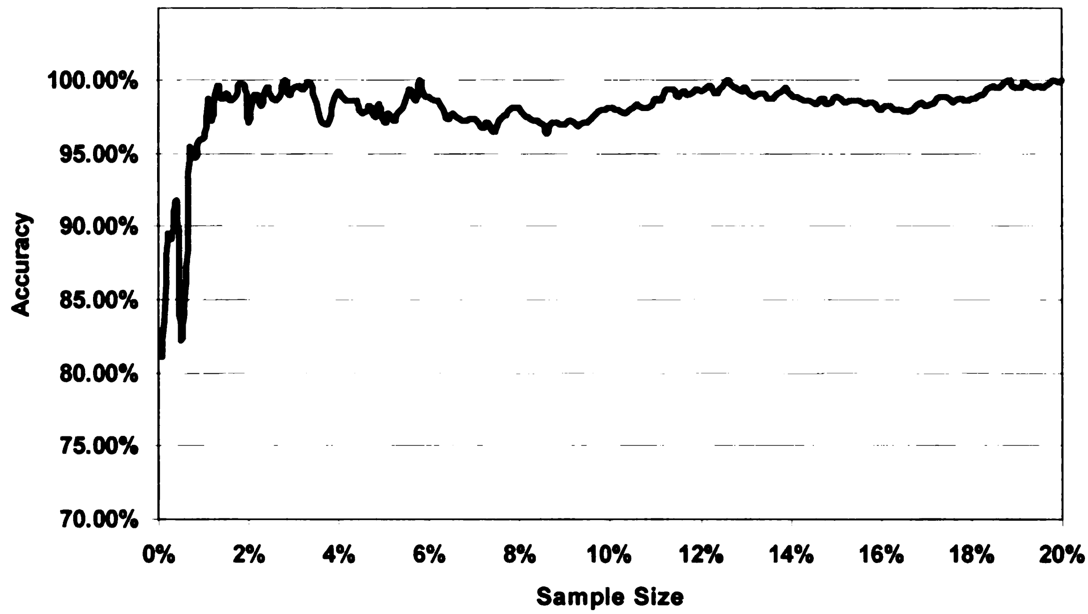

Figure 5.5.3 Accuracy vs. sample size for simulation #2

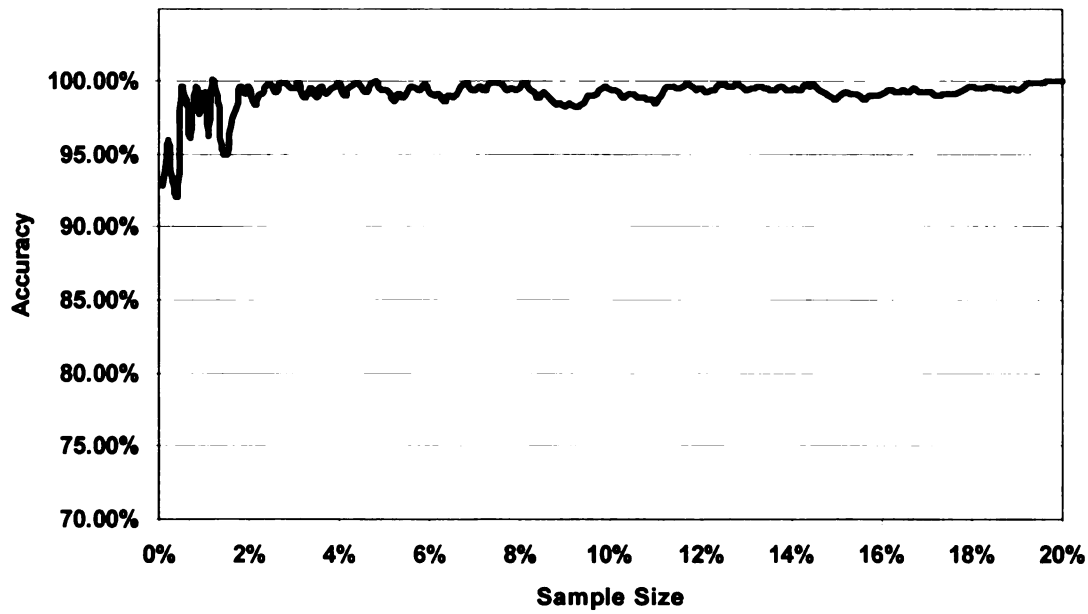

Figure 5.5.4 Accuracy vs. sample size for simulation #3

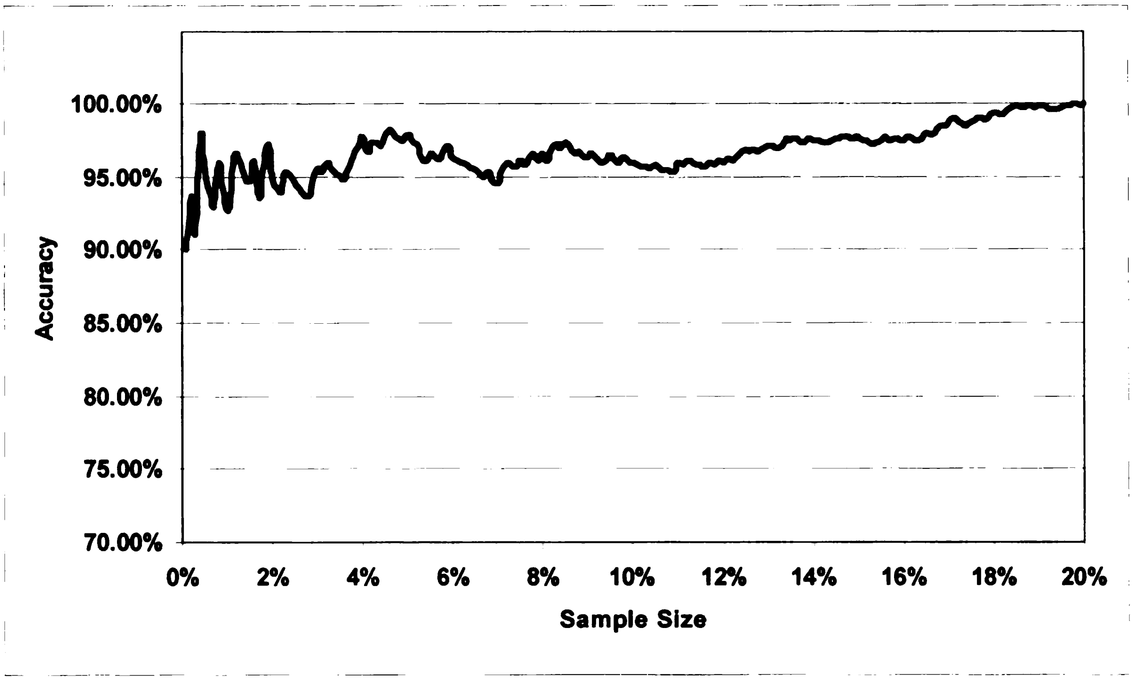

Figure 5.5.5 Accuracy vs. sample size for simulation #4

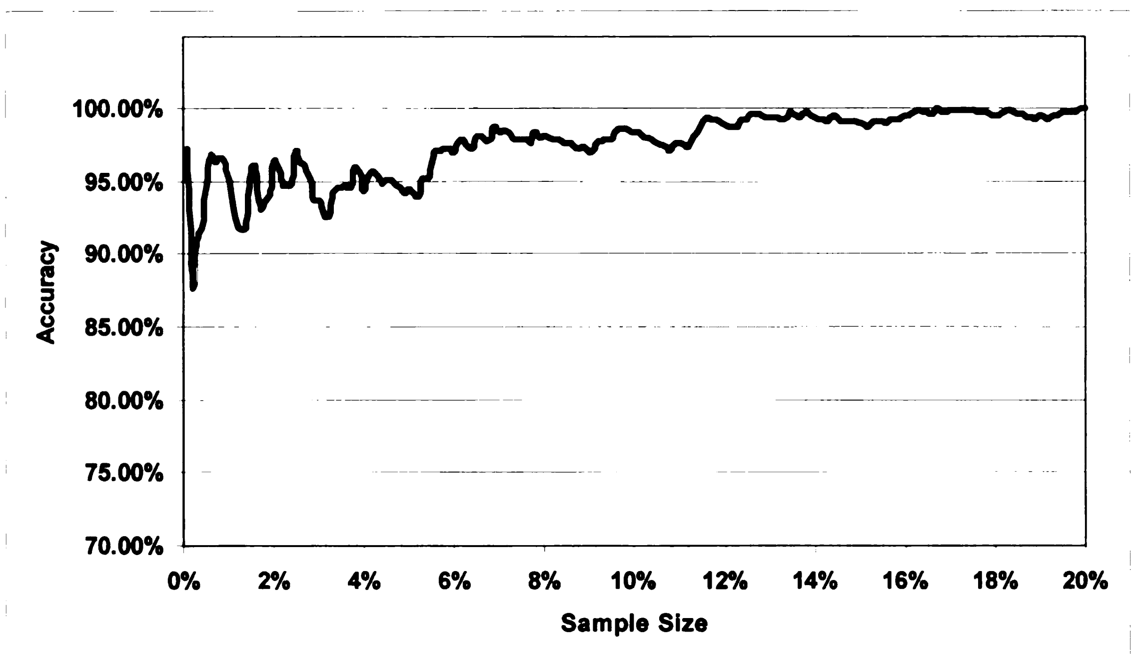

Figure 5.5.6 Accuracy vs. sample size for simulation #5

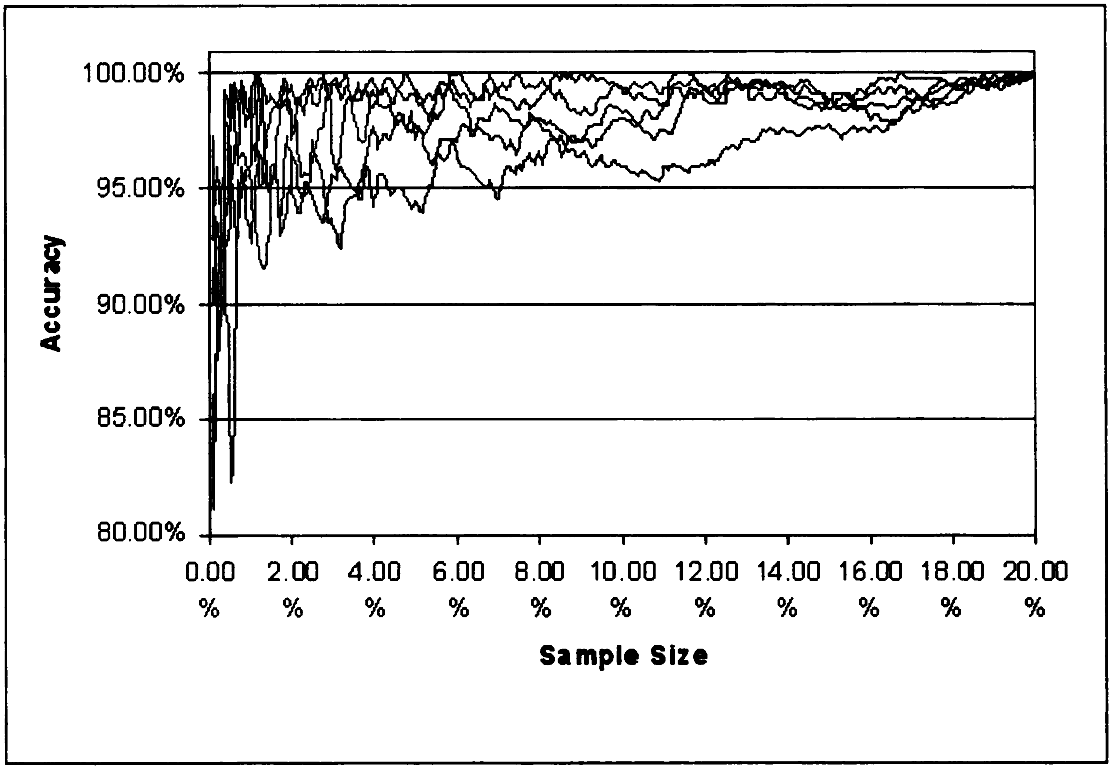

Figure 5.5.7 Accuracy vs. sample size for all simulations combined

From the VISSIM model outputs, and a review of figure 5.5.7, the following observations can be made:

- As expected, when sample size increases, so too does the accuracy.
- All five simulated models produced outputs generally following the same trend.
- In all five models, only a relatively small sample size (8%) was needed to achieve a high degree of accuracy (95%).
- With similar trends, and only a small sample size needed to achieve high accuracy, a sample could be used to project the overall delay occurring along an arterial of signalized intersections.

5.6 Significance of the Results

As shown, only a small sample size is needed to achieve high accuracy. This solves the challenge expressed earlier of obtaining the many individual delays that occur at each intersection. This also validates the claim that a macroscopic approach is in fact not needed, and that a microscopic procedure can be used to calculate control delay. By simply gathering information on a few vehicles, delay can be accurately estimated from a microscopic approach.

