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Analysis and evaluation of the impact of the length of left-turn lane on signalized intersection delays

Nitin Kalsi
University of Nevada, Las Vegas

ANALYSIS AND EVALUATION OF THE IMPACT OF THE LENGTH OF LEFT-TURN LANE ON SIGNALIZED INTERSECTION DELAYS

by

Nitin Kalsi

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Nitin Kalsi

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ABSTRACT

Analysis and Evaluation of the Impact the Length of Left-Turn Lane on Signalized Intersection Delays

by

Nitin Kalsi

Mohamed Kaseko, Ph.D., Examination Committee Chair
Associate Professor of Civil and Environmental Engineering
University of Nevada, Las Vegas

The most common guidelines for determining the lengths of left-turn lanes are based on probability of accommodating a left-turn traffic at least traffic 95 percent of the time. These guidelines do not directly take into account the delays caused by through traffic for potentially blocking left-turn lanes. In this research the impact of the lengths of left-turn lanes on intersection delays are considered to optimize the lengths of the left-turn lanes. Data for traffic counts, queue lengths and signal timing are collected from an intersection in Las Vegas. The methodology involves development of simulation model using Corridor Simulation (CORSIM) and simulating various scenarios by varying traffic parameters to evaluate delays caused by varying lengths of the left-turn lane. Optimal lengths are computed and are compared to the 95 percent guidelines. Significant differences in lengths of the left turn lane are found for protected-permitted phasing. For protected left-turn phasing, the difference was not significant. The corresponding delays to these lengths are compared. The difference between control delays for protected-permitted phasing are found to be significant whereas for protected left phasing are found to be similar.

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CHAPTER 1

INTRODUCTION

1.1. Left-Turn Lanes

Left-turns lanes are auxiliary lanes provided to separate left-turning traffic from through traffic at intersections. The main purposes of these lanes are to provide space for deceleration and separate storage for the left-turning traffic at intersections. Left-turn lanes have been extensively used as a tool for improving the operational performance of traffic at intersections. They reduce delays by decreasing obstacles to through traffic and increase the safety at an intersection by decreasing the number of crashes.

1.2. Elements of Left-Turn

According to the Transportation Research Institute (TRI, 1996), the elements of left-turn lanes similar to the element of functional area are as shown in Figure 1.1.

In Figure 1.1, the length of left-turn lane is referred as the summation of d3 and d4. For a signalized intersection, d4 is a function of turning volume, cycle length, and percentage of trucks.

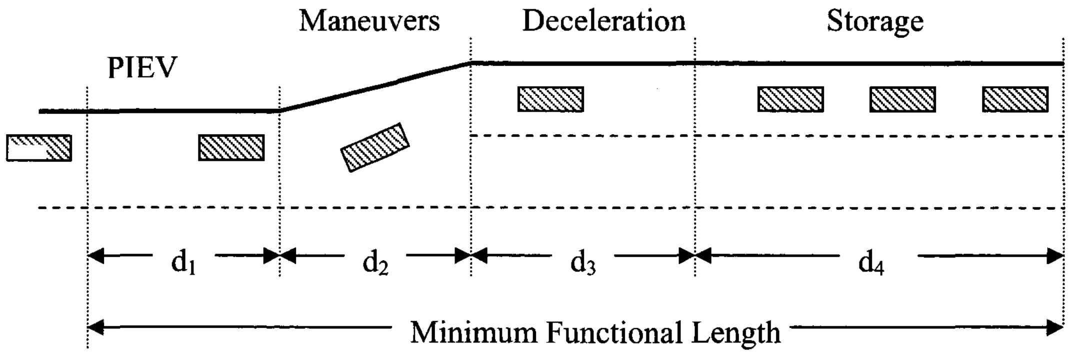


Figure 1.1 Elements of functional area of an intersection.

d1 = distance traveled during perception - reaction time

d2 = distance traveled while driver decelerates and maneuvers laterally

d3 = distance traveled during full deceleration and coming to a stop or to a speed at which the turn can be comfortably executed

d4 = storage length for stopped vehicles

Length of left lane is a component of functional length. The functional length is the summation of d1, d2, d3, and d4 CTRE (2007), states that the Florida Department of Transportation suggests the minimum functional lengths for the intersections are based on speed on the road segment. Table 1.1 presents values for minimum function length.

Table 1.1 Minimum functional length (source: CTRE, 2007)

Speed (MPH)	L(feet)
30	280
35	348
40	422
45	505

1.3. Background Information

Various methodologies and guidelines have been developed for adding left-turn lanes and computing their lengths. These methodologies and guidelines are based on operational requirements, safety requirements, or both. These methods correlate the factors such as location, traffic carrying capacity, number of lanes, and coordination of intersections. While designing left-turn lanes, the following measures of effectiveness (MOE) must be considered:

- Intersection delays
- Queue lengths
- Operational safety

Insufficient lengths can result in overflow of left-turning vehicles onto the adjacent through lanes and adversely affect the operation and safety of the intersection. As there would be longer queues that would result in additional delays, this would affect the operation of the intersection. Further, safety would be affected for an intersection if there were no left-turn lanes as the vehicles would be decelerating in the through lane and would have erratic lane changing behavior.

According to the Federal Highway Administration (FHWA, 2002) for an urban area, there is an expected reduction of 10 percent of intersection crashes with the installation of a single left-turn lane on one approach of a four-legged intersection. The resulting effectiveness measure for total intersection crashes would be expected to increase but not double with the installation of left-turn lanes on both the major-road approaches to a four-legged intersection.

1.4. Problem Statement

Exclusive left-turn lanes are provided to minimize the interference of left-turning traffic with adjacent through traffic. When the left-turn traffic is high and the length of left-turn lane is inadequate, the left-turning traffic will overflow onto the through lane. On the contrary, when the through traffic is high and the length of the left-turn lane is inadequate, the through traffic may block the entry of left-turning vehicles into the left-turn lane. Both the cases will result in the additional delays caused to the left-turning traffic as well as through traffic. The cases are shown in Figure 1.2 and 1.3 respectively.

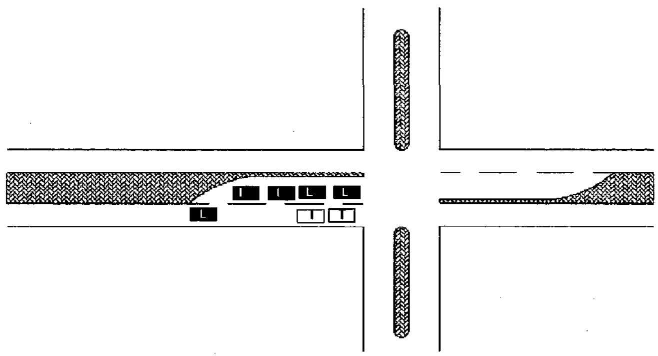


Figure 1.2 Left-turn lane overflow

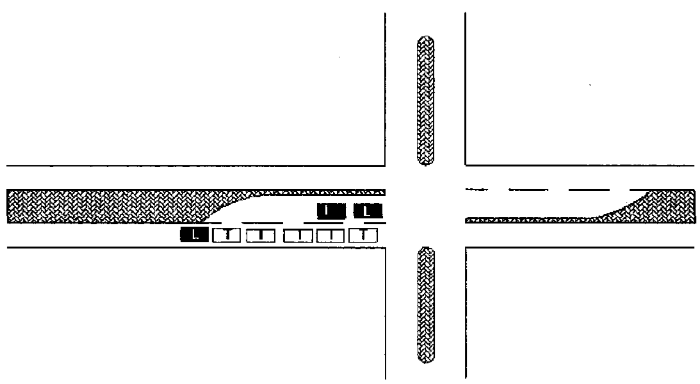


Figure 1.3 Through lane overflow

The current guidelines for determination of lengths of left-turn lanes are based on the probabilistic approach to accommodate the 95^{th} percentile queue lengths for left-turning vehicles in left-turn lane. These guidelines do not consider through traffic to determine the length and does not consider the potential delays. This research includes the effect of left turning as well as through traffic on the delays to determine the optimized lengths.

1.5. Objective

The objectives of this research are as follows:

- To evaluate the impact of the lengths of left-turn lanes on intersection delays at signalized intersections.
- To determine the optimum lengths for left-turn lanes for signalized intersections.
- To compare the optimum lengths obtained in this study with the length based on existing guidelines to accommodate left-turning vehicles 95 percent of the time in the left-turn lane.

This is achieved by using computer simulation on a selected case study location.

1.6. Organization of Thesis

This thesis consists of six chapters. The introduction to the study and its scope are presented in Chapter 1. Chapter 2 offers a brief literature review on the general guidelines for left-turn lane installation and design, the parameters involved, and design approaches and criteria. The case study location, data requirement, data collection methodology, and guidelines for selecting proper simulation model are discussed in Chapter 3. Chapter 4 describes the development of a simulation model, calibration, and validation of this model. The results are summarized in Chapter 5. The conclusion and recommendations for future research are discussed in Chapter 6.

CHAPTER 2

LITERATURE REVIEW

2.1. Introduction

This chapter focuses on familiarizing the reader with the existing design criteria to determine the lengths of the left-turn lanes. Section 2.2 discusses warrants for the left-turn lanes. Section 2.3 describes the various parameters affecting the lengths of the left-turn lanes. Section 2.4 discusses the governing Measures of Effectiveness (MOEs) used for designing the length of the left-turn lanes. Section 2.5 provides the description of various existing design approaches used for determining the length of left-turn lanes. Section 2.6 describes the criteria for dual left-turn lanes. Finally, section 2.7 explains how the design approach adopted for this study is different from the existing approaches.

2.2. Warrants for left-turn Lanes

Warrants are defined as the minimum conditions for which an intersection should be provided with a left-turn lane. According to FHWA, 1997 the primary factors for determining the requirement for exclusive left-turn lanes for signalized intersections are:

- Left-turning volumes,
- Accident experience, and
- General capacity relationship like saturation flow rates, volume to capacity ratios.

Highway Capacity Manual (HCM, 2000), shows the relationship between the left-turn volume and the probable necessity for the left-turn lanes. Table 2.1 shows the relationship between left-turn lane and left-turn volume.

Table 2.1 Warrants for left-turn lane

Turn Lane	Minimum Left-turn Volume (vph)
Single exclusive Left-turn Lane	100
Double exclusive Left-turn Lane	300

At signalized intersections, the required length of the left-turn lane is a function of cycle length and approach volume. The factors affecting the lengths of the left-turn lanes are explained in detail in the next section.

2.3. Parameters Affecting the Length of Left-Turn Lanes

Various factors that affect the lengths of the left-turn lanes as stated by Kikuchi et al., 1993 are as follows:

- Traffic volume
- Vehicle mix and space required for vehicles standing in a queue.
- Signal timing
- Time required to make a left-turn

Following is a brief discussion of these factors:

Traffic volume: The lengths of left-turn lanes depend on the number of left-turning vehicles. A higher volume of left-turning traffic necessitates a longer left-turn lane. The queue length of through vehicles also affects the length of a left-turn lane. A long queue on a through lane would prevent the left-turning vehicles from entering the left-turn lane. If the left-turn phase is permitted then the volume of opposing vehicles are taken into account for determination of the lengths of left-turn lanes. In this case, the left-turning vehicles have to wait to maneuver a gap from the opposing vehicles. Therefore, a greater volume of the opposing vehicles necessitates longer lengths of left-turn lanes.

Vehicle mix and space required for vehicles standing in a queue: The type of vehicles using the left-turn lane influences its length. For a higher percentage of trucks for a given lane length, the probability of overflow of left-turn lane would increase, as the space required by heavy vehicles are larger as compared to the space required by a passenger car. Similarly, if the proportion of trucks in through lanes is large, the probability of lane blockage increases.

Signal phase and cycle length: The number of vehicles accumulating in the left-turn lanes depends on the cycle length, signal phases, and the duration of green. For longer cycle lengths, the number of vehicles accumulated in the left-turn lanes would be higher and hence, longer lengths of left-turn lanes are required.

Time required for making a left-turn: The time required to make a left-turn determines the maximum number of vehicles that can make a left-turn during a protected phase. For lower turning speed, lesser number of vehicles would be able to make a left-turn. Therefore, a larger number of vehicles would accumulate in the left-turn lanes thus increasing the required lengths. Equation 2.1 can be used to determine the number of vehicles which can make a left-turn during protected phase, as stated by Kikuchi et al., 1993.

$$m = \text{nearest integer to} \left(\frac{D - RT}{T} \right) \tag{2.1}$$

where

m = Maximum number of left-turns during duration D,

D = Duration of protected green,

RT = Perception/ reaction time of the first vehicle in the queue, and

T = Time required by a passenger car to complete a left-turn maneuver.

2.4. Measures of Effectiveness (MOEs) for Left-turn lanes

Success of left-turn lane can be quantified using the MOEs that are measurements of traffic parameters used to compare traffic operations. The important measures of effectiveness for studying the impact of left-turn lanes on traffic conditions are discussed below:

2.4.1. Queue Length

Queue length is an MOE that is used to determine the lengths of left-turn lanes. If queues are longer, they will overflow the available storage space and have an adverse effect on the overall operation of the intersection. Therefore, queue lengths are considered so that the incoming traffic does not overflow onto the adjacent lanes.

Figure 2.1 explains the relationship between queue lengths and cycle phase timing. The figure shows that the maximum queue length is observed at the end of the red phase. This criterion is generally used to compute the length of the left-turn lanes.

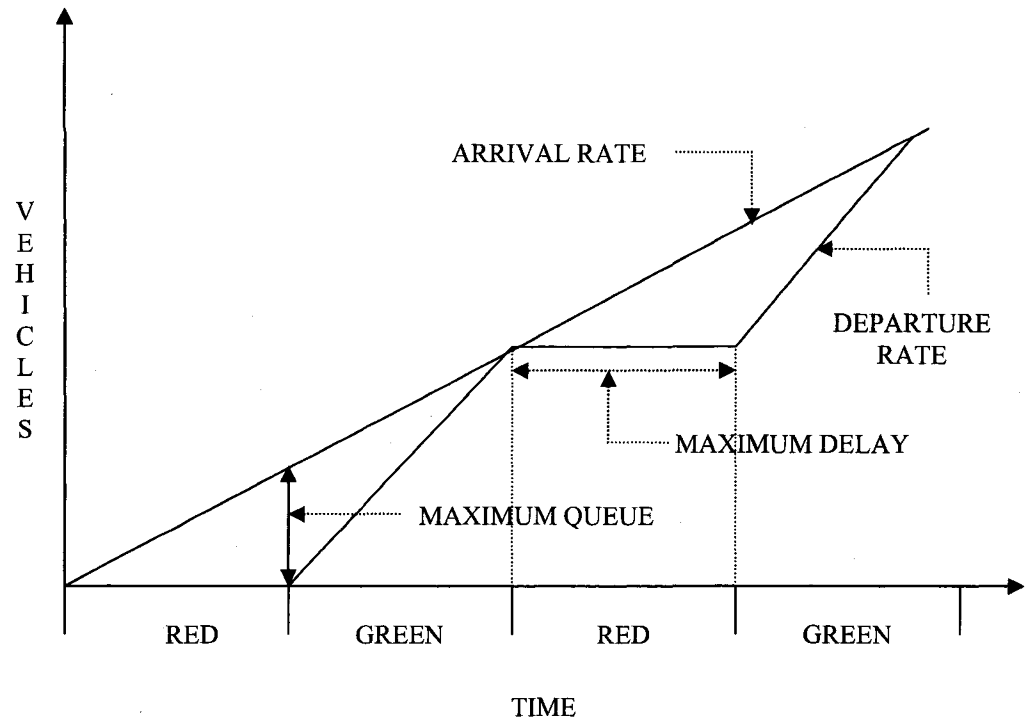


Figure 2.1 Deterministic component of delay model

HCM, 1985 computes the lengths of left-turn lanes based on the requirement to accommodate the queues for minimum of 95% of the time. The queues should not overflow onto the through lanes for more than 5 percent of the time. This criterion is designed to minimize the effect of the left-turning queue on through traffic.

The HCM, 1985 guidelines can be interpreted using a Poisson probability model. The probability of the number of vehicles arriving during the red duration can be calculated using

$$P(n) = \frac{(\lambda t)^n e^{-\lambda t}}{n!} \tag{2.3}$$

where

n= number of vehicles arriving,

λ = average flow (vehicle per second), and t = red phase duration (seconds).

For smooth functioning of the intersection, the number of vehicles arriving during the red time should not exceed the required queue length (L) more than 5 percent of the time. To determine the number of vehicles that can be accommodated within the length L, can be calculated using the probability equation

$$P(N \geq L) = 1 - \sum_{n=0}^{L} \frac{(\lambda t)^n e^{-\lambda t}}{n!} \tag{2.4}$$

where

n = number of vehicles arriving,

L = queue length to accommodate the left-turning vehicles 95% of time,

λ = average flow (vehicle per second), and

t = red phase duration (second).

2.4.2. Control Delay

Control delay is defined as the difference between the time taken by a vehicle traveling through a section of the road with or without traffic controls. Usually, some time is lost during deceleration, stopping, and acceleration while the vehicles follow the traffic controls. According to a study conducted by Messer et al., 1977 the delays increase with the increase of traffic volume, saturation ratio, cycle length, and shortening of left-turn lanes. Figure 2.2 is the graphical representation of the control delay.

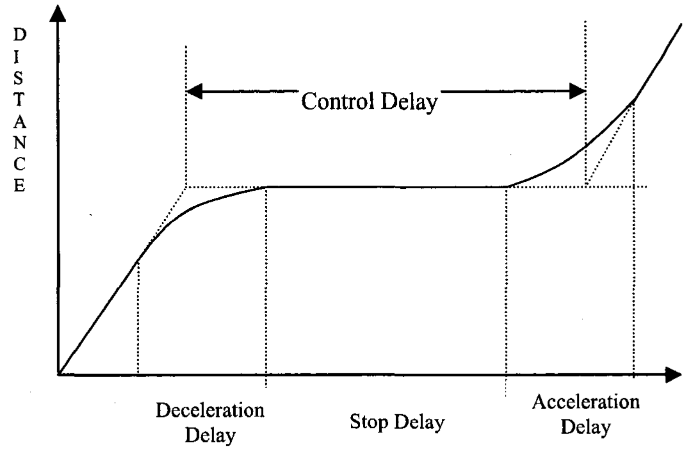


Figure 2.2 Control delay diagram

2.5. Design Approaches for Computing the Lengths of Left-Turn Lanes

Based on the available literature and studies, the following are the major methods for computing the lengths of the left-turn lanes. Typical examples of major methods described in this section are rule of thumb, analytical, and simulation method.

2.5.1. Rule of Thumb

Different studies suggest a number of methods to compute the lengths of left-turn lanes. Prominent among them are the ones proposed by AASHTO 1973, Neuman 1985, and Transportation Research Institute (TRI, 1996).

AASHTO, 1973 recommends that, "At signalized intersections, the required storage length depends on the cycle length, the signal phase arrangement, and the rate of arrival and departures of left-turning vehicles. The storage length should be based on 1.5 to 2 times the average number of vehicles that would store per cycle, predicted on the design volume."

Neuman, 1985 suggest that the lengths of the left-turn lanes should be long enough to accommodate the queued vehicles within the left-turning lane without affecting the working of through lanes. Further, the study recommends that desirable design length should be based on twice the average number of vehicles that arriving during one signal cycle. This guideline to compute the lengths of left-turn lanes is similar to AASHTO, 1973. The minimum design lengths proposed in this study were based on mean arrival rate, but it should be long enough to accommodate a minimum of one vehicle.

Neuman, 1985 prepared a nomograph to determine the desirable and minimum lane lengths. The nomograph took account of the percentage of heavy vehicles and was prepared for left-turning volume ranging from 100 to 600 vehicles and, cycle length varying from 40 to 120 seconds in incremental of 10 seconds.

The rule of thumb as stated by TRI, 1996 recommends the lengths for left-turn lane should be one foot for each vehicle per hour (vph) turning left during peak hour. TRI, 1996 gives another rule of thumb for estimating the lengths of left-turn lanes as explained in Equation 2.5. In this rule, to determine the lengths of left-turn lanes, cycle length, vehicle length, location and were considered.

$$L = \left(\frac{V}{N}\right) \times t \times s \tag{2.5}$$

where

L = length for left-turn storage (ft),

V = left-turn volume [vehicles per hour (vph),]

N= number of cycles per hour,

t = variable, the value of which is selected based on the minimum acceptable likelihood that the storage length will be adequate to store the longest expected queue. The suggested value are reported in Table 2.2, and

s = average length per vehicle, including the space between vehicles, generally assumed to be 25 ft (7.6 m). The suggested values of "s" are reported in Table 2.3.

Table 2.2 Values of "t" based on storing probability

Minimum t	Approximate probability of storing all vehicles
2.00	> 0.98
1.85	0.98
1.75	0.95

Table 2.3 Value of "s" based on percent of trucks – traffic mix

Percent trucks	Average queue storage length (feet)
< 2%	25
5 %	27
10%	29

All the rules of thumb compute the length of left-turn lanes depending upon the left-turn arrival rates. This research proposes a method to estimate the required lengths of left-turn lanes, taking into account the through traffic.

2.5.2. Analytical Methods

Analytical methods use a more scientific approach to determine the lengths of the left-turn lanes. It uses queuing theory based on statistical and probabilistic approaches to estimate the number of vehicles arriving during the red phase, based on which the lengths of left-turn lanes are finalized.

The HCM, 1985 suggests that the traffic on the left-turn lanes should not overflow for more than 5 percent of the time. the length of the left-turn lanes can be calculated using

$$L = Q \times PCE \times s \qquad (2.6)$$

where

L = Length of the left-turn lane,

Q = Number of vehicles which the left-turn lane can accommodate 95% of time without overflow of left-turn lane using Equation 2.4,

PCE = Passenger car equivalent, and

s = Average length of the vehicle.

Another method was developed by Oppenlander and Oppenlander, 1989 to compute the lengths of the left and right-turn lanes that are controlled by separate signal phase. Poisson arrival rate and exponential service distribution was assumed for computing the percentile lengths. The arrival rates were computed for the turning volume ranging from 25 to 1000 vehicles per hour (vph) in increments of 25 vph. For computing service rates, green duration to cycle length ratios were selected for a range of 0.05 to 0.90 in increments of 0.05. Tables to determine the lengths of turning lanes for 50^{th}, 85^{th} and 95^{th} percentile queue lengths were prepared. These tables correspond to lane saturation flow of 1500 and 1800 vehicles per hour of green per lane (vphg).

In the methods proposed by Oppenlaneder and Oppenlander, 1989 the impact of through traffic was not taken into account. Through traffic can block the entry of the left-turn lane if the queue extends beyond the length of the left-turning lane. Therefore, while designing the length of the left-turn lane the through traffic should also be taken into account.