The data in figure 5.5.7, is significant, because it can be used to determine what sample size is needed to achieve a given accuracy. Further, a "general range of accuracy" can be developed for various sample sizes. As shown below in figure 5.6.1, all plots fall above a boundary that can be used to predict the amount of accuracy for a given sample size. Thus using the general range of accuracy above this lower bound, one could be confident that delay with 90% accuracy can be obtained from a sample size of 3%. Similarly, achieving an accuracy of 95% can be achieved with a sample size of 12%. Using this information, and a knowledge of what degree of accuracy is needed, a proper sample size could be selected to calculate the total delay along an arterial. While all the results from a microscopic simulation can be easily tabulated, collection of all delays from the field is not practical. This is why a sample is chosen.

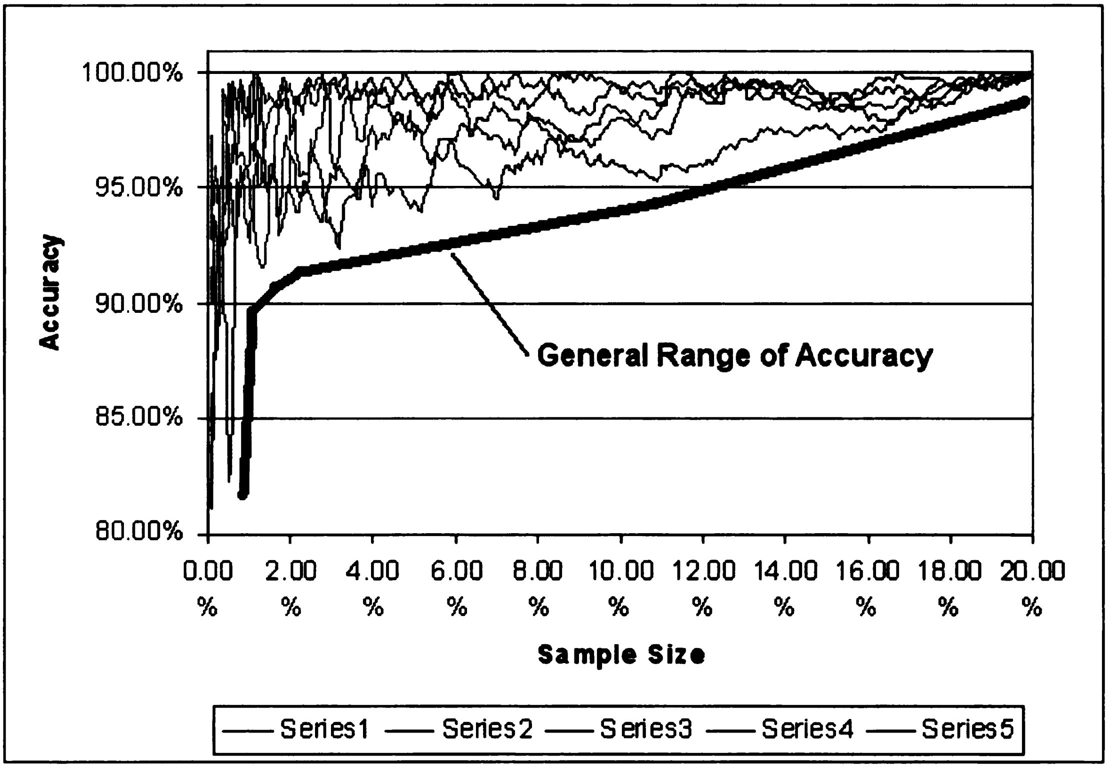

Figure 5.6.1 General range of accuracy

The three main objectives of the simulated model were to validate the assertions that total control delay is a summation of the individual delays, develop a procedure for predicting delay, and evaluating its accuracy. Table 5.2.2 addressed the first objective in validating the assertion that the overall delay of an arterial is a sum of the total delay of each vehicle, and that the total delay of each vehicle, is the sum of the individual delays at each intersection. The objective of developing a method to predicting delay can be met by using figure 5.6.1, and the objective of evaluating the model's accuracy can also be validated by figure 5.6.1 which show that accuracy is a trend that can be linked to sample size.