Kikuchi et al., 1993 determined the lengths of the left-turn lanes based on two criteria namely, lane overflow probability, and lane blockage probability. To study the overflowing and blocking of left-lane, two models were developed to determine the lengths of the left-turn lanes. A threshold probability of 2 percent for overflow and 10 percent for blockage were assumed to compute the length of the left-turn lane. Further, the design tables were developed based on arrival rate, cycle length, turning volume, and green duration for overflow, and red duration for blockage.

For blockage, 10 sets of parameters were compared with the Network simulation (NETSIM). The left-turn lane lengths from the study were similar to NETSIM results. These results also matched the guidelines provided by AASHTO, 1990 and HCM, 1985. The findings of the left turn-lane overflow model however gave results that differed considerably from AASHTO,1990 and HCM, 1985 guidelines. The study suggested that the lengths of the left-turn lanes should be based depending upon overflow or blockage conditions.

Qi et al., 2007 performed a study to estimate the length of the left-turn lanes at signalized intersections to prevent lane overflow. The queue lengths were computed based on two criteria namely, vehicles arriving during the red phase, and leftover queues from the previous cycle. The study assumes that arrival of vehicles varies randomly with Poisson distribution. The left-turn green duration and cycle length were also assumed to be constant. The numbers of vehicles arriving at an intersection were assumed to be less than the less than the maximum number of vehicles that can turn left during a green phase.

In order to determine the queue lengths, two models were developed. The model determining the queue lengths for the red phase were based on probability of arrivals during the red phase. The second model was developed to estimate the number of vehicles leftover in the lane from the previous cycle.

A probability of 97.5 percent to accommodate the left-turn traffic was used to determine the length of left-turn lane. The lengths of the left-turn lanes were determined by adding the queue lengths obtained from two models i.e red duration queues and left-over queues.

The lengths for the left-turn lanes from the study were compared with the 95th percentile observed queue lengths, queue lengths obtained from vehicles arriving during red phase only (red phase model), and queue lengths corresponding to MM1 model. The comparison shows that the results obtained by Qi et al., 2007 were slightly higher as compared to the other models. The discrepancies in the results were due to underestimation of queue lengths by red phase model because it does not consider the left-over queues. Qi et al., 2007 state that the MM1 model significantly underestimates the queue lengths because it works on the principle of stop and go operation, which is not the actual representation of the signalized intersection. The comparison of the results shows that Qi et al., 2007 model provides better estimates as compared to the other three models.

An HCM, 1985, and Oppenlander and Oppenlander, 1989, method to compute the lengths of left-turn lanes are based on left-turning traffic and do not take into account of through traffic for potentially blocking the entry of left-turn lane. In the methods proposed by Kikuchi et al., 1993 and Qi et al.,2007, the green durations for left-turns were generated randomly; however, to ensure the proper working of the intersection a balance between the number of vehicle arrivals and green duration should be achieved. Therefore, the present study will optimize the green duration with respect to the number of vehicles arriving at the intersection.

2.5.3. Simulation Methods

Messer et al., 1977 developed a periodical scan computer simulation program to investigate the impact of signal phasing, and length of left-turn on capacity. In the model, the left-turn lane and through lanes were divided into discrete storage units. The junction was defined as the point where the left-turn lane begins. The storage unit for the through lane was numbered from 0 to 26 and left-turn lane was numbered from 0 to one number less than through lane storage unit number corresponding to the junction. The storage unit can accept three states namely, empty, moving, and queued. The empty storage unit was defined as the unit with no vehicle stored in it. The moving unit was defined as the unit which can proceed to the next storage unit if empty and queued unit was the one whose next unit was not empty and can not proceed until the next unit is empty. The storage unit 0 was before the stop line and acted as queued when the signal was red and moving when the signal turned green. Every second the simulations scanned the system periodically and recorded the changes in the states of storage units. At junction, the left vehicles storage state was based on the state of the storage unit of left-turn lane and for through vehicles the state of storage was based on the storage state of through lane storage unit. On scanning the system when one queue storage unit is immediately behind another storage unit, a delay of one second was recorded. The operational measures of effectiveness were also recorded for each scan. Headway equal to or more than 2 seconds was used for the vehicles to enter the system.

The simulations were run for cycle lengths of 60 and 80 seconds for equal nominal v/c ratio for right and left-turn lane. The nominal v/c ratio defined by Messer et al., 1977 as "normal demand on the movement divided by the phase's capacity when left-turn bay is long enough to prevent blockage or interaction between left-turners and the throughs." The left-turn saturation flow rate was assumed to be 1700 vehicles per hour of green (vphg). For a cycle length of 60 seconds, the green time was portioned to yield uniform demand-capacity ratios.

The results showed as expected that the delays increase with the increase of traffic volume, nominal volume to capacity ratio and cycle length and delays increases with decreasing length of the left-turn lane. Messer et al., 1977 observed that the impact of length of left turn on delays started be significant for v/c greater than 0.6.

Additional analyses were performed using modified Poisson approach, to determine the relationship between the multiplying factors (1.5 to 2) provided by AASHTO, 1973 and design left-turn volumes. These analysis were performed to compute the length of the left-turn lanes and to support the lengths computed with the help of simulations.

The number of vehicles in queue was determined by adding the vehicles arriving during the red phase and the number of vehicle remaining in the left-turn lane at the end of green phase. The flow rate was selected so that during the design 15 minutes peak period the probability of cycle failure is 50 percent. The results were plotted for different volume to capacity ratios and different left-turn volume. A maximum value of 0.8 for volume to capacity ratio was assumed practical and the length of the left-turn lanes were determined for cycle lengths ranging from 60 to 100 seconds in increments of 10 seconds. The results showed that the length of left-turn increase with the increase in the cycle length as the longer cycle lengths requires more vehicles to be stored per cycle.

A comparison using a cycle length of 75 seconds and a saturation ratio of 0.8 was performed between the length of left-turn lane obtained from the modified Poisson approach and the AASHTO, 1973 guidelines. The comparison between Messer et al., 1977 study and AASHTO, 1973 guidelines shows that the lengths computed using AASHTO, 1973 guidelines by a multiplying factor of 2 gave longer lengths at high volume and similar lengths at lower volumes as compared to lengths computed using Messer et al., 1977 study. Whereas, lengths computed using AASHTO, 1973 guidelines by a multiply factor of 1.5 gave lower lengths as compared to lengths computed using Messer et al., 1977 study.

Oppenlander and Oppenlander, 1994 developed a Monte Carlo simulation model to determine the length of the left-turn lane with separate phase control. Arrivals in the left-turn lane were assumed to have a Poisson relationship. The start up time was modeled based on a triangular distribution using minimum and maximum values of headway. For the discharge of stopped vehicles on the protected phase from the left-turn lane, a triangular distribution was used. To study the interaction of vehicles arriving at the intersection, the model was incorporated with cycle lengths, signal operation, and movement of vehicles within the intersection. The arrival of vehicles on the green phase was processed from the intersection without being stored in the left-turn lane. The simulations were performed for various lane volumes ranging from 50 to 400 vehicles per hour (vph) in intervals of 50 vph, and for cycle lengths 60 to 120 seconds in increments of 15 seconds over various green duration ranging from 10 to 30 seconds in increments of 5 seconds. The design tables to determine the lengths were prepared for turning lanes for 50^{th}, 85^{th} and 95^{th} percentile queue lengths.

Oppenlander and Oppenlander, 1996 modified the previous simulation model developed by Oppenlander and Oppenlander (1994) by expanding the range of parameters used in the simulation model to incorporate the design and operational aspects for signalized intersections. The traffic signal operation was modified to stop and go rather than a continuously served queue. The interactions between the arriving vehicles and signal operations were modeled using simulation. The Poisson probability distribution was used to generate the random arrival of the vehicles at the intersection. The vehicles arriving at the intersection were placed in the queue to be served by the traffic signal. The vehicles departing the queues and entering the intersection, cycle length and green time were used to assign the time for simulations. The vehicles arriving at the intersection on green were allowed to pass the intersection and the arrival on red was placed in the queue to wait for the signal to turn green. For each queue position, the departure time was based on triangular probability distribution based on three headway values.

The simulations were performed for various lane volume ranging from 50 and 800 vehicles per hour (vph) in intervals of 50 vph, and for cycle lengths 60, 75,90, 120,150 and 180 seconds over various green duration at an interval of 5 seconds.The design tables to determine the lengths were prepared for turning lanes for 50th, 85th and 95th percentile queue lengths.

The method proposed by Messer et al., 1977 using a modified Poisson approach does not consider through traffic to compute the length of the left-turn lanes. Oppenlaneder and Oppenlander, 1989, Oppenlaneder and Oppenlander, 1994 selected the green duration randomly to compute the length of the left-turn lane over various left-turning traffic flow. The optimization of the green duration was not taken into account. Therefore, in this study to the green durations were optimized to determine the length of the left-turn lanes.

2.6. Storage Length for Dual-Left-turn Lanes

Although the focus of this research in not dual left-turn lane, the goal of this section is to provide information to the readers that dual left-turn lanes should be onstructed if the length of single left-turn lane is long and can not serve the intersection efficiently. A dual left-turn lane can discharge more vehicles as compared to the single left-turn lane and gives better operation of the intersection.

The storage for a dual left-turn lane at a signalized intersection can be estimated the by using methods to determine the length of single left-turn lanes and multiplying it with a factor of lane utilization. Stokes et al., 1986 states that the saturation flow rate for a dual left-turn lane is approximately same as for two through lanes, as cited in TRI, 1996. Therefore, a factor of 1.8 is used to compute the length of dual left-turn lane as this factor recognizes that the left-turn traffic is not equally distributed between the two left-turn lanes. In most cases, the imbalance between dual turn lanes may be much greater. To estimate the length of the dual left-turn storage lane the single left-turn storage length is divided by a factor of 1.8 as shown in Equation 2.7.

$$D = \frac{L}{1.8} \tag{2.7}$$

Where:

L = total length of the left-turn lane when one left-turn lane is provided.

D = length of dual left-turn lane

Study by the Regional Transportation Commission of Southern Nevada (RTC, 2007) used a double left-turn lane if the minimum threshold limit of 300 left-turning vehicles per hour is met as stated by HCM, 2000.

2.7. Summary

According to the HCM, 2000 the lengths of the left-turn lanes should be designed as per state or local guidelines. Most of the guidelines use the principle of queuing theory based on probability. To compute the queue lengths, the rules of thumb do not take into account the through volume and green duration. Most of the analytical methods do not take into account the through volumes and the optimization of green phase. In simulation methods the lengths for the left-turn lanes were computed without optimizing the green phase.

In this study, to compute the lengths of the left-turn lanes simulation method is used. In the simulation model, all the approach volumes are considered and optimizations of green phases are taken into account. The lengths of left-turn lanes are determined based on the principle of minimizing the delays.

CHAPTER 3

METHODOLOGY AND DATA COLLECTION

3.1. Introduction

This chapter presents the methods and techniques used in this study for site selection, data collection, formulation of analysis scenarios, development of simulation model and analysis of results. Figure 3.1 shows a flowchart for steps that are followed in this study.

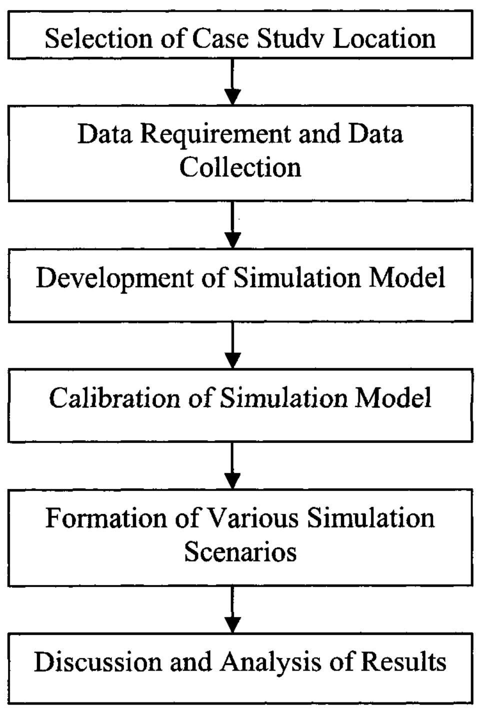


Figure 3.1 Flow Chart of Model Development

3.2. Selection of Case Study Location

To study the problem described in Section 1.4, the following criteria are shortlisted for selecting the study site.

- Existence of left-turning vehicles overflowing onto the through lanes during peak hour period.
- Existence of through vehicles blocking the entry of left-turn during peak hour period.
- Having a single left-turn lane on the approach leg under study.

After the preliminary surveys are conducted on the sites initially chosen for the study, the intersection of South Main Street and Charleston Boulevard intersection is selected for the study. This site fulfills the three criteria mentioned above. It is observed that on the northbound approach of the intersection during the evening peak hour, left-turn lanes overflow most of the time. Hence, the northbound approach of the intersection is selected for the study.

Figure 3.2 is an aerial view of the case study location. The site is a four-legged signalized intersection. South Main Street runs north-south with one left-turn lane and two through lanes with a shared right lane. Charleston Boulevard runs east-west with one left-turn lane and three through lanes with a shared right lane. Left-turns are serviced using the protected-permitted phase. The S. Main Street roadway segment under consideration has a posted speed limit of 30 miles per hour.


Figure 3.2 Case study location (www.maps.google.com)

3.3. Data Requirements and Data Collection

The following data is required and collected for model development, calibration and simulation:

a) Geometric data for the intersection: The geometric features of the intersection namely, lane widths, existing lengths of the left-turn lanes, and number of lanes are obtained after visiting the site.

b) Speed limits: The posted speed limits at each approach road are obtained after visiting the site.

Figure 3.3 shows the intersection layout with speed limits and lane width and existing length of left-turn lanes for Charleston Boulevard and S. Main Street.

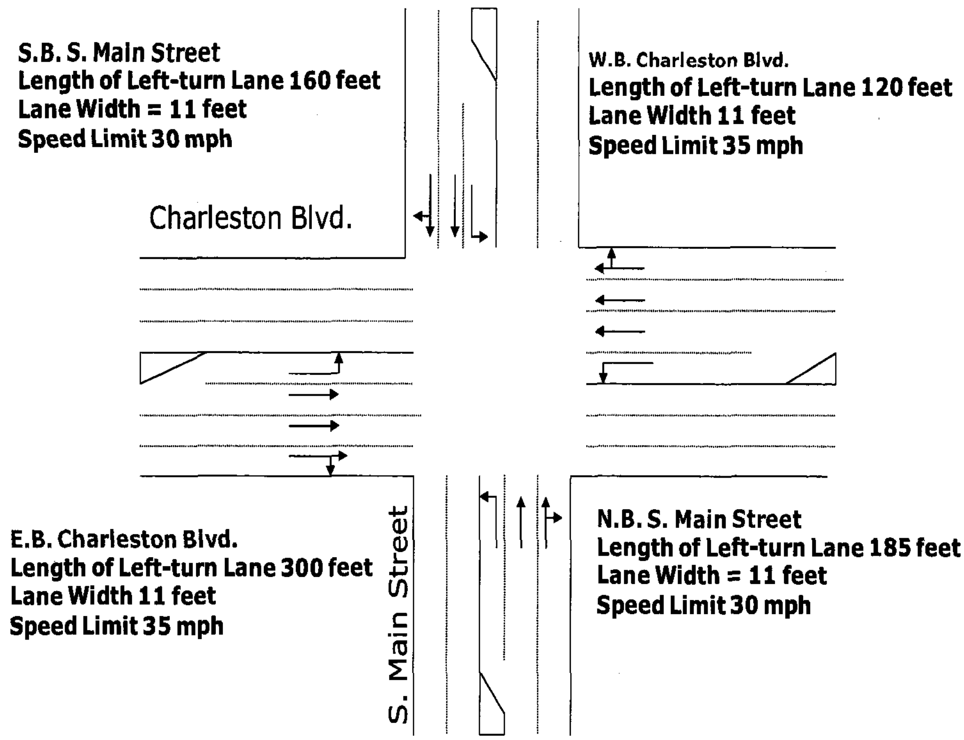


Figure 3.3 Intersection layout

c) Signal timing: The signal phase diagram and phase split timing data obtained from the Freeway and Arterial System of Transportation (FAST) which is an agency that operates and controls traffic signals for Las Vegas Valley. The intersection has a fixed cycle length of 140 seconds with 4 seconds of yellow time and 2 seconds of all red time. The data is presented in Figure 3.4 and Table 3.1.

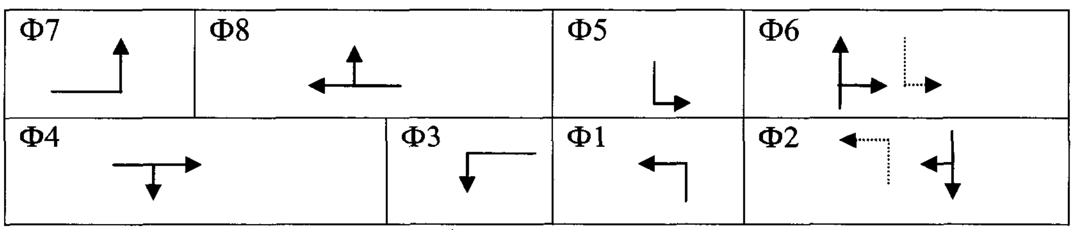


Figure 3.4 Phase diagram

Table 3.1 Phase green split

Phase	Description	Phase split timing (sec)
Φ1	North bound left	16
Φ2	South bound through with permitted north bound left	41
Φ3	West bound left	15
Φ4	East bound through	68
Φ5	South bound left	16
Φ6	North bound through with permitted south bound left	41
Φ7	East bound Left	29
Φ8	West bound through	54

d) Traffic counts: To develop the model, the traffic counts collected in year 2006 are obtained from Silver State Traffic, a firm that specializes in conducting traffic counts for various projects in the Las Vegas valley. The data are attached in Appendix A1.1 and A1.2.

As the control delays and queue lengths are collected from the field for calibration therefore, to match the output control delays obtained from the model with the field control delays, the traffic counts from field are collected and are input in the model for northbound traffic on South Main Street during the evening peak period. The Traffic data is collected on Wednesday for duration of 40 minutes from 4:40 pm to 5:20 pm. The summary of traffic count data is presented in Table 3.2. Three observers are used for collecting the traffic count data, one each for left-turning vehicles, through vehicles, and right turning vehicles. The field data sheets containing the data from this survey are presented in Appendices A2.1, A2.2, and A2.3 for left-turning vehicle, through vehicles and right turning vehicles respectively.

Table 3.2 NB traffic count for 40 minutes duration

Traffic Direction	Left	Through	Right
Traffic Volume	144	478	48
Total Traffic Volume	670		

The simulation model is developed using traffic counts for peak one hour duration. Therefore, 40-minute traffic counts are interpolated into equivalent one-hour traffic counts as shown in Table 3.3.

Table 3.3 Interpolated NB traffic count for one hour duration

Traffic Direction	Left	Through	Right
Traffic Volume	216	717	72
Total Traffic Volume	1005		

e) Queue Length and Control Delay: In order to determine control delays the HCM, 2000 method is used in this study. A field survey is conducted and observations are recorded for the northbound approach of the intersection from 4:40 pm to 5:20 pm that corresponds to the evening peak period. The flowing steps are followed to count the queue lengths and determine the control delays.

1. Counting vehicles in the queue

In this step, the vehicles queued on the left lane and through lanes are counted. Successive 30 second intervals are used to count the vehicles in the queue at the intersection approach. The counts are started at the beginning of the red phase for a lane group for those cycles which had no vehicles remaining from the previous cycle.

One observer each is used for counting the number of vehicles in queues for the left-turning lane and the through lanes. The observers counted the vehicles that arrived after the green phase ends. Tables 3.4 and 3.5 present the data for the queue lengths for left-turn lane and two through lanes for northbound approach of the intersection for 40-minute duration respectively. Field data sheets are attached in Appendix A3.1 and A3.2

Table 3.4 Queue lengths for northbound left-turn lane

Time	Queue Lengths (in vehicle units)			
	0 sec	30 sec	60 sec	90 sec
4:30:00	12	10	5	8
4:32:00	10	3	5	7
4:34:00	9	10	5	4
4:36:00	8	10	12	12
4:38:00	0	4	7	10
4:40:00	2	4	5	6
0:00:00	8	4	3	8
4:44:00	9	12	5	3
4:46:00	8	10	0	5
4:48:00	8	10	11	2
4:50:00	4	6	7	8
4:52:00	3	1	5	6
4:54:00	0	3	6	12
4:56:00	12	5	6	12
4:58:00	13	14	6	7
5:00:00	7	7	0	6
5:02:00	8	9	11	8
5:04:00	10	11	12	13
5:06:00	5	8	10	10
5:08:00	0	7	7	7
5:10:00	7	5	4	5
5:12:00	8			
ΣViq	575			

Table 3.5 Queue lengths for northbound through and shared right lane

Time	Queue Lengths (in vehicle units)							
	0 sec		30 sec		60 sec		90 sec	
	Lane 1	Lane 2	Lane 1	Lane 2	Lane 1	Lane 2	Lane 1	Lane 2
4:30:00	8	10	0	0	1	4	5	8
4:32:00	8	11	9	13	0	0	6	8
4:34:00	12	14	14	16	9	8	0	0
4:36:00	8	9	10	12	14	16	0	0
4:38:00	3	3	8	9	13	11	14	13
4:40:00	0	0	2	5	6	6	8	11
4:42:00	1	1	0	0	4	5	8	7
4:44:00	9	11	1	2	4	5	6	8
4:46:00	8	9	10	11	0	0	5	4
4:48:00	7	7	9	12	3	4	0	0
4:50:00	5	4	7	7	9	12	0	0
4:52:00	1	3	7	9	9	10	14	13
4:54:00	0	0	3	4	7	9	13	11
4:56:00	2	3	0	0	4	4	9	10
4:58:00	11	13	0	0	5	7	8	11
5:00:00	4	15	13	12	0	0	8	10
5:02:00	9	12	13	13	6	4	0	0
5:04:00	7	8	9	11	14	16	0	0
5:06:00	5	6	8	8	10	9	12	13
5:08:00	0	0	8	7	10	11	14	14
5:10:00	2	3	0	0	7	9	10	9
5:12:00	8	12						
ΣViq	1129							

2. Counting vehicles that stopped

In this step, the vehicles that stopped at the intersection at each cycle length are counted and recorded. One observer each is used for counting the number of vehicles that stopped for the left-turning lane and the through lanes. Table 3.6 presents the data for the northbound leg of the intersection. The field data sheets are attached in Appendices A4.1 and A4.2.

Table 3.6 Stopped and not stopped vehicles for northbound approach

Cycle Number	Stopped (Left)	Stopped (Through)	Not Stopped (Left Lane)	Not Stopped (Through Lanes)
1	10	20	2	5
2	7	22	0	6
3	8	23	1	3
4	7	24	0	6
5	7	20	2	3
6	4	23	2	7
7	7	22	0	7
8	5	20	2	10
9	9	23	1	8
10	9	23	2	6
11	4	23	3	9
12	6	22	2	8
13	6	28	1	7
14	7	22	1	8
15	6	25	0	9
16	5	20	3	6
17	6	25	1	4
18	7	24	1	5
TOTAL	ΣVstop = 120	ΣVstop = 409	ΣVnot stop = 24	ΣVnot stop = 117

3. Counting vehicles that did not stop

In this step, the vehicles that did not stop at the intersection at each cycle length are counted and recorded. One observer each is used for counting the number of vehicles that did not stop for the left-turning lane and the through lanes. The through vehicles are considered to exit the intersection when the rear wheel crossed the stop line. For turning vehicles, the exiting occurred when the vehicle turning left cleared the opposing through vehicles or pedestrian flow to which they should have yielded before turning. Table 3.7 presents the data for the northbound leg of the intersection.

4. Computing control delay for left-turn vehicles

In order to compute control delay, the HCM (2000) method is used. The number of vehicles in the queue, number of vehicles that stopped, and number of vehicles that did not stop for left-turn lane are obtained from Tables 3.4 and 3.6.

The control delay for the left lane is calculated as follows;

Total Number of Lanes (N) = 1

Free Flow speed = 30 mph (posted speed limit is taken as Free Flow Speed)

Number of cycles surveyed (Nc) = 18

Interval between vehicle on queue counts Is= 30 seconds

Total Number of vehicles arriving during survey period ΣVTot = 144

Total Number of vehicles stopped during survey period ΣVstop = 120

$$\text{Total number of vehicle in queue} = \Sigma V_{iq} = 595$$

$$\text{Time in queue per Vehicle} = \left(I_S \times \frac{\Sigma V_{iq}}{V_{tot}} \right) \times 0.9$$

$$= \left(30 \times \frac{595}{144} \right) \times 0.9 = 111.6\,\text{sec}$$

HCM, 2000 Exhibit A16-2 recommends a acceleration /deceleration correlation factor (CF) of 5 for the free flow speed less than 37 mph and less than 7 vehicles in queue.

Acceleration / Deceleration correlation factor (CF) = 5

$$\text{Fraction of vehicles stopping (FVS)} = \left(\frac{\Sigma V_{Stop}}{V_{tot}} \right)$$

$$= \left(\frac{120}{144} \right) = 0.83\,\text{sec}$$

$$\text{Acceleration / Deceleration correlation delay } (d_{ad}) = \mathit{FVS} \times \mathit{CF}$$

$$= 0.83 \times 5 = 4.17 \sec$$

$$\text{Control Delay per Vehicle (d)} = d_{vq} + d_{ad}$$

$$= 111.6 + 4.17 = 115.77 \sec$$

The control delay for the left-turn lane is calculated as 115.77 seconds/vehicle.

5. Computing Control delay for through vehicles

From the data presented in Tables 3.5 and 3.6 for through lane, the control delay is computed using the HCM, 2000 method. The control delay for the through lanes is calculated below;

Total Number of Lanes (N) = 3

Free Flow speed = 30 mph (posted speed limit is taken as Free flow speed)

Number of cycles surveyed (Nc) = 18

Interval between vehicle on queue counts Is= 30 seconds

Total Number of vehicles arriving during survey period ΣVTot = 526

Total Number of vehicles stopped during survey period ΣVstop = 409

$$\text{Total number of vehicle in queue} = \Sigma V_{iq} = 1129$$

$$\text{Time in queue per Vehicle } (d_{vq}) = \left(I_S \times \frac{\Sigma V_{iq}}{V_{tot}} \right) \times 0.9$$

$$= \left(30 \times \frac{1129}{409} \right) \times 0.9 = 57.95 \sec$$

HCM, 2000 Exhibit A16-2 recommends a acceleration / deceleration correlation factor (CF) of 5 for the Free Flow Speed less than 37 mph and less than 7 vehicles in queue.

Acceleration / Deceleration correlation factor (CF) = 5

$$\text{Fraction of vehicles stopping (FVS)} = \left(\frac{\Sigma V_{Stop}}{V_{tot}} \right)$$

$$= \left(\frac{409}{526} \right) = 0.78 \sec$$

$$\text{Acceleration / Deceleration correlation delay } (d_{ad}) = FVS \times CF$$

$$= 0.78 \times 5 = 3.89 \sec$$

$$\text{Control Delay per Vehicle (d)} = d_{vq} + d_{ad}$$

$$= 57.95 + 3.89 = 61.84 \sec$$

The control delay for the through lane is calculated as 61.84 seconds/vehicle.

3.4. Development of Simulation Model

The data obtained from the field and various local agencies is used for development of the simulation model. Corridor Simulation (CORSIM) is used as the simulation software for this study. The data collected is input into TRAFED module and property toolbars. The model development is discussed in detail in Chapter 4.

3.5. Calibration of Simulation Model

Calibration is required, in order to replicate the field condition in the model. The MOEs and the governing parameters are selected to calibrate the model. Different values, within the allowable range, for the network parameters are used, and simulation runs are performed to achieve the MOE closest to that obtained from the field measurements. The procedure for calibration is discussed in detail in Chapter 4.

3.6. Formation of Simulation Scenarios

Various scenarios are generated in order to study the effects of varying left-turn lane lengths, traffic volumes, cycle lengths, and different signal phase control on traffic delays. For example, a case scenario for protected-permitted left-turn, cycle length of 100 seconds, and existing traffic flow is generated. Other scenarios corresponding to protected left-turns, increased cycle lengths, and varying traffic flows are also generated. For each case scenario 12 different simulations with varying lengths of the left-turn lanes from 100 to 600 feet are used for simulation. The detailed discussion of various scenarios is presented in Chapter 4.

3.7. Discussion and Analysis of Results

The results from simulations included the control delays and v/c ratios corresponding to the various left-turn lengths. For different simulations the impact of the lengths of the left-turn lanes on the control delays is studied. The optimum length is determined for each scenario based on the principle of minimum control delays. Regression analysis is performed to determine the relationship between the length of left-turn lane and other traffic parameters such as traffic volume, v/c ratio and cycle length. Further, a comparison is performed between the lengths of left-turn lanes obtained from this study and 95th percentile guidelines. In addition to the comparison between the lengths, comparisons are performed between control delays corresponding to existing length, 95th percentile guideline lengths, and the optimized lengths. This comparison is performed to study the effectiveness of the lengths of left-turn lane computed using this study.

CHAPTER 4

THE SIMULATION MODEL

4.1. Introduction

Traffic simulation models are effective tools for evaluating the impacts of changes in system parameters where the situations are too complex for analytical method or field observations. This approach provides the freedom to modify the different traffic parameters within the model and observe the changes without disrupting the traffic flow or modifying the infrastructure. Simulation models can be classified according to the level of detail at which they represent the traffic stream. The following are the classifications of the different simulation approaches:

Microscopic approach: This approach models individual vehicle movements within a system of transportation facility. Microscopic approach accounts for various aspects of traffic like individual vehicular characteristics, vehicular movement, driver behavior etc.

Macroscopic approach: This approach simulates traffic flow, taking into consideration the aggregate traffic stream characteristics (speed, flow, and density) and their relationships to each other. Macroscopic models employ equations on the conservation of flow and propagation of traffic disturbances through the system.

Mesoscopic Approach: In this approach, models simulate individual vehicles, but describe their activities and interactions based on aggregate (macroscopic) relationships.

Mesoscopic models are relatively less consistent as compared to microsimulation tools, but are superior to traffic analysis techniques such as macroscopic models.

For this study, a microscopic model is selected because it is able to simulate individual vehicle movements. Therefore, it can simulate vehicle overflow more accurately as compared to macroscopic models.

The microscopic model, Corridor Simulation (CORSIM) is selected for the study. CORSIM has a Network Simulation (NETSIM) module that allows detailed network modeling. A brief description of NETSIM is provided in Appendix B1.1. CORSIM also provided adjustable network parameters that make the model easy to calibrate.

4.2. Model Development

This section describes the simulation model used for this study. The following are the steps used to develop the simulation model for signalized intersections.

- Description and building of the model.
- Selection of measures of effectiveness.
- Determination of the sample size.
- Model calibration.
- Generation of simulation scenarios.
- Analysis of results.

4.3. Description and Building of the Model

To build the network in CORSIM, the data required included

- Geometric data consisting of the roadway geometry, lane width, number of lanes, and length of turning lanes.
- Traffic volume data consisting of the approach volumes, turning movements and percentage of heavy vehicles
- Signal timing data consisting of cycle length, cycle phase splits, and clearance time (yellow and all red time).

CORSIM uses the concept of links and nodes to define a traffic network as shown in Figure 4.1. Nodes are usually intersections of two or more links. The network is built in the TRAFED file which is an integrated user interface tool for CORSIM. In this model, the road segments can be developed using the two-way links. An intersection is represented by crossing of two or more links by placing of a surface node. The geometric data i.e. the lane width, number of lanes, and other geometric features are input using the surface link property toolbar as shown in Figure 4.2. After the geometric data, the traffic volume data is input into the nodes. The total volume entering and the percentage of trucks are input into the entry node using entry node property toolbar as shown in Figure 4.3. The turning volumes are input into the turn movements of the intersection properties toolbar as shown in Figure 4.4. In the network, there are dummy nodes that connect entry nodes to the network. The signal timing is then input using the actuated control properties toolbar as shown in Figure 4.5. As CORSIM cannot optimize the cycle phase splits, therefore, Synchro, a Trafficware® software for traffic signal timing and capacity analysis is used to optimize the phase splits.

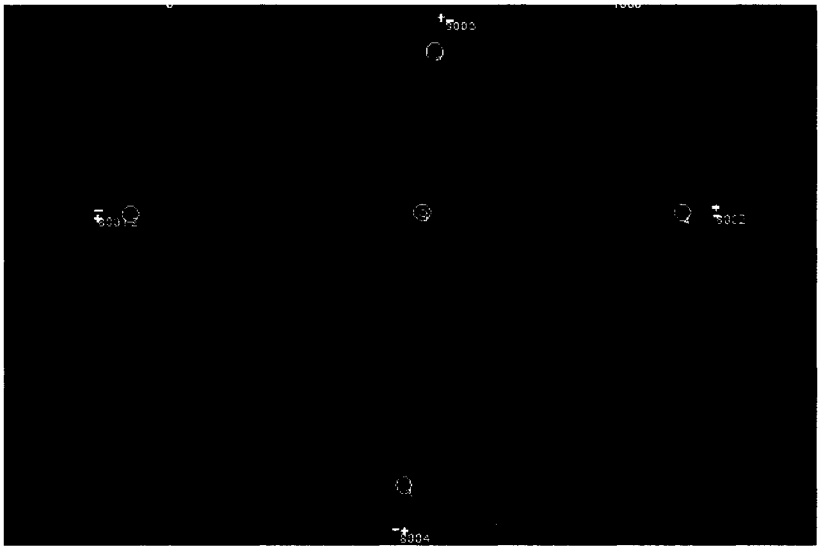


Figure 4.1 Network Layout in CORSIM

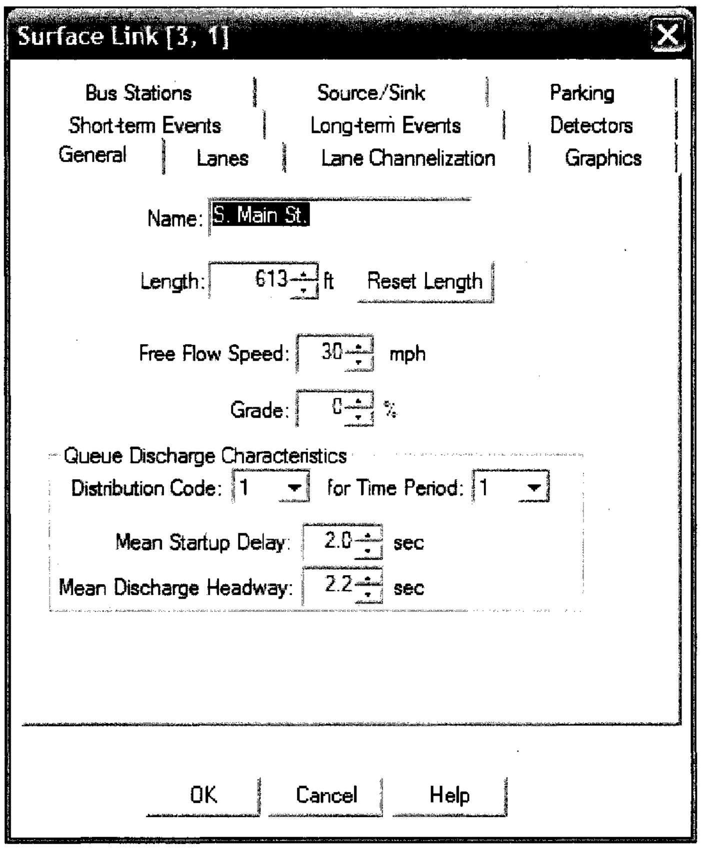


Figure 4.2 Surface link properties

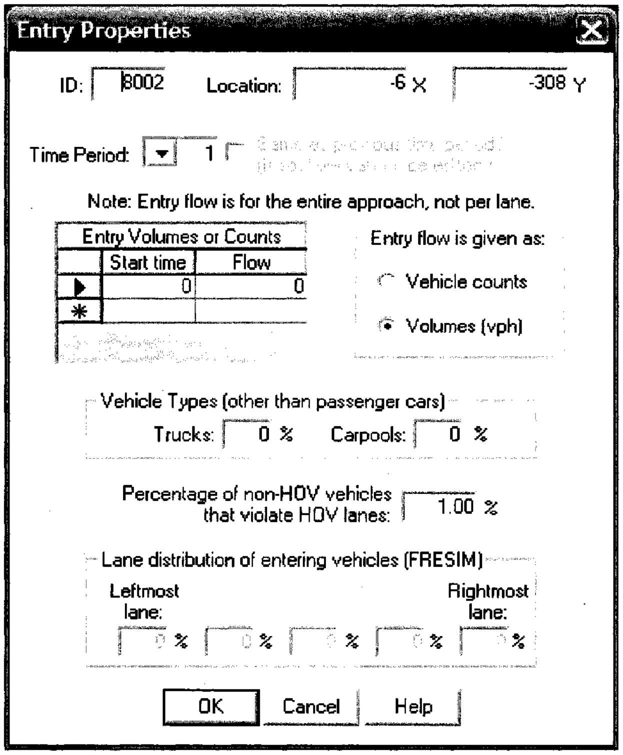


Figure 4.3 Entry node properties

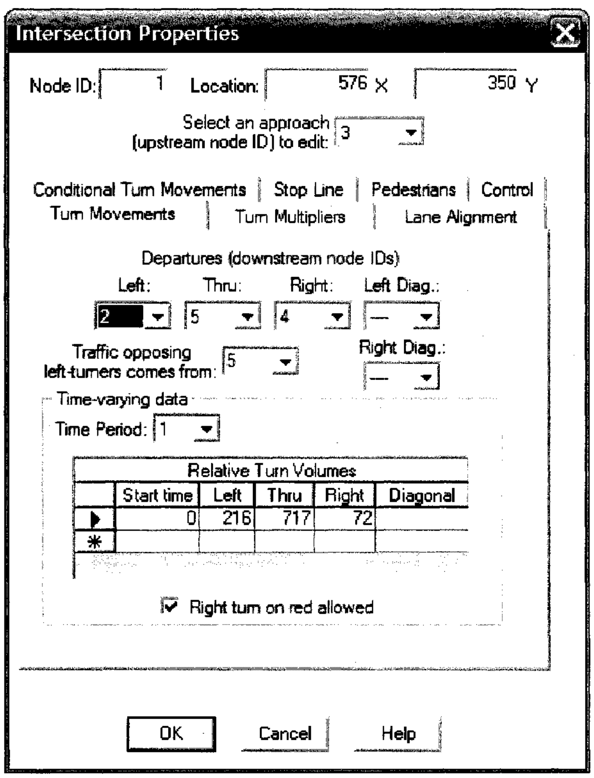


Figure 4.4 Intersection properties

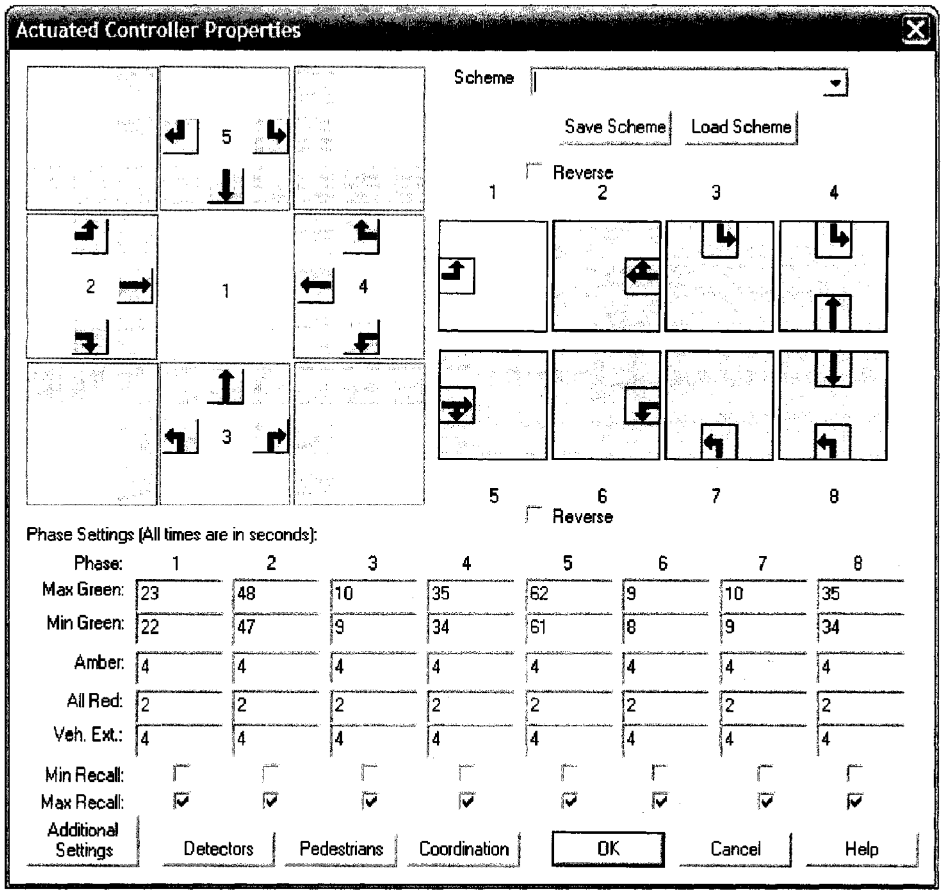


Figure 4.5 Actuated controller properties

4.4. Selection of Measures of Effectiveness (MOEs)

MOEs that can be used for model calibration include speed, density, travel time, delay, stops, and queues. In this study, the impact on control delays are determined. Therefore, control delay is selected in the MOE for model calibration. Hence, the network parameters namely turning speeds, mean startup delay, and mean discharge headway that can affected the control delay, are used for calibration. CORSIM outputs control delay in vehicle-minutes while control delays computed from the field data are in seconds per vehicle. Equation 4.1 is used to convert vehicle-minutes of control delays into seconds per vehicle of control delay.

$$\text{Control delay (seconds/vehicle)} = \frac{\text{Control Delay (vehicle - minutes)} \times 60}{\textit{Trips}} \tag{4.1}$$

The numbers of trips are the number of vehicles using the subjected link under consideration during the given interval of time.

4.5. Determination of Sample Size

Since microscopic simulations are based on creation of random events, results for same simulation scenario can change from one simulation run to other. It is therefore a general practice to perform multiple runs for each simulation scenario and compute average values for the output MOEs. The required number of multiple runs for each simulation scenario i.e. the sample size, is determined based on the desired level of accuracy in the value of the output MOE. Equation 4.2 is used to determine the minimum required number of simulation runs.

$$n = \left(\frac{Z_{\alpha/2}\sigma}{E} \right)^2 \tag{4.2}$$

where

n = required minimum number of simulation runs

$Z_{\alpha/2}$= value from the normal table corresponding to area of $\alpha/2$ in the right tail.

$Z_{\alpha/2}$ = 1.96 with a 95% confidence interval

σ = sample standard deviation. σ is computed from the preliminary simulation runs.

E = maximum allowable error

In this study, control delay for left-turning traffic is the MOE used to determine the minimum number of simulation runs required. From the preliminary 100 simulation runs, the standard deviation of 27.55 vehicle-minutes and an allowable error of 8.6 vehicle-minutes is assumed that is 5 percent of the mean. For a confidence interval of 95 %, the minimum required number of simulation runs is calculated using equation 4.2. The minimum Number of simulations = 40. Therefore, for this study 50 simulation runs are used.

4.6. Model Calibration

For a simulation model to be used for analysis and evaluation, it must first be calibrated, as any base model developed does not exactly represents the existing traffic condition in the field. Therefore, the model has to be adjusted so that it can closely reproduce the observed conditions. The process of calibration involves iterative adjustments of the values of selected input parameters in an attempt to obtain the output MOE values that match the observed values from the field. CORSIM provides certain sets of user-adjustable input parameters to calibrate the model to match field conditions.

4.6.1. Model Calibration Procedure

The following are the steps involved in the calibration procedure as shown in Figure 4.6 adopted for this study.

- Selection of MOE for calibration
- Selection of the calibrated input parameters and their allowable range
- Formation of simulation cases with various combination of the input parameters within the given range
- Performing a simulation run for each case to obtain output MOE

- Comparison of output MOE obtained from different cases with field MOE
- Selection of the calibrated model with an MOE closest to the field MOE.

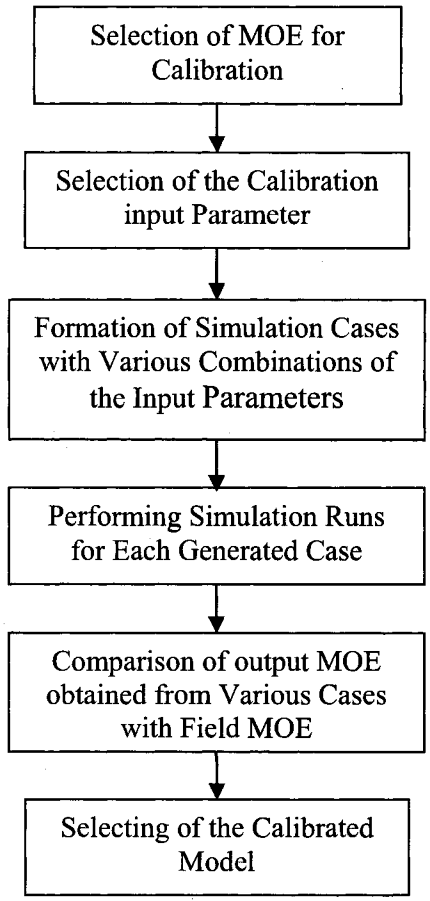


Figure 4.6 Flow chart for calibration procedure

1. Selection of MOE for Calibration

In this, control delay is selected as the MOE to be calibrated as discussed earlier. The value of field control delays are presented in Table 4.1.