Thus the objective of calculating total delay along an arterial of signalized intersections is obtained by simply by summing up the individual delay components of each vehicle. By sampling the delays from a small set of vehicles, the overall delay of the arterial can be predicted with a high degree of accuracy. Finally, by creating a simulated model, the amount of accuracy can easily be predicted for various sample sizes.

CHAPTER 6

CONCLUSONS AND RECOMMENDATIONS

6.1 Introduction

Current models for calculating delay at a signalized intersection overlook the impact of downstream conditions on upstream, signalized intersection operations. A situation where queues from downstream intersections can and do have an impact are at upstream, closely-spaced signalized intersections operating in congested conditions. These queues affect the operation and capacity of the upstream intersection, and can have significant impact on the control delay that is experienced. The interaction of traffic between neighboring intersections must be taken into account, otherwise a portion of the experienced delay will be unaccounted for in oversaturated conditions. In certain conditions this consideration could be for just two or three intersections, in other cases it could be for an entire arterial.

The research focuses on the method that control delay is calculated in the HCM (4), and also adds the d4 delay term defined by Ahmed (5). Together, the d1, d2, d3, and d4 terms can be microscopically summed to obtain a control delay. Unfortunately because of the complex macroscopic interaction of the delay terms, control delay cannot be modeled independently for one signal, making it of more value and practicality to calculate delay across an entire arterial of signalized intersections.

6.2 Conclusions

The following points are the main conclusions of this research:

- To model delays at a signalized intersection, a microscopic model is the most straight-forward and effective approach. By studying the individual vehicles, and not the macroscopic trends of the traffic stream, manageable data can be gathered microscopically and studied.

- There is interaction among the d1, d2, d3, and d4 terms, as one may influence, create, or eliminate another. Each delay that occurs is represented exclusively by only d1, d2, d3, or d4, and never by two components at the same time. As a result, the control delay at any one intersection is simply the sum of all d1, d2, d3, and d4 delays that occur.

- The queues from downstream intersections can have a significant effect on the delays at an upstream intersection in congested conditions. Thus closely spaced intersections in congested conditions cannot be modeled independently, and that delays must be calculated for multiple intersections.

- Further, because delays at intersections cannot be modeled independently, it is of more value and practicality to calculate control delay across an entire arterial of signalized intersections.

- The total delay of an arterial is simply the sum of all the total delays of all vehicles traversing the network. The total control delay of each vehicle is also the sum of every d1, d2, d3, and d4 delay that as experienced along the route.

- A microscopic simulation model is the practical choice to obtain the necessary data without having to collect actual data for every vehicle along a given location. Actual data collection would be difficult, expensive, and impractical. Yet to evaluate the procedure of predicting intersection delay based on a sample set of vehicles, this data is needed.

- VISSIM can be used to simulate a model of closely spaced signalized intersections. Using the output files from the VISSIM simulation, the interaction of the closely spaced signalized intersections can be studied for congested conditions.

- Only a small sample size is needed to achieve highly accurate control delay predictions, solving the challenge expressed earlier of obtaining many individual delays occurring at each intersection. This also validates the claim that a macroscopic approach is in fact not needed, and that a microscopic procedure can be used to calculate control delay for an intersection.

- Finally, the questions as to whether delay is an appropriate measure of effectiveness must also be considered. With federal funding for remediation based on air quality standards, and with the level of comfort and productivity increasing for drivers in a vehicle, delay in terms of time may not be as effective a measurement as it once was. This then raises the question as to whether the

Highway Capacity Manual can be used as an effective analytical procedure for such conditions.

6.3 Recommendations

Based upon the stated conclusions, the following recommendations are made for further studies:

- A d4 term should be added to the equation for calculating control delay in the Highway Capacity Manual. (4)
- Other factors such as sink and source traffic, turning movements at the signalized intersections, and pedestrian influences could also be studied to see how they compliment control delay in determining the actual overall delay experienced by a given vehicle.
- Other parameters such as lane changes, heavy vehicles, and decelerations unrelated to signals all have effects on delay. While not addressed in control delay, these causes of delay could be sources for further study.
- The effects of d4 delays on adaptive control signals may be significantly different than those at traditional signals. This could be used for further research.

In summary, the development of the d4 terms raises awareness to other causes of delay occurring among signalized intersections. The d4 term can be used to develop new procedures and models to increase the understanding of delay. Through increased knowledge and understanding of why delay occurs, engineers will be better equipped to deal with the growing issue of congestion.

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