Table 4.1 Target values for Control Delay for model calibration

Control Delay Left (seconds)	115.77
Control Delay Through (seconds)	61.84

2. Selection of the Calibration input Parameter

The following traffic parameters are selected and adjusted for the model calibration:-

a) The left and right turning speeds: The turning speeds are the maximum allowable speed at which the vehicles can maneuver a turn comfortably.

b) Mean startup delay: The mean startup delay is the additional delay taken by first few vehicles in a queue at a signalized intersection that are beyond the saturation headway. The startup delay is due to the time required to react to the start of the green phase and for the vehicle to accelerate from a stopped position. HCM recommends a value of 2.0 seconds under ideal conditions.

c) Mean discharge headway: It is the time taken by the vehicle to react to its leader vehicle while discharging from a standing queue.

Table 4.2 presents the calibration input parameters used to calibrate the model with allowable range. The allowable range for calibration parameters is selected based on the criteria that could be achieved in the field.

Table 4.2 Calibration Network parameters for calibration

Parameters	Default Value	Calibration range
Mean discharge headway	1.8 seconds	1.8 to 2.2 seconds
Mean startup delay	2.0 seconds	1.9 to 2.1 seconds
Left-turning speed	22 fps	18 to 24 fps
Right turning speed	13 fps	10 fps to 15 fps

3. Formation of Simulation Cases with Combinations Input Parameters

Various cases are formed using combinations of the calibration input parameters by changing their values within the allowable range. Table 4.3 presents the various simulation cases used for calibration.

4. Performing Simulation Runs for Each Generated Case

Simulation runs are performed on the various cases formed to obtain the output control delays. The output control delays corresponding to various values for calibration input parameters used for the model calibration are tabulated in the Table 4.3.

Table 4.3 Calibration network parameters

Cases	Mean discharge headway (seconds)	Mean startup Delay (seconds)	Left-turning speed		Right turning speed		Control delay	
			(fps)	(mph)	(fps)	(mph)	Left	Right
Case 0	1.8	2.0	22	15.0	13	8.9	93.10	50.90
Case 1	1.8	1.9	22	15.0	13	8.9	73.57	49.14
Case 2	1.8	2.0	18	12.3	10	6.8	75.60	49.02
Case 3	1.8	2.1	22	15.0	12	8.2	77.42	50.42
Case 4	2.0	1.9	24	16.4	15	10.2	90.47	53.38
Case 5	2.0	2.0	18	12.3	10	6.8	89.095	52.51
Case 6	2.0	2.1	22	15.0	12	8.2	88.28	51.98
Case 7	2.2	1.9	24	16.4	15	10.2	113.05	63.45
Case 8	2.2	2.0	18	12.3	10	6.8	113.04	61.31
Case 9	2.2	2.1	22	15.0	12	8.2	126.10	65.86
Case 10	1.8	1.9	24	16.4	15	10.2	75.85	48.82
Case 11	2.0	2.0	18	12.3	10	6.8	89.10	52.51
Case 12	2.2	2.1	22	15.0	15	10.2	121.54	64.47

5. Comparison of output MOE obtained from various cases with field MOE

Comparisons are performed between the output control delays and field control delays. Tables 4.1 and 4.3 show the control delays corresponding to case 7 and case 8 are closest to the values of control delays obtained from the field.

The field control delay for left-turn lane is 115.77 seconds per vehicle and the calibrated model gave a value of 113.05seconds per vehicle with a difference of 2.73 seconds per vehicle. Whereas for through control delay the calibrated model gave a value of 61.31 seconds per vehicle as compared to a field value of control delay of 61.84 seconds per vehicle with a difference of 0.53 seconds per vehicle.

6. Selecting of the Calibrated Model

Case 8 is selected as the calibrated simulation model because the output control delays for left-turn and through traffic computed by this model are closest to the control delays obtained from the field. Therefore, the following values of network parameters obtained from case 8 are used as the calibrated model for further simulations:

- Mean discharge headway of 2.2 seconds
- Mean startup delay of 2.0 seconds.
- The Left-turning of 18 fps equivalent to 12.5 mph
- The right turn speed of 10 fps equivalent to 7 mph

4.7. Simulation Scenarios

Various simulation scenarios are generated to determine the optimum lengths of the left-turn lanes. Traffic Signal phases, cycle length and traffic volume are varied to form case scenarios. The signal phases used in this study are presented in Table 4.4. The various values used for cycle length and traffic volume are presented in Tables 4.5 and 4.6 respectively. Each of the case scenarios are further simulated for different lengths of the left-turn lanes. The lengths of left-turn lanes used are presented in Table 4.7. Tables 4.8, 4.9 and 4.10 present the various case scenarios formed for this study. The tables are categorized based on the cycle length and phase controls.

Table 4.4 Signal Phases

Case	Signal Phases (left turns)
A	Protected- permitted
B	Protected

Table 4.5 Variation in cycle length

Case	Cycle Length (sec)
C1	100
C2	120
C3	140

Table 4.6 Variation in traffic volume.

Traffic Flow Cases	Traffic Volume in relation to existing Volume
T0	Existing Traffic
T1	10% increase of existing traffic
T2	20% increase of existing traffic
T3	30% increase of existing traffic
T4	10% decrease of existing traffic
T5	20% decrease of existing traffic
T6	30% decrease of existing traffic
T7	10% increased left traffic
T8	20% increased left traffic
T9	30% increased left traffic
T10	10% decreased left traffic
T11	20% decreased left traffic
T12	30% decreased left traffic
T13	10% increased through traffic
T14	20% increased through traffic
T15	30% increased through traffic
T16	10% decreased through traffic
T17	20% decreased through traffic
T18	30% decreased through traffic

Table 4.7 Variation in length of left-turn lane.

Scenarios	Length of Left-turn Lane
S0	185
S1	100
S2	150
S3	200
S4	250
S5	300
S6	350
S7	400
S8	450
S9	500
S10	550
S11	600

Table 4.8 Case scenarios for 100 seconds cycle length

Cycle length	scenario number (protected – permitted)	scenario number (protected)	Traffic Volume percentage	Length of turn lane (Feet)
	A1-1	B1-1	Existing traffic	100 to 600
	A1-2	B1-2	10% increase of existing traffic	100 to 600
	A1-3	B1-3	20% increase of existing traffic	100 to 600
	A1-4	B1-4	30% increase of existing traffic	100 to 600
	A1-5	B1-5	10% decrease of existing traffic	100 to 600
	A1-6	B1-6	20% decrease of existing traffic	100 to 600
	A1-7	B1-7	30% decrease of existing traffic	100 to 600
	A1-8	B1-8	10% increased Left traffic	100 to 600
	A1-9	B1-9	20% increased Left traffic	100 to 600
100	A1-10	B1-10	30% increased Left traffic	100 to 600
	A1-11	B1-11	10% decreased Left traffic	100 to 600
	A1-12	B1-12	20% decreased Left traffic	100 to 600
	A1-13	B1-13	30% decreased Left traffic	100 to 600
	A1-14	B1-14	10% increased through traffic	100 to 600
	A1-15	B1-15	20% increased through traffic	100 to 600
	A1-16	B1-16	30% increased through traffic	100 to 600
	A1-17	B1-17	10% decreased through traffic	100 to 600
	A1-18	B1-18	20% decreased through traffic	100 to 600
	A1-19	B1-19	30% decreased through traffic	100 to 600

Table 4.9 Case scenarios for 120 seconds cycle length

Cycle Length	scenario number (protected – permitted)	scenario number (protected)	Traffic Volume percentage	Length of turn lane (feet)
	A2-1	B2-1	Existing traffic	100 to 600
	A2-2	B2-2	10% increase of existing traffic	100 to 600
	A2-3	B2-3	20% increase of existing traffic	100 to 600
	A2-4	B2-4	30% increase of existing traffic	100 to 600
	A2-5	B2-5	10% decrease of existing traffic	100 to 600
	A2-6	B2-6	20% decrease of existing traffic	100 to 600
	A2-7	B2-7	30% decrease of existing traffic	100 to 600
	A2-8	B2-8	10% increased Left traffic	100 to 600
	A2-9	B2-9	20% increased Left traffic	100 to 600
120	A2-10	B2-10	30% increased Left traffic	100 to 600
	A2-11	B2-11	10% decreased Left traffic	100 to 600
	A2-12	B2-12	20% decreased Left traffic	100 to 600
	A2-13	B2-13	30% decreased Left traffic	100 to 600
	A2-14	B2-14	10% increased through traffic	100 to 600
	A2-15	B2-15	20% increased through traffic	100 to 600
	A2-16	B2-16	30% increased through traffic	100 to 600
	A2-17	B2-17	10% decreased through traffic	100 to 600
	A2-18	B2-18	20% decreased through traffic	100 to 600
	A2-19	B2-19	30% decreased through traffic	100 to 600

Table 4.10 Case scenarios for 140 seconds cycle length

Cycle Length	scenario number (protected – permitted)	scenario number (protected)	Traffic Volume percentage	Length of turn lane (feet)
140	A3-1	B3-1	Existing Traffic	100 to 600
	A3-2	B3-2	10% increase	100 to 600
	A3-3	B3-3	20% increase	100 to 600
	A3-4	B3-4	30% increase	100 to 600
	A3-5	B3-5	10% decrease	100 to 600
	A3-6	B3-6	20% decrease	100 to 600
	A3-7	B3-7	30% decrease	100 to 600
	A3-8	B3-8	10% increased Left traffic	100 to 600
	A3-9	B3-9	20% increased Left traffic	100 to 600
	A3-10	B3-10	30% increased Left traffic	100 to 600
	A3-11	B3-11	10% decreased Left traffic	100 to 600
	A3-12	B3-12	20% decreased Left traffic	100 to 600
	A3-13	B3-13	30% decreased Left traffic	100 to 600
	A3-14	B3-14	10% increased through traffic	100 to 600
	A3-15	B3-15	20% increased through traffic	100 to 600
	A3-16	B3-16	30% increased through traffic	100 to 600
	A3-17	B3-17	10% decreased through traffic	100 to 600
	A3-18	B3-18	20% decreased through traffic	100 to 600
	A3-19	B3-19	30% decreased through traffic	100 to 600

A total of 114 case scenarios are formed. For each case scenario, 12 different simulations are performed for different lengths of left-turn lanes. Therefore, 1368 simulations are performed.

In this study, the case scenarios with a v/c ratio for left-turn lane less than 1.2 are considered for analyzing the results. As for the value of v/c ratio greater than 1.2, the accuracy in estimating control delays decreases. For protected-permitted phasing less number of case scenarios are dropped as compared to protected, as for same volume of traffic the protected-permitted have lower volume to capacity ratio as it is served with and addition green time that lowers the v/c ratio. Table 4.11 and 4.12 present the case scenarios with v/c ratio more than 1.2 that are not considered for analysis of results. The v/c left ratios are obtained from Synchro.

Table 4.11 Dropped case scenario for protected-permitted left-turns

Case Scenario	Cycle length (seconds)	v/c left ratio
20 percent increased flow	100	1.23
30 percent increased flow	100	1.33
30 percent increased through flow	100	1.21
20 percent increased flow	120	1.24
30 percent increased flow	120	1.34

Table 4.12 Dropped case scenario for protected left-turns

Case Scenario	Cycle length (seconds)	v/c ratio
30 percent increased flow	100	1.34
10 percent increased flow	100	1.23
20 percent increased flow	100	1.45
30 percent increased flow	100	1.45
30 percent increased through flow	100	1.3
20 percent increased flow	120	1.33
30 percent increased flow	120	1.43
20 percent increased through flow	120	1.25
30 percent increased through flow	120	1.25
20 percent increased flow	140	1.25
30 percent increased flow	140	1.35

CHAPTER 5

RESULTS AND DISCUSSION

5.1. Introduction

This chapter discusses the analysis of results. To analyze the results 98 case scenarios are simulated to evaluate the impact on the delay on the northbound approach of S. Main Street. Further, the optimum lengths for each case scenario are obtained based on minimizing the delays. Regression analyses are performed to compute the lengths of the left-turn lanes as a function of various traffic and signal parameters. The lengths corresponding to the 95th percentile guidelines (referred to as "guidelines") are compared. Furthermore, the delays corresponding to guidelines, existing, and optimum lengths obtained from the simulation model are compared.

5.2. Evaluation of Impact of Length of Left-Turn Lane on Control Delay and Determining the Optimum Length

In order to determine the effect of lengths of left-turn lanes on the control delays, the analysis is performed using varying lengths of the left-turn lane. The control delay data is obtained from case scenarios discussed in Chapter 4. For v/c ratio for left-turn lanes less than 1.2, ninety-eight case scenarios for protected and protected-permitted left-turns are analyzed. This study is categorized based on protected and protected-permitted left-turns and two different cases are formed for each. In order to demonstrate the results two case scenarios are presented

For case scenario A1-1 that consists of:

- Protected-permitted left-turn,
- Cycle length of 100 seconds,
- Existing traffic flow, and
- Varying the length of left-turn lane from 100 to 600 feet.

For the second case scenario B1-1 that consists of:

- Protected left-turn,
- Cycle length of 100 seconds,
- Existing traffic flow, and
- Varying the length of left-turn lane from 100 to 600 feet

Tables 5.1 and 5.2 present the control delays for left-turning traffic and through traffic corresponding to the different lengths of left-turn lanes for case scenarios A1-1 and B1-1 respectively.

Table 5.1 Control delay corresponding to length of left-turn lane (case scenario A1-1)

Cycle length	Length of left-turn lanes	Control delay (Left) (seconds)	Control delay (Through) (seconds)
100	100	53.7	30.8
	150	41.5	31.3
	185	39.1	31.4
	200	36.5	29.8
	250	36.9	30.6
	300	37.8	32.5
	350	37.5	31.8
	400	37.4	31.4
	450	36.4	30.2
	500	36.3	30.6
	550	36.7	31.0
	600	37.2	32.5

Table 5.2 Control delay corresponding to length of left-turn lane (case scenario B1-1).

Cycle length	Length of left-turn lanes	Control delay (Left) (seconds)	Control delay (Through) (seconds)
100	100	164.6	33.6
	150	82.9	27.0
	185	57.4	26.7
	200	56.9	26.7
	250	56.5	26.8
	300	57.2	26.7
	350	57.8	26.8
	400	56.9	26.8
	450	56.2	26.7
	500	56.4	26.7
	550	58.0	26.7
	600	56.8	26.6

To study the impact of the length of the left-turn lane on the control delay for case scenarios A1-1 and B1-1, Figures 5.1 and 5.2 show the graphical variation between control delays corresponding to the different lengths of left-turn lane. The graph shows that on increasing the length, the control delay for left-turning traffic decreases. It can also be observed that after a certain length of the left-turn lane, there is no further significant change in the left-turn control delays. The point on the graph where there is no further significant change in left-turn control delay is referred to as an optimum point that corresponds to the optimum length of the left-turn lane.

In addition, it is observed that control delays for through traffic do not have any significant change. This is not expected as for very shorter lengths of left-turn lanes there should be certain increase in the through delays. As there are two through lanes, therefore, when the left-lane is overflowing onto the through lane the through traffic will change the lane and proceed, rather than pilling up in the blocked lane. The values for through control delays are lower as compared to the control delays for left-turn traffic. Therefore, control delays for left-turning traffic are taken into account to determine the optimum lengths.

From Figures 5.1 and 5.2 for case scenario A1-1 and B1-1, there is no significant change in the control delays beyond the length of 200 feet for the left-turn lane. Therefore, the optimum length of the left-turn lane for case scenario A1-1 and B1-1 is 200 feet.

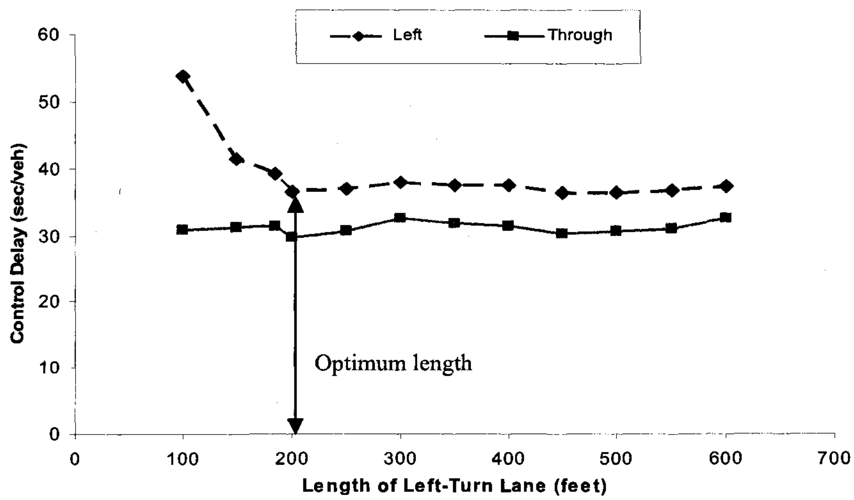


Figure 5.1 Control delay left v/s length of left-turn lane (protected-permitted left-turns)

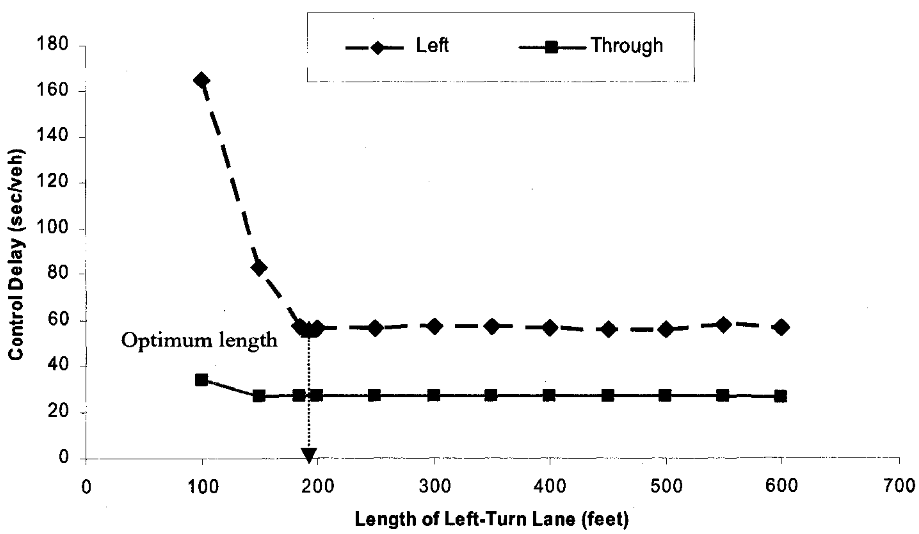


Figure 5.2 Control delay left v/s length of left-turn lane for protected left-turns

The comparison between Figure 5.1 and 5.2 shows that the control delays corresponding to protected left-turns are higher as compared to those for protected-permitted left-turns. This is due to additional green time allocated for the left-turning vehicles during permitted phase.

For all other case scenarios, for protected and protected-permitted left-turn, similar trends of decrease in control delays for left-turning traffic are observed. This decrease continues until optimum point and no significant change in control delays for through traffic are observed. The optimum lengths for protected-permitted and protected lanes are recorded using the optimum point and are presented in Tables 5.3 to 5.8 respectively.

Table 5.3 Optimum lengths for Case Scenarios for 100 second cycle length (protected-permitted)

Scenario number	Cycle Length	Case scenarios	Optimized Length of left - turn lane
A1-1	100	Existing Traffic	200
A1-5	100	10 Reduced Traffic	150
A1-6	100	20 Reduced Traffic	100
A1-7	100	30 Reduced Traffic	100
A1-2	100	10 increased Traffic	250
A1-8	100	10 Increased Left Traffic	200
A1-9	100	20 Increased Left Traffic	200
A1-10	100	30 Increased Left Traffic	250
A1-11	100	10 increased Through Traffic	200
A1-12	100	20 Increased Through Traffic	250
A1-13	100	10 percent decrease of Left Traffic	200
A1-14	100	20 percent decrease of Left Traffic	150
A1-15	100	30 percent decrease of Left Traffic	150
A1-16	100	10 percent decrease of Through Traffic	150
A1-17	100	20 percent decrease of Through Traffic	150
A1-18	100	30 percent decrease of Through Traffic	150

Table 5.4 Optimum lengths for Case Scenarios for 120 second cycle length (protected-permitted)

Scenario number	Cycle Length	Case scenarios	Optimized Length of left - turn lane
A2-1	120	Existing Traffic	200
A2-5	120	10 Reduced Traffic	150
A2-6	120	20 Reduced Traffic	150
A2-7	120	30 Reduced Traffic	100
A2-2	120	10 increased Traffic	250
A2-8	120	10 Increased Left Traffic	200
A2-9	120	20 Increased Left Traffic	250
A2-10	120	30 Increased Left Traffic	250
A2-11	120	10 increased Through Traffic	250
A2-12	120	20 Increased Through Traffic	250
A2-13	120	30 Increased Through Traffic	300
A2-14	120	10 percent decrease of Left Traffic	200
A2-15	120	20 percent decrease of Left Traffic	200
A2-16	120	30 percent decrease of Left Traffic	200
A2-17	120	10 percent decrease of Through Traffic	200
A2-18	120	20 percent decrease of Through Traffic	200
A2-19	120	30 percent decrease of Through Traffic	200

Table 5.5 Optimum lengths for Case Scenarios for 140 second cycle length (protected-permitted)

Scenario number	Cycle Length	Description	Optimized Length of left - turn lane
A3-1	140	Existing Traffic	250
A3-5	140	10 Reduced Traffic	200
A3-6	140	20 Reduced Traffic	200
A3-7	140	30 Reduced Traffic	150
A3-2	140	10 increased Traffic	250
A3-3	140	20 increased Traffic	300
A3-8	140	10 Increased Left Traffic	250
A3-9	140	20 Increased Left Traffic	300
A3-10	140	30 Increased Left Traffic	300
A3-11	140	10 increased Through Traffic	250
A3-12	140	20 Increased Through Traffic	250
A3-13	140	30 Increased Through Traffic	300
A3-14	140	10 percent decrease of Left Traffic	250
A3-15	140	20 percent decrease of Left Traffic	200
A3-16	140	30 percent decrease of Left Traffic	200
A3-17	140	10 percent decrease of Through Traffic	200
A3-18	140	20 percent decrease of Through Traffic	200
A3-19	140	30 percent decrease of Through Traffic	150

Table 5.6 Optimum lengths for Case Scenarios for 100 second cycle length (protected)

Scenario number	Cycle Length	Description	Optimized Length of left - turn lane
B1-1	100	Existing Traffic	200
B1-5	100	10 Reduced Traffic	200
B1-6	100	20 Reduced Traffic	200
B1-7	100	30 Reduced Traffic	150
B1-8	100	10 Increased Left Traffic	200
B1-9	100	20 Increased Left Traffic	200
B1-10	100	30 Increased Left Traffic	300
B1-14	100	10 Increased Through Traffic	200
B1-15	100	20 Increased Through Traffic	250
B1-11	100	10 percent decrease of Left Traffic	200
B1-12	100	20 percent decrease of Left Traffic	200
B1-13	100	30 percent decrease of Left Traffic	200
B1-17	100	10 percent decrease of Through Traffic	200
B1-18	100	20 percent decrease of Through Traffic	200
B1-19	100	30 percent decrease of Through Traffic	200

Table 5.7 Optimum lengths for Case Scenarios for 120 second cycle length (protected)

Scenario number	Cycle Length	Description	Optimized Length of left - turn lane
B2-1	120	Existing Traffic	200
B2-5	120	10 Reduced Traffic	200
B2-6	120	20 Reduced Traffic	200
B2-7	120	30 Reduced Traffic	150
B2-2	120	10 increased Traffic	250
B2-8	120	10 Increased Left Traffic	250
B2-9	120	20 Increased Left Traffic	250
B2-10	120	30 Increased Left Traffic	250
B2-14	120	10 increased Through Traffic	250
B2-11	120	10 percent decrease of Left Traffic	200
B2-12	120	20 percent decrease of Left Traffic	200
B2-13	120	30 percent decrease of Left Traffic	200
B2-17	120	10 percent decrease of Through Traffic	200
B2-18	120	20 percent decrease of Through Traffic	200
B2-19	120	30 percent decrease of Through Traffic	200

Table 5.8 Optimum lengths for Case Scenarios for 140 second cycle length (protected)

Scenario number	Cycle Length	Description	Optimized Length of left - turn lane
B3-1	140	Existing Traffic	250
B3-5	140	10 Reduced Traffic	250
B3-6	140	20 Reduced Traffic	200
B3-7	140	30 Reduced Traffic	200
B3-2	140	10 increased Traffic	300
B3-8	140	10 Increased Left Traffic	250
B3-9	140	20 Increased Left Traffic	300
B3-10	140	30 Increased Left Traffic	300
B3-14	140	10 increased Through Traffic	250
B3-15	140	20 Increased Through Traffic	400
B3-16	140	30 Increased Through Traffic	400
B3-11	140	10 percent decrease of Left Traffic	200
B3-12	140	20 percent decrease of Left Traffic	200
B3-13	140	30 percent decrease of Left Traffic	200
B3-17	140	10 percent decrease of Through Traffic	250
B3-18	140	20 percent decrease of Through Traffic	250
B3-19	140	30 percent decrease of Through Traffic	200

5.3. Evaluation of Impact of Cycle Length on Optimum Required Left-Turn Lane Length

In order to determine the impact of cycle length on the left-turn lane length, case scenarios are selected for 30 percent reduced traffic, and existing traffic for cycle lengths of 100,120 and 200 seconds. 30 percent reduced traffic case scenarios are selected to see the impact of increase in volume on the length of left-turn lane.

The selected case scenarios for protected-permitted left-turns are

- A1-7, A2-7 and A3-7
- A1-1, A2-1 and A3-1

For protected left-turns the case scenarios selected are

- B1-7, B2-7 and B3-7
- B1-7, B2-7 and B3-7

Tables 5.9 and 5.10 present the control delays for 30 percent reduced traffic for A1-7, A2-7 and A3-7 and B1-7, B2-7 and B3-7 respectively.

Table 5.9 Control delays corresponding to length of left-turn lane for case scenarios A1-7, A2-7 and A3-7

Length of left-turn	A1-7	A2-7	A3-7
	Control delay (Left) (sec/veh)	Control delay (Left) (sec/veh)	Control delay (Left) (sec/veh)
100	24.68	32.73	34.67
150	20.83	25.48	28.90
185	20.86	25.31	27.73
200	20.94	25.04	27.70
250	20.97	25.26	27.52
300	21.12	25.20	28.02
350	21.14	25.20	27.69
400	21.15	25.26	27.69
450	21.09	25.19	27.62
500	21.03	25.05	27.69
550	20.81	25.05	27.68
600	20.78	25.16	27.75

Table 5.10 Control delays corresponding to length of left-turn lane for case scenarios B1-7, B2-7 and B3-7

Length of left-turn	B1-7	B2-7	B3-7
	Control delay(Left) (sec/veh)	Control delay(Left) (sec/veh)	Control delay(Left) (sec/veh)
100	24.44	31.09	37.12
150	20.38	24.63	29.18
185	20.19	24.03	27.29
200	20.27	24.03	27.01
250	20.07	24.17	26.85
300	20.28	24.01	27.09
350	20.49	24.13	27.16
400	20.29	24.04	26.70
450	20.29	24.22	27.02
500	20.54	24.34	27.02
550	20.39	24.22	27.04
600	20.51	24.13	27.04

Tables 5.11 and 5.12 present the control delays for existing traffic for A1-1, A2-1 and A3-1, and B1-1, B2-1 and B3-1 respectively.

Table 5.11 Control delays corresponding to length of left-turn lane for case scenarios A1-1, A2-1 and A3-1

Length of left-turn	A1-1 Control delay (Left) (sec/veh)	A2-1 Control delay (Left) (sec/veh)	A3-1 Control delay (Left) (sec/veh)
100	53.69	60.11	77.18
150	42.52	46.72	61.64
185	39.14	40.62	52.28
200	37.52	39.91	47.13
250	37.91	38.67	42.79
300	38.78	39.69	42.66
350	38.52	39.28	42.38
400	38.40	39.07	41.97
450	37.45	40.47	42.11
500	38.28	39.39	41.81
550	37.74	39.84	42.29
600	38.22	40.39	42.08

Table 5.12 Control delay corresponding to length of left-turn lane for case scenarios B1-1, B2-1 and B3-1

Length of left-turn	B1-1 Control delay (Left) (sec/veh)	B2-1 Control delay (Left) (sec/veh)	B3-1 Control delay (Left) (sec/veh)
100	105.65	114.48	119.21
150	82.93	93.01	115.08
185	57.35	70.36	93.07
200	56.95	68.14	81.81
250	56.54	68.47	71.90
300	57.20	67.27	71.70
350	57.75	66.35	70.87
400	56.86	67.12	71.87
450	56.19	65.03	71.28
500	56.36	66.19	71.35
550	58.04	66.14	70.35
600	56.77	66.76	71.85

Figures 5.3 to 5.6 show the variation in control delays for left turning vehicles as a function of cycle length and the length of left-turn lane. The graphs show that with the increase of cycle length for same traffic conditions the control delay increases. The

optimized length on comparison from the graphs shows that for longer cycle length, a longer left-turn lane is required. This occurs because an increase in cycle length causes an increase in the waiting time, so more vehicle need to be stored if they arrive at the same arrival rate. From figure 5.3 and 5.5 it can be observed that on increasing the traffic volume there is increase in the length of the left-turn lane. For example for case scenario A3-7 the length of left-turn lane is 200 feet, where as for case scenario A3-1 the length is 250 feet.

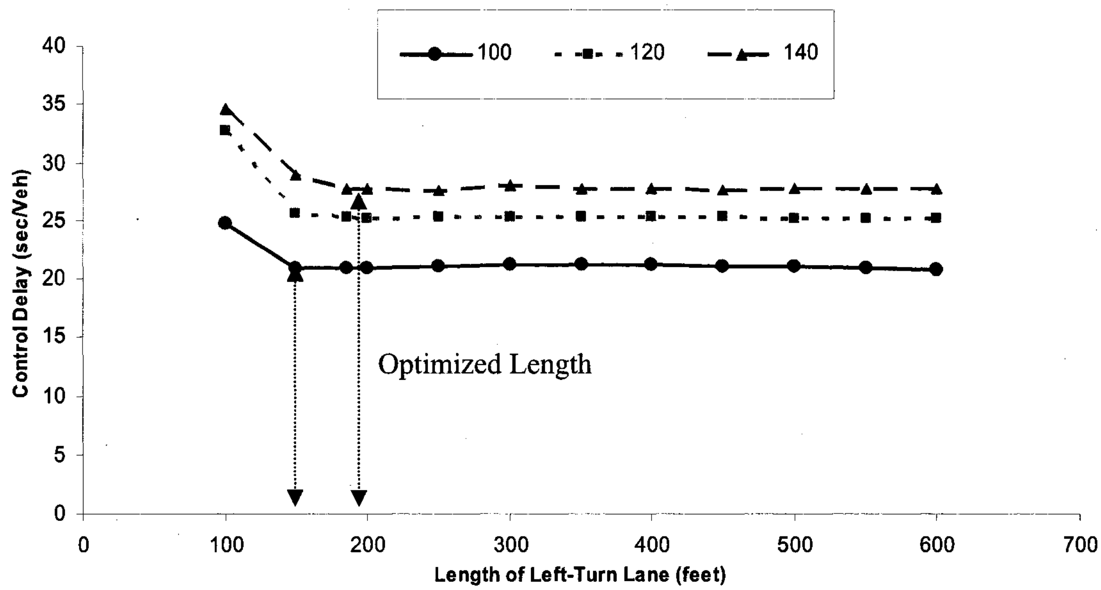


Figure 5.3 Comparison of length of left-turn lane for A1-7, A2-7, and A3-7 (Protected-permitted, 30 percent reduced traffic)

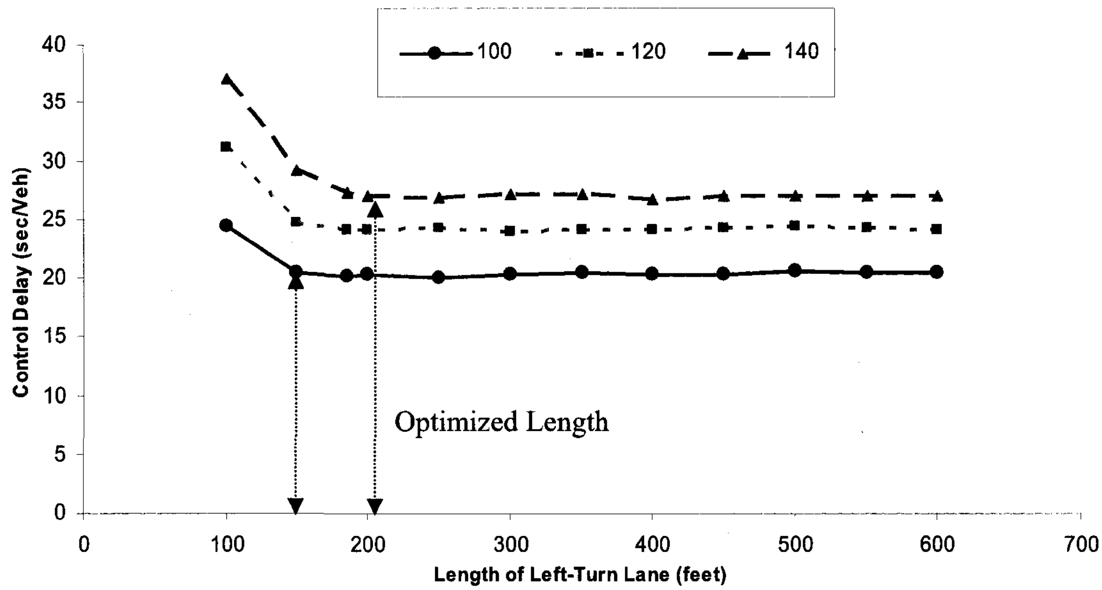


Figure 5.4 Comparison of length of left-turn lane for B1-7, B2-7, and B3-7
(Protected left-turns, 30 percent reduced traffic)

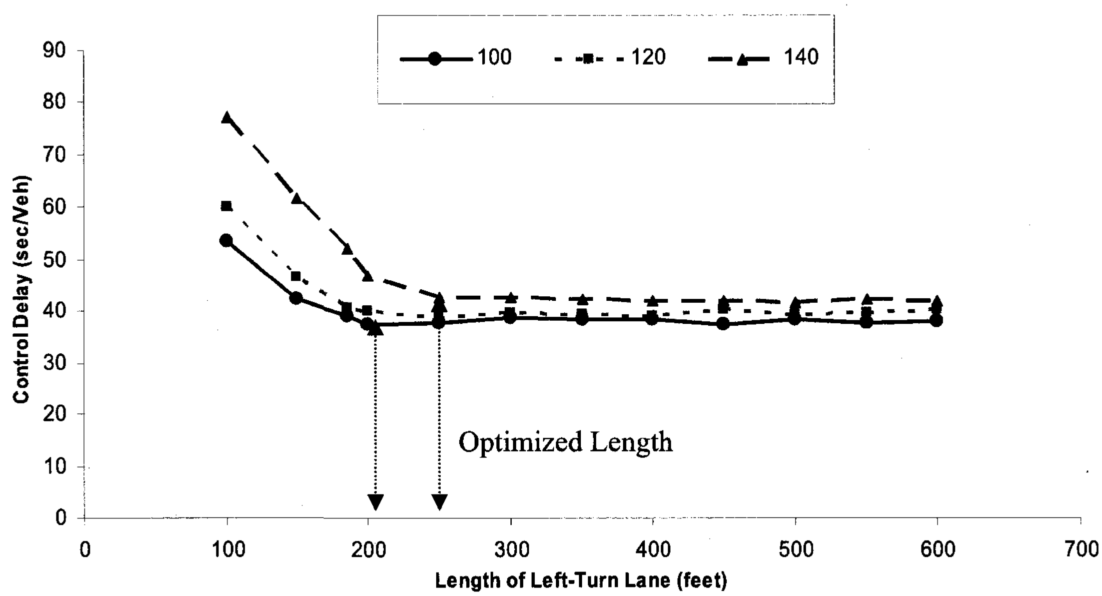


Figure 5.5 Comparison of length of left-turn lane for A1-1, A2-1, and A3-1
(Protected-permitted, existing traffic)

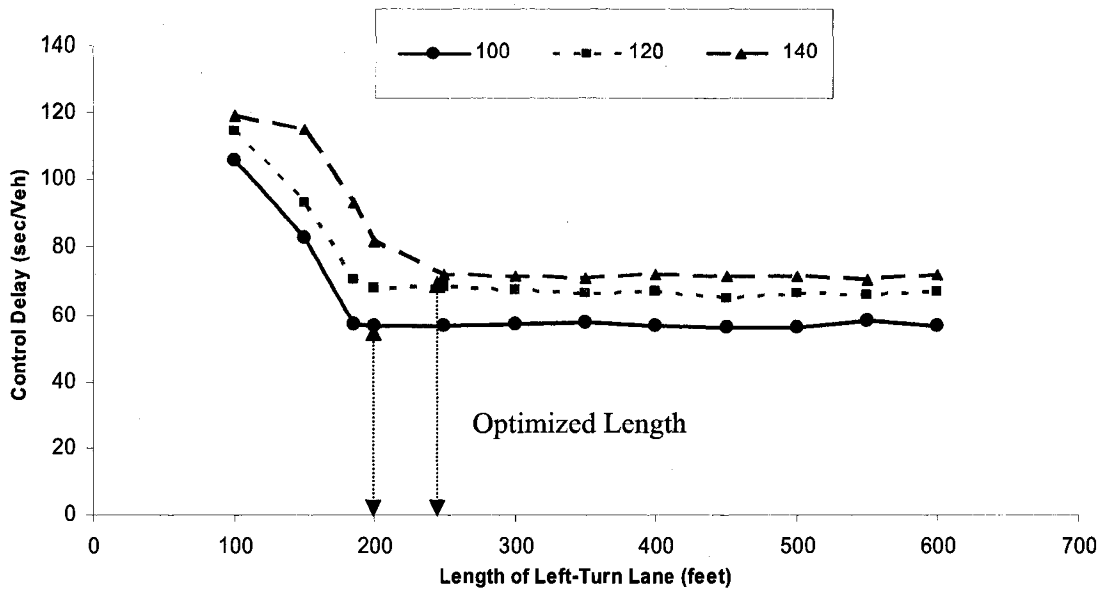


Figure 5.6 Comparison of length of left-turn lane for B1-1, B2-1, and B3-1 (Protected left-turns, existing traffic)

5.4. Modeling of Optimum Length of Left-Turn Lanes

Regression analysis is used to model the optimum length of left-turn lane lanes as a function of traffic volume and signal timing characteristics. The data used for the regression analysis is presented in Tables 5.13 and 5.14 for protected-permitted and protected left turns respectively.

Table 5.13 Data for protected-permitted left-turn for modeling the optimum length

Scenario Number	Optimal left-turn length	Volume Through	Volume Left turns	V/C Left	V/C Through	Cycle Length	Opposing Flow SB Through
A1-1	200	717	216	1.03	0.87	100	520
A1-5	150	646	195	0.87	0.77	100	468
A1-6	100	574	173	0.75	0.68	100	416
A1-7	100	502	152	0.58	0.62	100	364
A1-2	250	789	238	1.13	0.99	100	572
A1-8	200	717	238	1.06	0.87	100	520
A1-9	200	717	260	1.02	0.9	100	520
A1-10	250	717	281	1.12	0.87	100	520
A1-11	200	789	216	1.03	0.95	100	572

Table 5.13 (Continued)

Scenario Number	Optimal length	Volume Through	Volume Left	V/C Left	V/C Through	Cycle Length	Opposing Through
A1-12	250	861	216	1.18	1.03	100	624
A1-13	200	717	195	0.99	0.87	100	520
A1-14	150	717	173	0.95	0.85	100	520
A1-15	150	717	152	0.83	0.85	100	520
A1-16	150	646	216	0.96	0.75	100	468
A1-17	150	574	216	0.82	0.7	100	416
A1-18	150	502	216	0.78	0.61	100	364
A2-1	200	717	216	1.03	0.82	120	520
A2-5	150	646	195	0.85	0.72	120	468
A2-6	150	574	173	0.72	0.64	120	416
A2-7	100	502	152	0.56	0.56	120	364
A2-2	250	789	238	1.14	0.9	120	572
A2-8	200	717	238	1.02	0.84	120	520
A2-9	250	717	260	1.06	0.84	120	520
A2-10	250	717	281	1.09	0.86	120	520
A2-11	250	789	216	1.09	0.92	120	572
A2-12	250	861	216	1.06	1.02	120	624
A2-13	300	933	216	1.16	1.1	120	676
A2-14	200	717	195	0.93	0.79	120	520
A2-15	200	717	173	0.97	0.8	120	520
A2-16	200	717	152	0.87	0.81	120	520
A2-17	200	646	216	0.93	0.75	120	468
A2-18	200	574	216	0.85	0.67	120	416
A2-19	200	502	216	0.8	0.58	120	364
A3-1	250	717	216	0.99	0.82	140	520
A3-5	200	646	195	0.86	0.72	140	468
A3-6	200	574	173	0.73	0.63	140	416
A3-7	150	502	152	0.55	0.56	140	364
A3-2	250	789	238	1.08	0.87	140	572
A3-3	300	861	260	1.18	0.93	140	624
A3-8	250	717	238	1.04	0.84	140	520
A3-9	300	717	260	1.08	0.82	140	520
A3-10	300	717	281	1.08	0.87	140	520
A3-11	250	789	216	1.03	0.9	140	572
A3-12	250	861	216	1.08	0.97	140	624
A3-13	300	933	216	1.14	1.04	140	676
A3-14	250	717	195	0.93	0.79	140	520
A3-15	200	717	173	0.87	0.8	140	520
A3-16	200	717	152	0.81	0.77	140	520
A3-17	200	646	216	0.91	0.77	140	468
A3-18	200	574	216	0.83	0.65	140	416
A3-19	150	502	216	0.79	0.56	140	364

Table 5.14 Data for protected left-turn for modeling the optimum length

Scenario Number	Optimal length	Volume Through	Volume Left turns	V/C Left	V/C Through	Cycle Length
B1-1	200	717	216	1.04	0.84	100
B1-5	200	646	195	0.94	0.78	100
B1-6	200	574	173	0.83	0.65	100
B1-7	150	502	152	0.70	0.61	100
B1-8	200	717	238	1.14	0.84	100
B1-9	200	717	260	1.17	0.84	100
B1-10	300	717	281	1.19	0.84	100
B1-14	200	789	216	1.11	0.92	100
B1-15	250	861	216	1.20	1.03	100
B1-11	200	717	195	1.00	0.87	100
B1-12	200	717	173	1.04	0.82	100
B1-13	200	717	152	0.92	0.82	100
B1-17	200	646	216	1.04	0.82	100
B1-18	200	574	216	0.91	0.82	100
B1-19	200	502	216	0.87	0.59	100
B2-1	200	717	216	1.04	0.86	120
B2-5	200	646	195	0.93	0.77	120
B2-6	200	574	173	0.80	0.63	120
B2-7	150	502	152	0.65	0.57	120
B2-2	250	789	238	1.20	0.90	120
B2-8	250	717	238	1.08	0.84	120
B2-9	250	717	260	1.13	0.82	120
B2-10	250	717	281	1.16	0.82	120
B2-14	250	789	216	1.10	0.92	120
B2-11	200	717	195	1.00	0.86	120
B2-12	200	717	173	0.94	0.79	120
B2-13	200	717	152	0.94	0.79	120
B2-17	200	646	216	0.99	0.77	120
B2-18	200	574	216	0.90	0.68	120
B2-19	200	502	216	0.83	0.61	120
B3-1	250	717	216	1.04	0.84	140
B3-5	250	646	195	0.90	0.74	140
B3-6	200	574	173	0.78	0.66	140
B3-7	200	502	152	0.65	0.57	140
B3-2	300	789	238	1.14	0.89	140
B3-8	250	717	238	1.09	0.84	140
B3-9	300	717	260	1.10	0.84	140
B3-10	300	717	281	1.13	0.85	140
B3-14	250	789	216	1.09	0.88	140
B3-15	400	861	216	1.15	0.95	140
B3-16	400	933	216	1.20	1.02	140
B3-11	200	717	195	0.99	0.84	140
B3-12	200	717	173	0.97	0.82	140
B3-13	200	717	152	0.89	0.77	140
B3-17	250	646	216	0.95	0.75	140
B3-18	250	574	216	0.88	0.72	140
B3-19	200	502	216	0.83	0.60	140

A correlation matrix is developed to understand the correlation between the parameters to be used for regression analysis. The parameters that are least correlated to each other are take into consideration for regression analysis to determine the length of left-turn lane as a function of traffic parameters. The correlation matrixes are presented in Tables 5.15 and 5.16 for protected- permitted and protected left-turn respectively.

Table 5.17 presents the sets selected for protected-permitted and protected left-turn phasing for regression analysis for modeling the length of left-turn lane. For example for protected-permitted phasing the through volume is least correlated with volume left and cycle length. Therefore, for regression analysis, length of left-turn lane can be made a function of through volume, left-turn volume and cycle length.

Table 5.15 Correlation matrix for protected-permitted left-turn

Correlation		Vol. through	Vol. Left	V/C through	V/C left	Opp. vehicles through	Cycle length	Optimal left-turn length
Volume through	Correl	100.00%	36.12%	96.95%	86.43%	100.00%	8.87%	76.19%
	P-Value	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Volume Left	Correl	36.12%	100.00%	43.29%	72.81%	36.15%	3.80%	65.33%
	P-Value	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000
V/C through	Correl	96.95%	43.29%	100.00%	88.66%	96.96%	-8.88%	71.95%
	P-Value	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
V/C left	Correl	86.43%	72.81%	88.66%	100.00%	86.45%	-0.16%	82.48%
	P-Value	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
Cycle length	Correl	8.87%	3.80%	-8.88%	-0.16%	8.86%	100.00%	76.21%
	P-Value	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
Optimum left-turn length	Correl	76.19%	65.33%	71.95%	82.48%	43.36%	76.21%	100.00%
	P-Value	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
Opposing Through flow	Correl	100.00%	36.15%	96.96%	86.45%	100.00%	8.86%	76.21%
	P-Value	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000

Table 5.16 Correlation matrix for protected left-turn

Correlation		Vol. through	Vol. Left	V/C through	V/C left	Cycle length	Optimal left-turn length
Volume through	Correl.	100.00%	33.41%	95.43%	85.67%	9.20%	63.34%
	P-Value	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Volume Left	Correl.	33.41%	100.00%	42.40%	73.41%	2.68%	52.08%
	P-Value	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
V/C through	Correl.	95.43%	42.40%	100.00%	88.74%	-2.28%	57.68%
	P-Value	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
V/C left	Correl.	85.67%	73.41%	88.74%	100.00%	-5.42%	62.14%
	P-Value	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
Cycle length	Correl.	9.20%	2.68%	-2.28%	-5.42%	100.00%	43.34%
	P-Value	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
Optimal left-turn length	Correl.	63.34%	52.08%	57.68%	62.14%	43.34%	100.00%
	P-Value	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000

Table 5.17 combination of parameters to model the length of left-turn lane

Protected permitted phasing			Protected phasing		
Set 1A	Set 2A	Set 3A	Set 1B	Set 2B	Set 3B
vol. left	vol. left	vol. left	vol. left	vol. left	vol. left
vol. through	vol. through	v/c through	vol. through	vol. through	v/c through
cycle length	v/c through	cycle length	cycle length	v/c through	cycle length
	cycle length			cycle length	
	opp. through				

a) Modeling the length of left-turn lane for protected-permitted left-turn phasing

From the correlation matrixes, the following combinations of parameters are considered for the regression analysis based on the correlation coefficients and P-values:

- Set 1A: Left-turn length as a function of left-turn volume, through volume and cycle length,

- Set 2A: Left-turn length as a function of left-turn volume, volume through v/c through, opposing through volume and cycle length,
- Set 3A: Left-turn length as a function of left-turn volume, v/c through, and cycle length.

The Analysis of Variation (ANOVA) results for Set 1A, Set 2A and Set 3A are presented in Tables 5.18 to 5.23.

Table 5.18 Regression results for Set 1A for left-turn lane length for protected-permitted

S (std. error of estimate)	18.8456				
R-Sq	87.8%				
R-Sq(adj)	87.0%				
Predictor	Coef	SE Coef	T	P	VIF
Constant	-258.28	27.040	-9.550	0.000	
Volume Left turns	0.65142	0.082	7.910	0.000	1.150
Volume Through	0.27101	0.026	10.460	0.000	1.158
Cycle Length	1.1634	0.162	7.160	0.000	1.008

Table 5.19 ANOVA results from regression for Set 1A for left-turn lane length for protected-permitted

Source	DF	SS	MS	F	P
Regression	3	120170	40057	112.790	0.000
Residual Error	47	16692	355		
Total	50	136863			

Table 5.20 Regression results for Set 2A for left-turn lane length for protected-permitted

S(std. error of estimate)	18.6736				
R-Sq	88.5%				
R-Sq(adj)	87.3%				
Predictor	Coef	SE Coef	T	P	VIF
Constant	-278.150	31.040	-8.960	0.000	
Volume Left turns	0.585	0.096	6.090	0.000	1.593
Volume Through	-10.999	9.538	-1.150	0.255	159769.846
V/C Through	156.500	138.500	1.130	0.265	47.768
Cycle Length	1.397	0.253	5.520	0.000	2.492
Opposing SB Through	15.310	13.180	1.160	0.252	160199.542

Table 5.21 ANOVA results from regression for Set 2A for left-turn lane length for protected-permitted

Source	DF	SS	MS	F	P
Regression	5	121171	24234	69.500	0.000
Residual Error	45	15692	349		
Total	50	136863			

Table 5.22 Regression results for Set 3A for left-turn lane length for protected-permitted

S(std. error of estimate)	18.5929				
R-Sq	88.1%				
R-Sq(adj)	87.4%				
Predictor	Coef	SE Coef	T	P	VIF
Constant	-284.430	27.670	-10.280	0.000	
Volume Left	0.567	0.084	6.720	0.000	1.240
V/C Through	237.610	22.280	10.660	0.000	1.248
Cycle Length	1.501	0.161	9.330	0.000	1.015

Table 5.23 ANOVA results from regression for Set 3A for left-turn lane length for protected-permitted

Source	DF	SS	MS	F	P
Regression	3	120615	40205	116.300	0.000
Residual Error	47	16248	346		
Total	50	136863			

The Summary of ANOVA results for protected-permitted left-turn set 1A, set 2A and set 3A are presented in Table 5.24.

Table 5.24 Summary of ANOVA results for left-turn lane length for protected-permitted

Set 1A			Set 2A			Set 3A		
Variable	P-value	VIF	Variable	P-value	VIF	Variable	P-value	VIF
Constant	0.000		Constant	0.000		Constant	0.000	
Vol. Left	0.000	1.150	Vol. Left	0.000	1.593	Vol. Left	0.000	1.240
Vol. Through	0.000	1.158	Vol. Through	0.255	159769.846	V/C Through	0.000	1.248
Cycle Length	0.000	1.008	V/C Through	0.265	47.768	Cycle Length	0.000	1.015
			Cycle Length	0.000	2.492			
			Opposing SB Through	0.252	160199.542			

Variance inflation factor (VIF) measures the impact of co-linearity among the variables in a regression model on the precision of estimation. It expresses the degree to which co-linearity among the predictors degrades the precision of an estimate. The value of VIF greater than 10 is of concern and should be dropped. From Set 2A through volume, v/c through, and opposing through volume are dropped as these variables have a VIF greater than 10 and the P-values greater than 0.05.Therefore, a new Set 4A is formed after dropping the non significant variables from Set 2A. Regression analysis is performed for Set 4A and the ANOVA results for Set 4A are presented in Tables 5.25 and 5.26.

Table 5.25 Regression statistics for Set 4A for left-turn lane length for protected-permitted

S (std. error of estimate)	19.2869				
R-Sq	87.0%				
R-Sq(adj)	86.4%				
Predictor	Coef	SE Coef	T	P	VIF
Constant	-216.690	25.940	-8.350	0.000	
V/C Left	272.590	17.210	15.830	0.000	1.000
Cycle Length	1.381	0.166	8.340	0.000	1.000

Table 5.26 ANOVA results for Set 4A for left-turn lane length for protected-permitted

Source	DF	SS	MS	F	P
Regression	2	119008	59504	159.960	0.000
Residual Error	48	17855	372		
Total	50	136863			

On comparing the regression equation results for Set 1A, Set 3A and Set 4A, all the sets are statistically significant. The impact of the v/c through and left-turn volume on the length can be evaluated using Set 3A. The effect of through volume is also taken into account by Set 3A, hence Set 1A is dropped. Therefore, to model the length of left-turn lane, Set 3A is selected as Set 3A contains the v/c through, volume left and cycle length. Table 5.27 presents the coefficients of the independent variables for Set 3A to be used to determine the length of left-turn lane.

Table 5.27 ANOVA coefficients for modeling the length of left-turn lane for protected-permitted left-turn.

Independent Variable	Coefficients
Constant	-284.430
Volume Left	0.567
v/cThrough	237.610
Cycle Length	1.501

Equation 5.1 derived from the regression analysis describes the relation between the length of the left-turn lane and the parameters described in Set 4 for protected-permitted left-turn.

$$L = -284.43 + (0.567\times V_L) + (237.61\times v/c_T) + (1.501\times C) \quad (5.1)$$

where

L = modeled length of the left-turn lane

V_L = left-turn volume

v/c_T = volume to capacity ratio through lane

C = cycle length

b) Modeling the length of left-turn lane for protected left-turn phasing

To model the value of left-turn lane for protected left-turns, based on the correlation matrix, the following combinations of parameters are considered for the regression analysis:

- Set 1B: Left-turn length as a function of left-turn volume, through volume, and cycle length

- Set 2B: Left-turn length as a function of left-turn volume, through volume, v/c through, and cycle length
- Set 3B: Left-turn length as a function of v/c ratio for through lane, left-turn volume, and cycle length

The ANOVA results for Set 1B, 2B and 3B are presented in Tables 5.28 to 5.33.

Table 5.28 Regression results for Set 1B for left-turn lane length for protected left-turn phasing

S (std. error of estimate)	31.0499				
R-Sq	65.2%				
R-Sq(adj)	62.7%				
Predictor	Coef	SE Coef	T	P	VIF
Constant	-181.070	47.020	-3.850	0.000	
Volume Left	0.506	0.138	3.660	0.001	1.126
Volume Through	0.239	0.048	5.030	0.000	1.134
Cycle Length	1.160	0.276	4.200	0.000	1.009

Table 5.29 ANOVA results form regression for Set 1B for left-turn lane length for protected left-turn phasing

Source	DF	SS	MS	F	P
Regression	3	77586	25862	26.830	0.000
Residual Error	43	41456	964		
Total	46	119043			

Table 5.30 Regression results for Set 2B for left-turn lane length for protected left-turn phasing

S(std. error of estimate)	31.0644				
R-Sq	66.0%				
R-Sq(adj)	62.7%				
Predictor	Coef	SE Coef	T	P	VIF
Constant	-161.970	50.920	-3.180	0.003	
Volume Left	0.565	0.151	3.750	0.001	1.341
Vol.Through	0.399	0.170	2.350	0.023	14.371
V/C Through	-158.500	161.800	-0.980	0.333	15.466
Cycle Length	1.042	0.301	3.460	0.001	1.199

Table 5.31 ANOVA results from regression for Set 2B for left-turn lane length for protected left-turn phasing

Source	DF	SS	MS	F	P
Regression	4	78513	19628	20.340	0.000
Residual Error	42	40530	965		
Total	46	119043			

Table 5.32 Regression results for Set 3B for left-turn lane length for protected left-turn phasing

S (std. error of estimate)	32.6597				
R-Sq	61.5%				
R-Sq(adj)	58.8%				
Predictor	Coef	SE Coef	T	P	VIF
Constant	-192.830	51.730	-3.730	0.001	
Volume Left	0.459	0.151	3.030	0.004	1.221
V/C Through	206.600	47.790	4.320	0.000	1.221
Cycle Length	1.329	0.289	4.590	0.000	1.002

Table 5.33 ANOVA results from regression for Set 3B for left-turn lane length for protected left-turn phasing

Source	DF	SS	MS	F	P
Regression	3	73176	24392	22.870	0.000
Residual Error	43	45866	1067		
Total	46	119043			

The Summary of ANOVA results for protected-permitted left-turn Set 1, Set 2 and Set 3 are presented in Table 5.34.

Table 5.34 summary of ANOVA results from regression for protected left-turns

Set 1B			Set 2B			Set 3B		
Variables	P-value	VIF	Variables	P-value	VIF	Variables	P-value	VIF
Constant	0.000		Constant	0.003		Constant	0.001	
Volume Left	0.001	1.126	Volume Left	0.001	1.341	Volume Left	0.004	1.221
Volume Through	0.000	1.134	Vol.Through	0.023	14.371	V/C Through	0.000	1.221
Cycle Length	0.000	1.009	V/C Through	0.333	15.466	Cycle Length	0.000	1.002
			Cycle Length	0.001	1.199			

From Set 2B through volume, and v/c through, are dropped as these variables have a VIF greater than 10 and also v/c through have P-values greater than 0.05.Therefore, a new Set 4B is formed after dropping the non significant variables from Set 2B. Regression analysis is performed for Set 4B and the ANOVA results for Set 4B are presented in Tables 5.35 and 5.36.

Table 5.35 Regression statistics for Set 4B for left-turn lane length for protected left-turn phasing

S (std. error of estimate)	32.6956				
R-Sq	60.5%				
R-Sq(adj)	58.7%				
Predictor	Coef	SE Coef	T	P	VIF
Constant	-169.450	49.570	-3.420	0.001	
V/C Left	226.320	33.210	6.820	0.000	1.003
Cycle Length	1.430	0.290	4.940	0.000	1.003

Table 5.36 ANOVA results for Set 4A for left-turn lane length for protected left-turn phasing

Source	DF	SS	MS	F	P
Regression	2	72006	36003	33.680	0.000
Residual Error	44	47036	1069		
Total	46	119043			

On comparing the regression equation results for Set 1B, Set 3B and Set 4B, all the sets are statistically significant. The impact of the v/c through and left-turn volume on the length can be evaluated using Set 3B. The effect of through volume is also taken into account by Set 3B, hence Set 1B is dropped. Therefore, to model the length of left-turn lane, Set 3B is selected as Set 3B contains the v/c through, volume left and cycle length. Table 5.37 presents the coefficients of the independent variables for Set 3B to be used to determine the length of left-turn lane.

Table 5.37 ANOVA coefficients for modeling the length of left-turn lane for protected left-turn.

Independent Variable	Coefficients
Constant	-192.830
Volume Left	0.459
V/C Through	206.600
Cycle Length	1.329

Equation 5.2 derived from the regression analysis for protected left-turn describes the relation between the length of the left-turn lane and the parameters described in Set 3 A.

$$L = -192.830 + (0.459\times V_L) + (206.600\times v/c_T) + (1.329\times C) \qquad (5.2)$$

where

L = modeled length of the left-turn lane

V_L = left-turning volume

v/c_T = volume to capacity ratio through lane

C = cycle length

5.5. Comparison of Lengths of Left-Turn Lanes

Comparisons between the optimum lengths obtained from CORSIM, modeled length obtained from regression analysis and the lengths computed from the 95th percentile guidelines (referred as guidelines) are performed. The values for, guidelines, modeled and optimum lengths of the left-turn lanes for cycle lengths of 100, 120 and 140 seconds for protected-permitted left-turns are tabulated in Tables 5.38, 5.39 and 5.40 respectively. The existing length of the left-turn lane is 185 feet.

Table 5.38 Length of left-turn lanes for 100-second cycle length (protected-permitted)

V/C Left	Length of Left-turn Lane			Difference between guideline and optimum
	Guideline	Modeled	Optimized	
0.58	110	99	100	10
0.75	132	125	100	32
0.78	132	133	150	-18
0.82	153	154	150	3
0.83	110	154	150	-40
0.87	132	159	150	-18
0.95	132	166	150	-18
0.96	153	166	150	3
0.99	153	183	200	-47
1.02	175	227	200	-25
1.03	153	195	200	-47
1.03	153	214	200	-47
1.06	153	207	200	-47
1.12	175	232	250	-75
1.13	153	236	250	-97
1.18	153	233	250	-97

Table 5.39 Length of left-turn lanes for 120-second cycle length (protected-permitted)

V/C Left	Length of Left-turn Lane			Difference between guideline and optimum
	Guideline	Modeled	Optimized	
0.56	132	115	100	32
0.72	132	146	150	-18
0.8	153	156	200	-47
0.85	153	177	150	3
0.85	153	177	200	-47
0.87	132	174	200	-68
0.93	153	194	200	-47
0.93	153	196	200	-47
0.97	153	184	200	-47
1.02	175	230	200	-25
1.03	175	213	200	-25
1.06	175	243	250	-75
1.06	175	261	250	-75
1.09	197	259	250	-53
1.09	175	237	250	-75
1.14	175	244	250	-75
1.16	175	280	300	-125

Table 5.40 Length of left-turn lanes for 140-second cycle length (protected-permitted)

V/C Left	Length of Left-turn Lane			Difference between guideline and optimized
	Guideline	Modeled	Optimized	
0.55	132	145	150	-18
0.73	153	173	200	-47
0.79	153	181	150	3
0.81	132	195	200	-68
0.83	175	203	200	-25
0.86	175	207	200	-25
0.87	153	214	200	-47
0.91	175	231	200	-25
0.93	175	224	250	-75
0.99	175	243	250	-75
1.03	175	262	250	-75
1.04	197	260	250	-53
1.08	197	267	250	-53
1.08	197	268	300	-103
1.08	219	292	300	-81
1.08	175	279	250	-75
1.14	197	295	300	-103
1.18	197	294	300	-103

For protected-permitted left-turns, the comparisons between the guideline lengths, existing, and modeled length for left-turn lanes are graphically presented in Figures 5.7, 5.8 and 5.9. The following observations are made from the graphs:

1) For a higher v/c ratio for the left-turn lane, a longer length of left-turn lane is required.
2) The lengths of left-turn lane obtained from guidelines are generally lower than the optimum lengths. These observations are expected as the optimum lengths takes in to consideration of through volume and left-turn volume.

Therefore, based on these observations, the effectiveness of the optimum lengths compared to the guideline lengths will be analyzed.

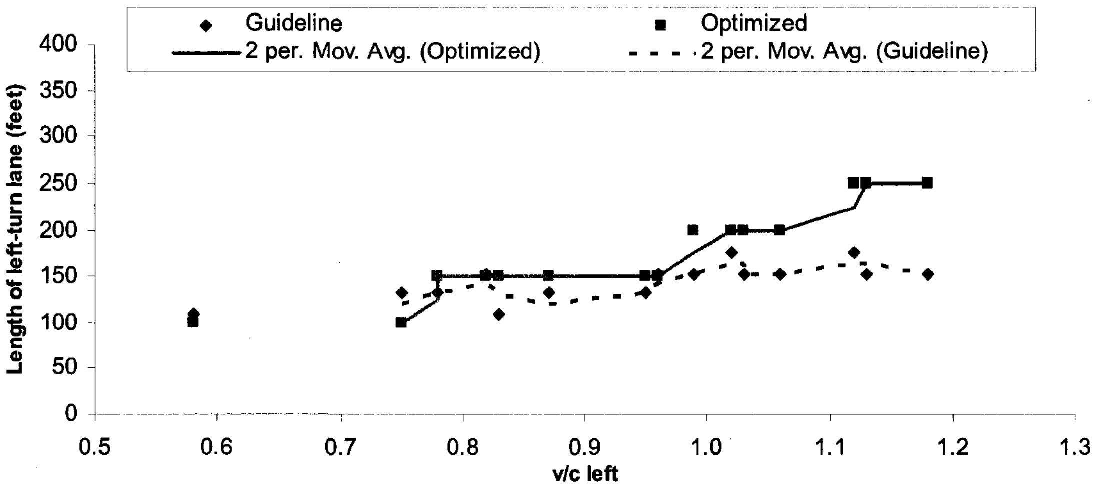


Figure 5.7 Comparison of optimized left-turn lane and guidelines for 100 sec cycle length and protected-permitted left-turns

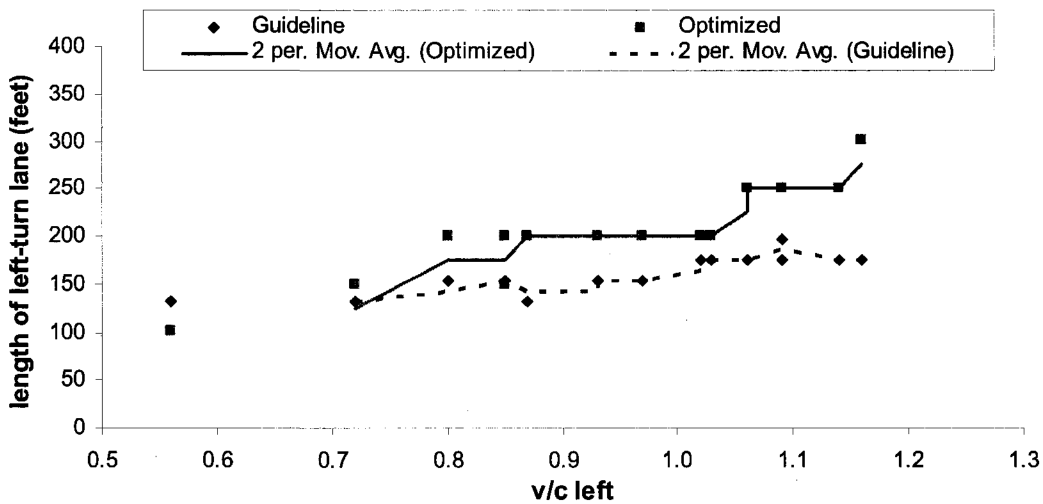


Figure 5.8 Comparison of optimized left-turn lane and guidelines for 120 sec cycle length and protected-permitted left-turns

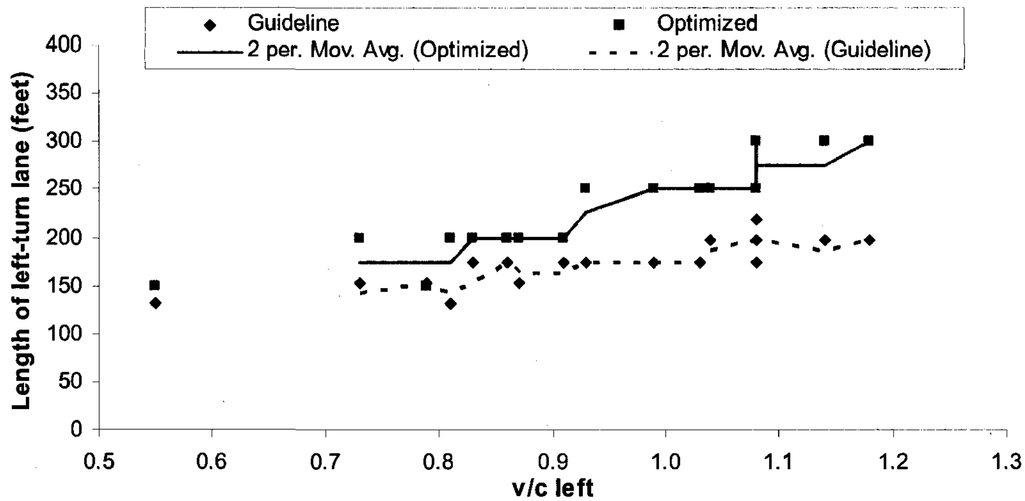


Figure 5.9 Comparison of optimized left-turn lane and guidelines for 140 sec cycle length and protected-permitted left-turns

In order to compare the impact of the cycle length on the modeled length a graph is plotted between v/c for left-turn lanes and the lengths of left-turn lane corresponding to the model. The observation from Figure 5.10 shows that a longer length of left turn lane is required for longer cycle lengths.

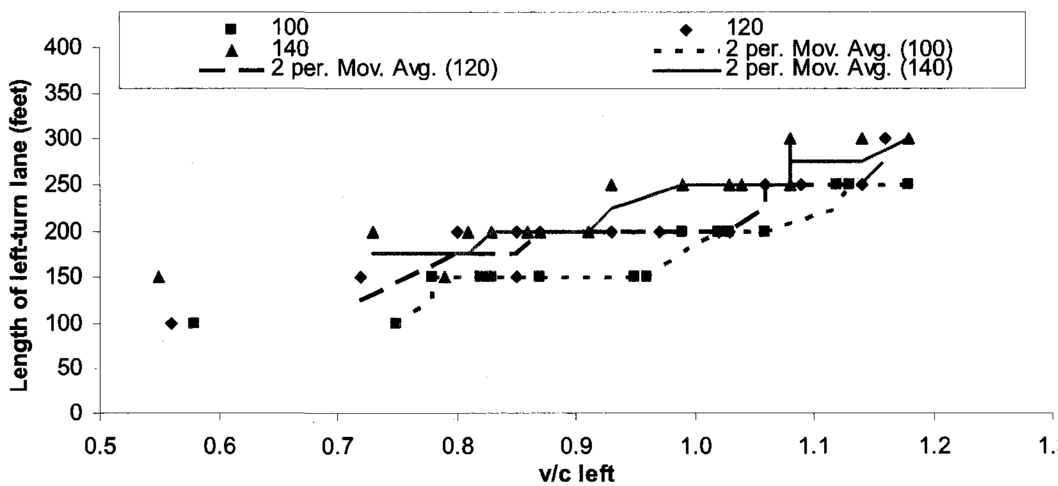


Figure 5.10 Comparison of optimized length of left-turn lane based on cycle length for protected-permitted left-turn

The values for protected left-turns for guidelines and optimized lengths for the left-turn lanes corresponding to cycle lengths of 100, 120 and 140 seconds are tabulated in Table 5.41, 5.42 and 5.43 respectively. The existing length of the left-turn lane is 185 feet.

Table 5.41 Data for existing, guidelines, and optimized length of left-turn lanes for 100 second cycle length (protected)

V/C Left	Length of Left-turn Lane			Difference between guideline and optimized
	Guideline	Modeled	Optimized	
0.70	153	136	150	3
0.83	175	154	200	-25
0.87	197	161	200	-3
0.91	197	209	200	-3
0.92	153	179	200	-47
0.94	175	191	200	-25
1.00	175	209	200	-25
1.04	197	213	200	-3
1.04	175	189	200	-25
1.04	197	209	200	-3
1.11	197	229	200	-3
1.14	219	223	200	19
1.17	219	233	200	19
1.19	241	243	300	-59
1.20	197	252	250	-53

Table 5.42 Data for existing, guidelines, and optimized length of left-turn lanes for 120 second cycle length (protected)

V/C Left	Length of Left-turn Lane			Difference between guideline and optimized
	Guideline	Modeled	Optimized	
0.65	175	154	150	25
0.80	197	176	200	-3
0.83	219	192	200	19
0.90	219	206	200	19
0.93	219	215	200	19
0.94	197	209	200	-3
0.94	175	200	200	-25
0.99	219	225	200	19
1.00	219	234	200	19
1.04	219	243	200	19
1.08	241	249	250	-9
1.10	241	256	250	-9
1.13	263	255	250	13
1.16	285	265	250	35
1.20	241	262	250	-9

Table 5.43 Data for existing, guidelines, and optimized length of left-turn lanes for 140 second cycle length (protected)

V/C Left	Length of Left-turn Lane			Difference between guideline and optimized
	Guideline	Modeled	Optimized	
0.65	197	181	200	-3
0.78	219	209	200	19
0.83	263	216	200	63
0.88	263	241	250	13
0.89	197	222	200	-3
0.90	241	236	250	-9
0.95	263	247	250	13
0.97	219	242	200	19
0.99	241	256	200	41
1.04	263	266	250	13
1.09	285	276	250	35
1.09	263	274	250	13
1.10	285	286	300	-15
1.13	307	298	300	7
1.14	285	286	300	-15
1.15	263	289	250	13
1.20	263	303	350	-87

For protected-permitted left-turn, the comparison between modeled and the guideline lengths has been graphically represented in Figure 5.11, 5.12 and 5.13. The following observations are made from the graphs:

1) For a higher v/c ratio for the left-turn lane, a longer length of left-turn lane is required.
2) For a cycle length of 100 seconds the length of the left-turn lane corresponding to guidelines are higher as compared to guidelines. The lengths of left-turn lanes for cycle lengths 120 and 140 seconds based on guideline are generally longer as compared to the optimized lengths. Overall there is not a big difference between the lengths corresponding to the guidelines and optimum lengths.

Therefore, based on these observations the effectiveness of the modeled length compared to the guideline lengths will be analyzed.

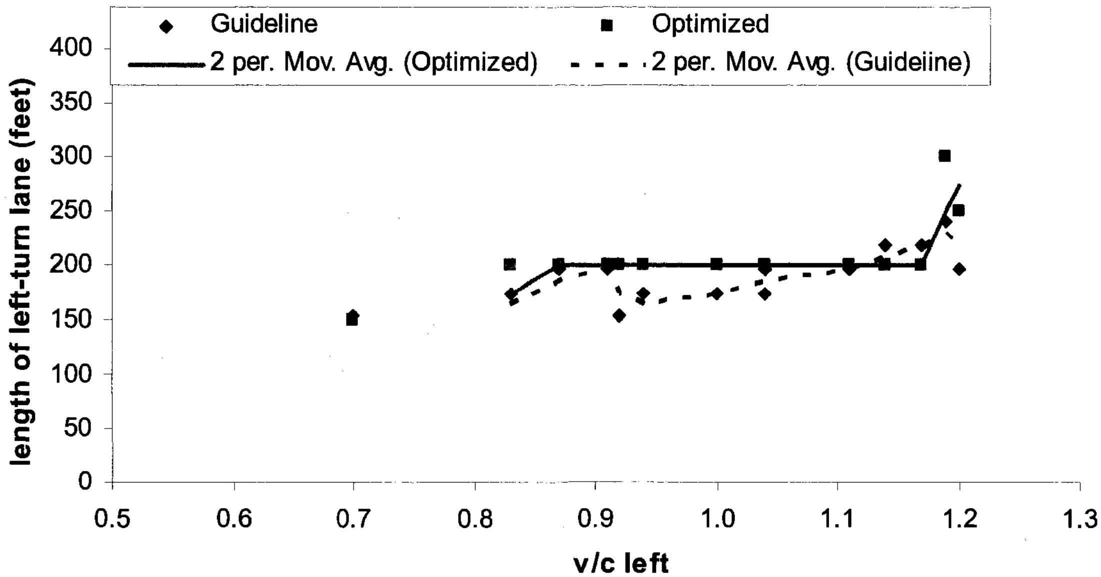


Figure 5.11 Comparison of optimized left-turn lane and guidelines for 100 sec cycle length and protected left-turns

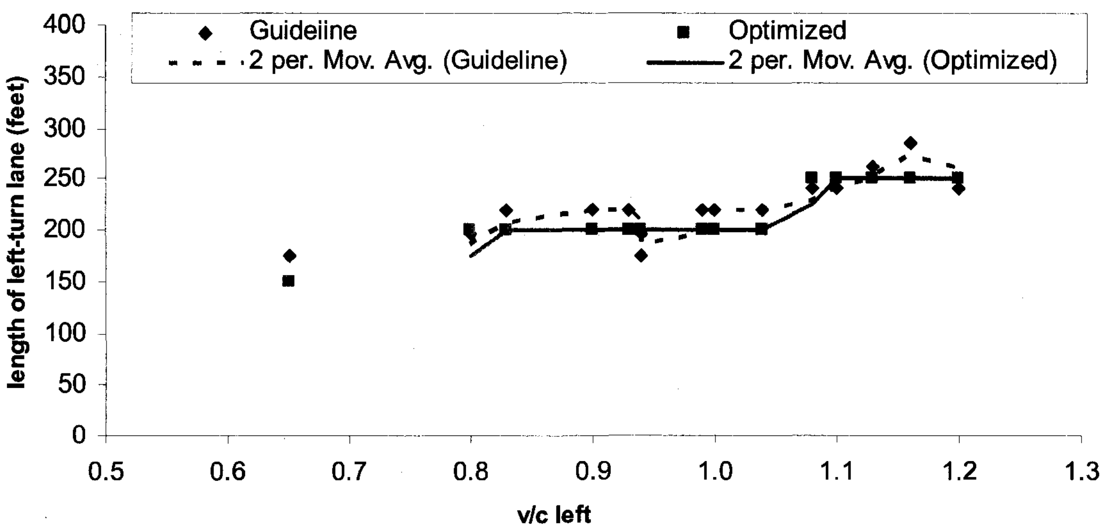


Figure 5.12 Comparison of optimized left-turn lane and guidelines for 120 sec cycle length and protected left-turns

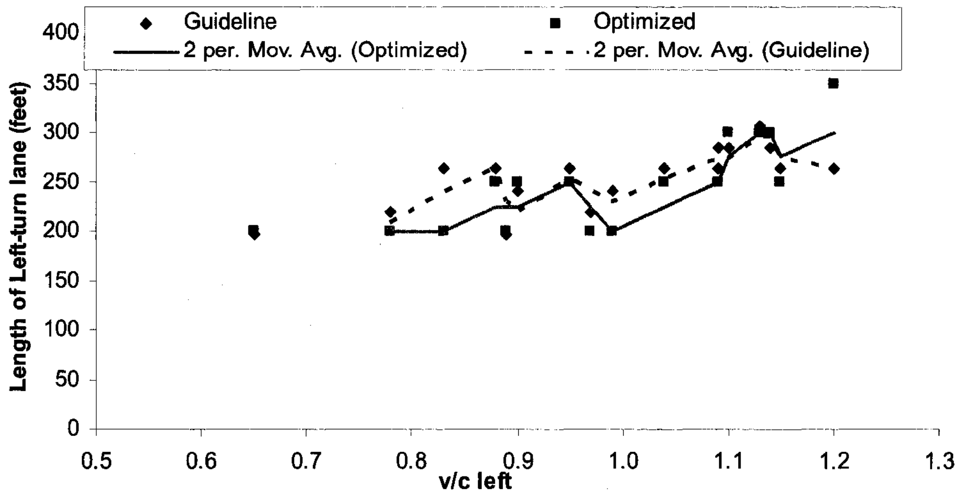


Figure 5.13 Comparison of optimized left-turn lane and guidelines for 140 sec cycle length and protected left-turns

In order to compare the impact of the cycle length on modeled lengths, a graph is plotted between v/c for left-turn lanes and corresponding lengths computed from the model. The comparison is performed for cycle lengths of 100 seconds, 120 seconds and 140 seconds and is shown in Figure 5.14. The observation from the graphs shows that a longer length of left turn lane is required for longer cycle lengths.

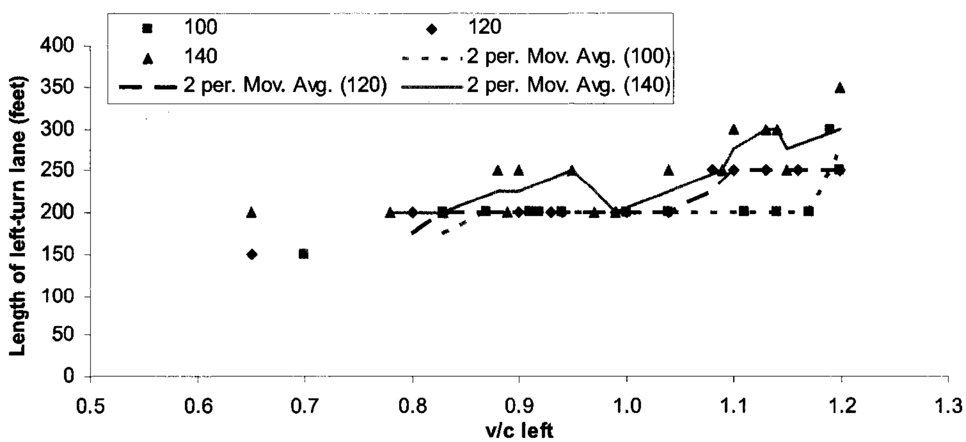


Figure 5.14 Comparison of optimized length of left-turn lane based on cycle length for protected left-turn

5.6. Comparison of Control Delays

In this section, comparisons between control delays are performed. Control delays corresponding to the existing length, optimized lengths, and guideline lengths for left-turn lanes are considered for comparisons. The control delays and v/c ratios for left-turn lanes are recorded for analysis.

a) Comparison for protected-permitted left-turn phasing

From case scenarios, the corresponding control delays and v/c ratios for left-turn lane is recorded and are presented in Tables 5.44, 5.45 and 5.46 for a cycle length of 100, 120 and 140 seconds respectively.

Table 5.44 Left-turn control delays and v/c ratio (left) for 100-second cycle length (protected-permitted lefts turns)

V/C Left	Control Delay (Left)		
	Existing	Guideline	Optimized
0.58	20.86	21.54	22.68
0.75	24.17	24.59	24.22
0.78	23.04	23.98	23.1
0.82	26.24	27.05	26.24
0.83	29.01	34.33	28.52
0.87	29.36	31.44	29.83
0.95	31.08	34.58	31.5
0.96	30.22	31.02	29.59
0.99	37.77	39.02	37.67
1.02	44.4	45.33	44.68
1.03	39.14	44.45	37.52
1.03	43.94	48.07	42.55
1.06	37.35	39.69	36.6
1.12	43.78	44.3	43.15
1.13	55.3	57.7	53.08
1.18	69.36	78.72	64.57

Table 5.45 Left-turn control delays and v/c ratio (left) for 120-second cycle length (protected-permitted lefts turns)

V/C Left	Control Delay (Left)		
	Existing	Guideline	Optimized
0.56	25.31	26.09	25.48
0.72	26.79	29.21	27.72
0.8	25.92	26.75	26.1
0.85	31.89	34.74	31.31
0.85	28.29	29.88	27.95
0.87	32.41	36.32	32.7
0.93	36.89	41.28	36.7
0.93	34.96	38.93	34.25
0.97	35.5	40.04	34.89
1.02	43.63	45.88	41.64
1.03	38.62	39.4	36.91
1.06	50.4	52.25	46.61
1.06	73.3	80.68	67.98
1.09	52.91	49.93	48.35
1.09	52.3	55.43	47.76
1.14	69.58	73.12	63.74
1.16	74.9	75.75	59.82

Table 5.46 Left-turn control delays and v/c ratio (left) for 140-second cycle length (protected-permitted lefts turns)

V/C Left	Control Delay (Left)		
	Existing	Guideline	Optimized
0.55	27.73	31.12	27.7
0.73	32.12	36.04	31.58
0.79	29.42	31.25	29.43
0.81	38.33	49.73	36.03
0.83	34.82	36.23	33.65
0.86	36.23	37.92	34.21
0.87	41.89	47.58	38.32
0.91	41.13	43.33	38.58
0.93	47.18	48.43	39.39
0.99	52.28	55.17	42.79
1.03	70.93	75.48	54.44
1.04	52.75	49.18	43.52
1.08	77.99	71.02	60.2
1.08	65.77	59.84	51.28
1.08	68.65	54.46	51.78
1.08	88.92	91.57	71.42
1.14	91.26	85.04	70.25
1.18	80.6	78.96	62.53

Figures 5.16, 5.17 and 5.18 for protected-permitted left-turns shows the graphical variation for v/c ratios for left-turn lanes and corresponding control delays for existing length, optimized and guideline lengths for cycle lengths of 100, 120 and 140 seconds.

The following observations are made from the graphs:

1) Higher control delays for higher v/c ratio for left-turn lane.
2) The delays computed by optimum lengths are lower than the delays computed using guidelines lengths for a v/c ratio exceeding about 0.8. For a cycle length of 140 seconds the existing length of left-turn lane are not sufficiently conservative.
3) The difference between the control delay corresponding to guidelines and model length increases with the increase of v/c ratio left and cycle length. This observation is expected as with the increase of v/c left ratio and longer cycle length, the difference in the lengths becomes longer.

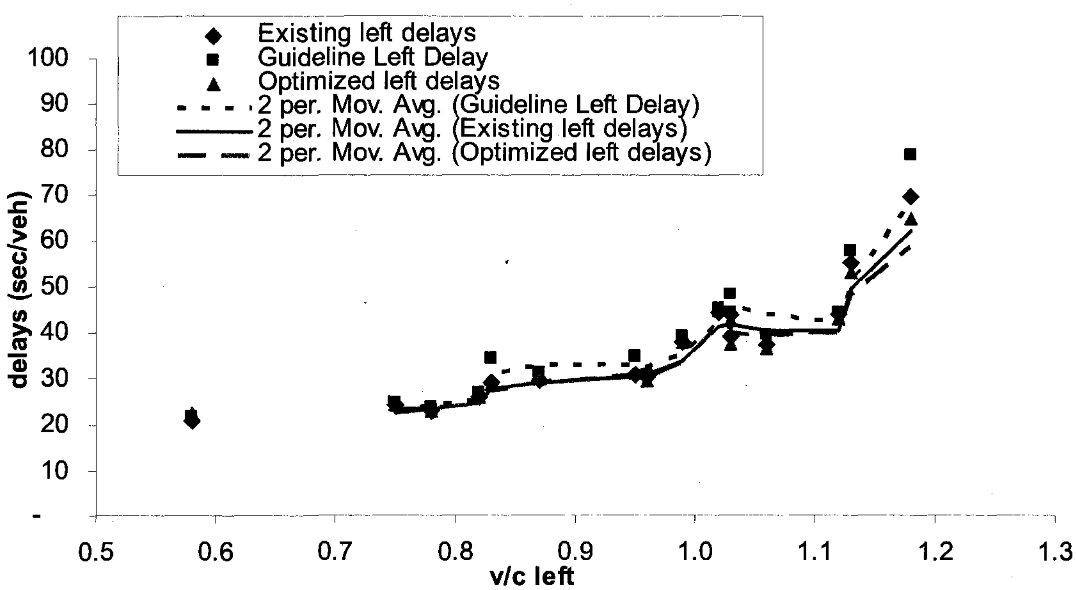


Figure 5.15 Control delay v/s v/c ratio (left) for 100-seconds cycle length (protected-permitted left-turns)

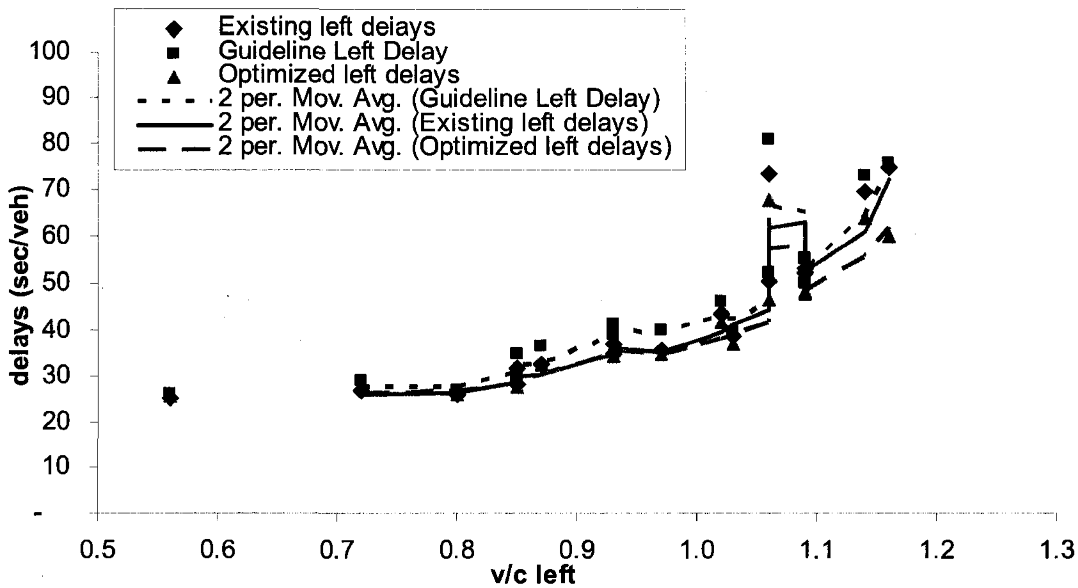


Figure 5.16 Control Delay v/s v/c ratio (left) for 120-seconds cycle length (protected-permitted left-turns)

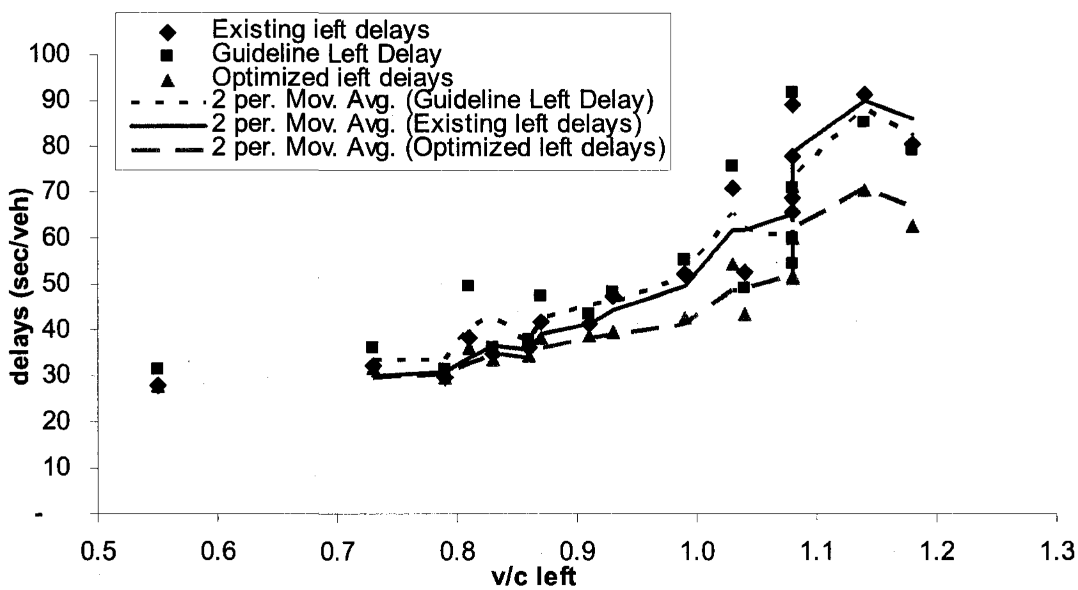


Figure 5.17 Control Delay v/s v/c ratio (left) for 140-seconds cycle length (protected-permitted left-turns)

Further, to compare the significant difference between control delays, paired T-tests are performed between the control delays corresponding to optimize and guideline lengths. The paired t-test can be used to test the hypothesis that the difference between the two population means is 0. So, if μ_1 is the mean of difference of control delay corresponding to guideline and μ_2 is the mean of difference of control delay corresponding to optimized lengths, the hypotheses are:

Ho: $\mu_1 - \mu_2 = 0$ (the difference between the two means is 0)

H1: $\mu_1 - \mu_2 \neq 0$ (the difference between the two means is not 0)

The computed test statistics t-value is given by:

$$t_{OBS} = \frac{\bar{d} - d_0}{s_d / \sqrt{n}} \qquad (5.3)$$

where

t_{OBS} = value of t-statistic for the sample,

$\bar{d}$ = sample mean of difference,

$d_0 = 0$,

s_d = standard deviation of difference, and

n = number of observations.

For a cycle lengths of 100, 120 and 140 seconds, the output results from MINITAB statistical software are presented in Table 5.47.

Table 5.47 Paired T-test Results for Guideline and Optimized Control delays (Protected-permitted)

Cycle Length	100			120			140		
Variables	GL	Opt	Diff	GL	Opt	Diff	GL	Opt	Diff
N	16	16	16	17	17	17	18	18	18
Mean	39.11	35.97	3.14	45.63	40.58	5.05	54.58	45.39	9.18
SD	14.49	11.59	3.703	17.04	13.27	4.25	18.70	13.76	6.12
SE Mean	3.62	2.90	0.93	4.13	3.22	1.03	4.41	3.24	1.44
CI (95%)	(1.171, 5.118)			(2.86, 7.23)			(6.14, 12.22)		
T-Value	3.40			4.90			6.37		
P Value	0.004			0.000			0.000		

As the P-values for all the three cases are less than 0.05 therefore, the null hypothesis of equal mean is rejected. Therefore, the difference between the control delays corresponding to guidelines and optimizes lengths are significant.

In addition to the paired t test, one way ANOVA calculations are performed for cycle length and difference in the control delays corresponding to the guidelines, and optimized lengths. One way ANOVA uses the following linear model

$$D_{ij} = \mu + D_{CLi} + e_{ij} \tag{5.4}$$

where

D_{ij} = difference in the control delays corresponding to guideline and optimized lengths,

μ = overall mean for the sample

D_{CLi} = effect of cycle length on delay

e_{ij} = random error assumed to be normally distributed with 0 mean, and constant standard deviation σ

The following hypothesis is tested to determine if cycle length has an effect on the control delays:

Ho: $D_{CL1} = D_{CL2} = D_{CL3} = 0$ (Null hypothesis)

H1: at least one of these is not 0 (Alternate hypothesis)

Figure 5.18 shows the one way ANOVA results from MINITAB to determine the significant difference in control delays for protected-permitted left-turns.

```
Source         DF      SS     MS     F      P
cycle length    2   327.7  163.9  6.96  0.002
Error          48  1130.6   23.6
Total          50  1458.3
S = 4.853   R-Sq = 22.47%   R-Sq(adj) = 19.24%

Individual 95% CIs For Mean Based on Pooled StDev
Level   N   Mean  StDev  --------+---------+---------+---------+-
100    16  3.143  3.704  (-------*--------)
120    17  5.044  4.249         (-------*-------)
140    18  9.180  6.116                       (-------*------)
                         --------+---------+---------+---------+-
                               3.0       6.0       9.0      12.0
```

Figure 5.18 One-way ANOVA: difference of delays versus cycle length

Since the P- value is less than 0.05, we conclude that the cycle length does impact the difference between the control delays corresponding to guidelines and optimized lengths. Next, since the confidence intervals for mean difference for cycle lengths do not contain 0, there is a significant difference in the mean of difference between control delays corresponding to guideline and optimized lengths.

b) Comparison for protected left-turn phasing

From the various case scenarios for protected left-turns, the corresponding control delays and v/c ratios for left-turn lane are recorded and presented in Tables 5.48, 5.49 and 5.50 for a cycle length of 100, 120 and 140 seconds respectively.

Table 5.48 Control delays 100-second cycle length (protected lefts)

V/C Left	Control Delay (Left)		
	Existing	Guideline	Optimized
0.70	20.19	20.42	20.38
0.83	46.92	47.64	46.56
0.87	43.43	43.25	43.21
0.91	47.53	47.05	47.71
0.92	55.29	59.24	56.33
0.94	52.02	52.52	52.41
1.00	61.15	60.62	60.09
1.04	57.35	56.65	56.95
1.04	65.98	65.03	66.01
1.04	59.05	58.75	58.49
1.11	69.68	70.18	68.45
1.14	70.86	69.63	71.09
1.17	82.86	78.87	78.97
1.19	82.69	78.19	77.92
1.20	93.81	97.71	96.69

Table 5.49 Control delays for 120-second cycle length (protected lefts)

V/C Left	Control Delay (Left)		
	Existing	Guideline	Optimized
0.65	24.03	24.13	24.63
0.80	53.08	52.56	52.08
0.83	48.69	47.73	48.11
0.90	55.09	53.37	53.51
0.93	61.85	60.65	61.05
0.94	65.05	63.91	63.07
0.94	68.03	70.90	67.51
0.99	64.46	62.84	62.49
1.00	69.61	66.83	67.97
1.04	70.36	66.08	68.14
1.08	81.93	73.45	70.51
1.10	85.76	77.90	78.84
1.13	98.02	77.78	79.87
1.16	104.12	79.10	82.55
1.20	110.17	102.46	98.82

Table 5.50 Left-turn Control corresponding to the v/c left for 140-second cycle length (protected lefts)

V/C Left	Control Delay (Left)		
	Existing	Guideline	Optimized
0.65	27.29	26.99	27.01
0.78	61.14	57.99	58.50
0.83	57.09	54.83	56.31
0.88	65.68	59.49	59.52
0.89	74.27	72.19	71.34
0.90	73.58	64.63	63.59
0.95	77.67	64.82	66.03
0.97	83.14	77.17	76.49
0.99	87.71	72.59	71.47
1.04	93.07	71.61	71.90
1.09	109.73	76.86	77.85
1.09	110.11	83.77	82.92
1.10	119.49	78.14	75.20
1.13	125.44	80.20	81.03
1.14	124.07	83.18	86.89
1.15	135.76	105.22	104.23
1.20	158.54	122.50	117.04

For protected left-turns, Figures 5.19, 5.20 and 5.21 shows the graphical variation for v/c ratios for left-turn lanes and corresponding control delays for existing length, optimized and guideline lengths for cycle lengths of 100, 120 and 140 seconds.

The following observations are made from the graphs.

1) Higher control delays for higher v/c ratio for left-turn lane.
2) For a cycle length of 100 seconds no difference can be seen in the control delays corresponding to existing optimized and guidelines lengths. Where as for cycle lengths of 120 and 140 seconds, the delays corresponding to existing length are higher compared to optimized and guidelines lengths. Control delays corresponding to existing lengths are higher after a v/c left greater than 1.0 for 120 seconds cycle length and 0.9 for 140 cycle length.

3) On analyzing the graphs, it can be seen that control delays corresponding to guidelines overlapped the control delays corresponding to optimized lengths. Therefore there is no significant difference between the control delays. This is due to less difference between the lengths computed by guideline and the optimized lengths are not big.

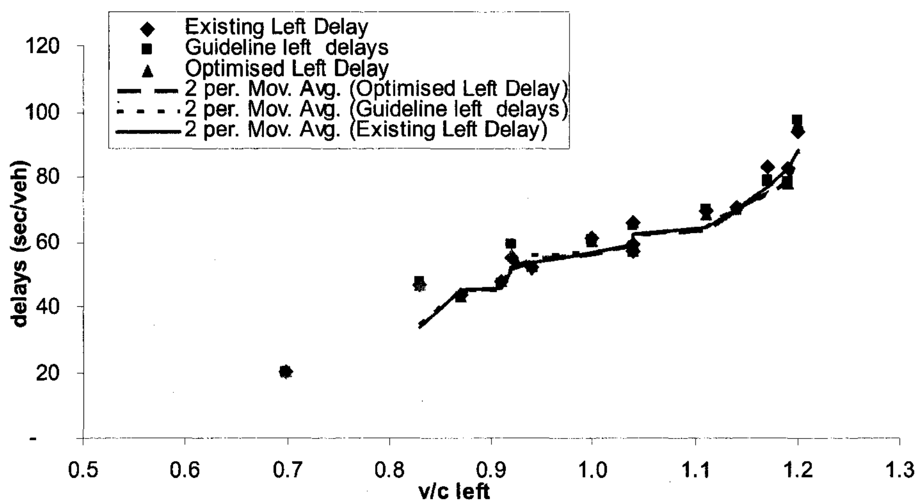


Figure 5.19 Control Delay 100-seconds cycle length (protected left-turn)

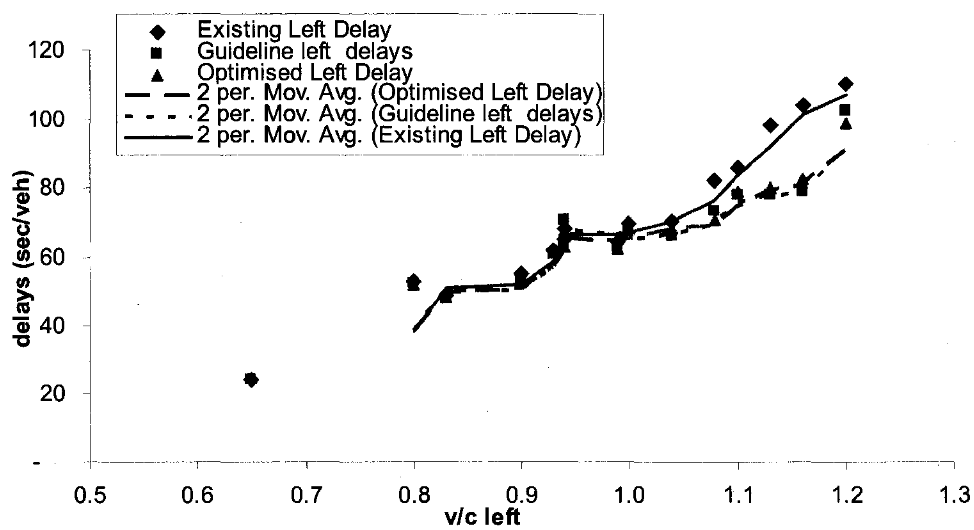


Figure 5.20 Control delays for 120-seconds cycle length (protected left-turns)

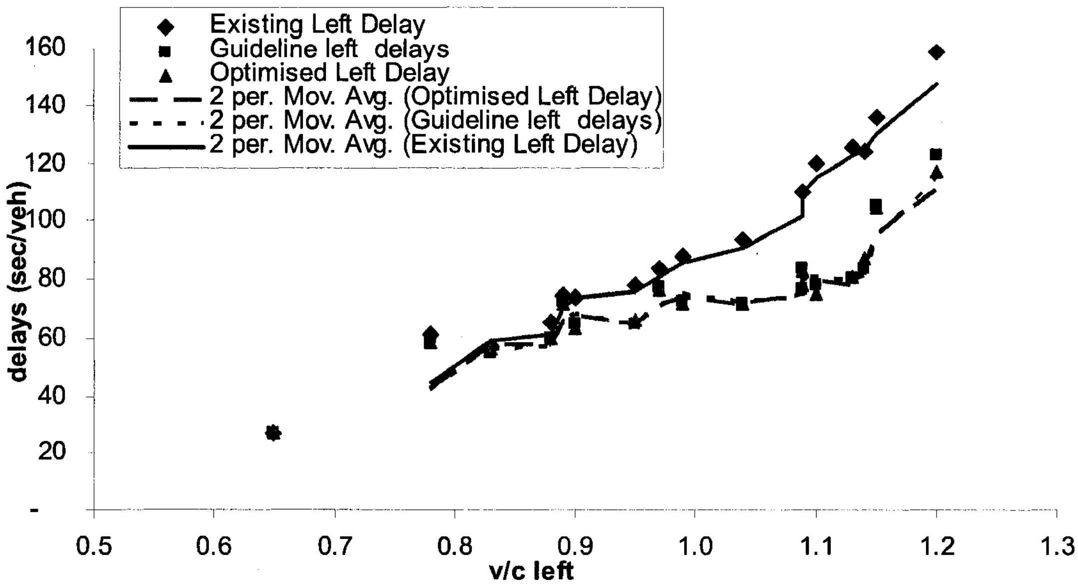


Figure 5.21 Control delays for 140 second cycle length (protected left-turn)

Further, to compare the significant difference between control delays, paired T-tests are performed between the control delays corresponding to optimize and guideline lengths.

The paired t-test is a test checks that the difference between the two observations is 0. So, if $\mu 1$ is the mean of difference of control delay corresponding to guideline and $\mu 2$ is the mean of difference of control delay corresponding to optimized lengths, the hypotheses are:

H_o: $\mu 1 - \mu 2 = 0$ (the difference between the two observations is 0)

H_1: $\mu 1 - \mu 2 \neq 0$ (the difference is not 0)

The t-values can be computed using Equation 5.3. For a cycle lengths of 100, 120 and 140 seconds, the output results from MiniTab, statistical software are presented in Table 5.51.

Table 5.51 Paired T for Guideline and Optimized Control delays (protected)

Cycle Length	100			120			140		
Variables	GL	Opt	Diff	GL	Opt	Diff	GL	Opt	Diff
N	15	15	15	15	15	15	17	17	17
Mean	60.38	60.08	0.299	65.31	65.28	0.036	73.66	73.37	0.29
SD	18.06	17.98	1.082	17.58	17.23	2.030	20.62	19.75	1.96
SE Mean	4.66	4.64	0.279	4.54	4.45	0.524	5.00	4.79	0.476
CI (95%)	(-0.300, 0.898)			(-1.088, 1.160)			(-0.724, 1.296)		
T-Value	1.07			0.07			0.60		
P Value	0.302			0.946			0.557		

The P-values for all the three cases are greater than 0.05 therefore, the null hypothesis of equal mean is not rejected. Therefore, the difference between the control delays corresponding to guidelines and optimizes lengths are not significant.

In addition to paired t test, a one way ANOVA is performed for cycle length and difference in the control delays corresponding to the guidelines, and optimized lengths. A linear model is developed to test if the mean difference is zero or not by using Equation 5.4. The following hypothesis are developed to test the significant of control delays with respect to cycle length. Figure 5.22 shows the Minitab result to determine the significant difference.

```
Source        DF      SS    MS     F      P
CYCLE LENGTH   2    1.50  0.75  0.22  0.806
Error         44  152.91  3.48
Total         46  154.41

S = 1.864   R-Sq = 0.97%   R-Sq(adj) = 0.00%

                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level   N   Mean  StDev   ------+---------+---------+---------+---
100    15  0.299  1.081        (---------------*---------------)
120    15  0.037  2.032   (---------------*---------------)
140    17  0.286  2.218            (--------------*--------------)
                          ------+---------+---------+---------+---
                             -0.60      0.00      0.60      1.20
```

Figure 5.22 One-way ANOVA: difference of delays versus cycle length

Since the P value is greater than 0.05 therefore, the null hypothesis not rejected. Hence there is no significant difference in the control delay corresponding to guideline lengths and optimized lengths. Further, the confidence intervals for mean of difference between the guideline and optimized length overlap hence, three means are equal. Therefore, the mean difference for each cycle length is zero.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1. Introduction

In this study, analyses are performed to evaluate the impact of lengths of left-turn lanes on signalized intersection delays. The optimum lengths are determined using the principle of minimizing the delays. The delays corresponding to the optimum lengths and 95^{th} percentile guidelines (referred to as "guidelines") are compared to determine the effectiveness of the optimum lengths of the left-turn lanes. For this study, protected and protected-permitted left-turn phasing are analyzed for a case study intersection.

6.2. Conclusions

In order to evaluate the effect of length of left-turn lane on control delays, the lengths are varied from 100 to 600 feet and corresponding delays are obtained for various combinations of approach traffic, turning movements, and cycle lengths using computer simulation.

6.2.1. Impact of Length of Left-Turn Lane on Through Control Delays

The results obtained from simulation for through delays, showed no significant change in the delays on varying the length of the left-turn lane. Furthermore, the delays caused to through traffic are lower as compared to the delays caused to left traffic.

6.2.2. Effect on Control Delays by Traffic Parameters

- Impact of length of left-turn lane

The results of this study, are as expected and showed that the left-turn delays decrease with the increase of the length of left-turn lane. The decrease in the delays for left-turn lanes leveled-off after a certain length, and the point of leveling off is referred as the optimum length for the left-turn lane.

- Effect of traffic volume

The results from this study are as expected and show that on decreasing the traffic volumes there is a decrease in the left-turning delays which results in the increase in the required length of the left-turn lane. For example, for protected left-turn phasing and a cycle length of 140 seconds, it is observed that on decreasing the left-turning traffic by 10 percent from existing left-turning traffic i.e. reducing the number of vehicles from 216 to 195 vph, the required length obtained from model decreases by 12 feet, and there is a decrease in control delay for left-turning traffic of 0.43 seconds per vehicle. Whereas on increasing the left-turning traffic by 10 percent with respect to existing traffic, i.e. the number of vehicles increased from 216 to 238 vph, the required length increases by 12 feet and the control delay for left-turning traffic also increase by 5.95 second/vehicle. Similarly for protected- permitted left-turn phasing on decreasing the left-turning traffic by 10 percent with respect to existing traffic, i.e. the number of vehicles increased from 216 to 195 vph, the required length for left-turn lane decrease by 16.36 feet and there is decrease in control delay by 3.40 seconds per vehicle. Whereas on increasing the left-turning traffic by 10 percent with respect to existing traffic, i.e. the number of vehicles increased from 216 to 238 vph, the required length of left-turn lane increases by 13.63 feet and the control delay for left-turning traffic is increased by 0.75 seconds per vehicle.

- Effect of volume to capacity ratio

The results obtained from the analysis are according to expectation. For higher volume to capacity ratio for left-turn lanes, the left-turn delays are higher; therefore longer lengths are required for left-turn lanes. From example, for protected-permitted left-turn phasing and a cycle length of 140 seconds, it is observed that on increasing the v/c ratio for left-turn lane from 0.81 to 0.99, the control delay for left-turn traffic increases by 6.76 seconds per vehicle, and the required length of left-turn lane increase by 49 feet. Similarly for protected left-turn phasing for a cycle length of 140 seconds, on increasing the v/c ratio for left-turn lane from 0.83 to 0.99, there is an increase in left-turn control delay by 15.16 seconds per vehicle, and the required length of left-turn lane increased by 21 feet.

- Effect of cycle length

The results obtained from the analysis are as per expected, and show that for longer cycle lengths, longer lengths of left-turn lanes are required. For example, for protected-permitted-left turn phasing, for a given v/c ratio of 1.13, 1.14 and 1.14 the delays corresponding to a cycle length of 100, 120 and 140 are 53.08, 63.74 and 70.25 seconds per vehicle respectively. The corresponding required lengths for the left-turn lanes are 229, 260 and 287 feet respectively. For protected left-turn phasing for a v/c ratio of 1.04 for left-turn lane for cycle lengths of 100,120 and 140 seconds the corresponding delays are 58.49, 68.14 and 71.51 seconds per vehicle respectively. The corresponding required lengths of left-turn lanes are 203, 232 and 250 feet respectively. Therefore, with the increase of cycle length the delays increases and longer lengths for left-turn lanes are required.

6.2.3. Modeling of the Length of left-Turn Lane

From the different simulation scenarios, the optimum lengths are obtained using minimizing left-turn delays. The regression analysis is used to model the length of left-turn lane based on various traffic parameters and signal characteristics.

For protected-permitted left-turn phasing, the optimum lengths of the left-turn lanes are determined using the following traffic and signal characteristics:

- Left-turn volume
- Volume to capacity ratio for through lane
- Cycle length

For protected left-turn phasing, the lengths of the optimized left-turn lanes are determined using the following traffic and signal characteristics:

- Left-turn Volume
- Volume to capacity ratio for through lane
- Cycle length

6.2.4. Length of left-turn lane: guideline v/s optimum lengths

From this study, it is found that the lengths of left-turn lanes for protected-permitted phasing are longer than the guidelines. This is because the guidelines do not directly take into account the through traffic; therefore, the guidelines underestimate the required length. For example, for a cycle length of 140 seconds, for a v/c ratio of 0.81 the optimum length and the length corresponding to guideline are 200 and 132 feet respectively. For a v/c ratio of 0.99 the optimum length and the length corresponding to guidelines are 250 and 175 feet respectively. From these observations, the optimum lengths are longer than the lengths corresponding to guidelines and the difference between them increases with the increase in v/c ratio for left-turn lanes.

For protected left-turns there is no significant difference in the required lengths corresponding to the guidelines and optimum lengths. For example, for a cycle length of 140 seconds, for a v/c of 0.80 the optimum length and length corresponding to guideline are 200 and 197 feet respectively and for a v/c of 1.1 the optimum length and length corresponding to guidelines are 250 and 141 feet respectively. From these observations, there is no significant difference between the lengths.

6.2.5. Delays Caused to Left Traffic: Guideline v/s Optimum Lengths

For protected-permitted left-turns, there is a significant difference between the control delays corresponding to guidelines and the optimized lengths. The control delays corresponding to the optimum lengths are lower as compared to the delays corresponding to guidelines. This is due to a significant difference in the lengths for left-turn lanes corresponding to guidelines and optimum lengths. From this study, for a cycle length of 140 seconds and for a v/c ratio of 0.81 for left-turn lane, the corresponding delays for guidelines and optimum lengths are 49.73 and 36.03 seconds per vehicle. For a v/c ratio of 1.03 for left-turn lane the corresponding delays for guidelines and optimum lengths are 75.48 and 54.44 seconds per vehicle. From these observations it can be seen that the control delays for guidelines are higher as compared to control delays corresponding to optimum lengths. Further it can be seen that the difference in the delays increase with the increase of v/c ratio.

For protected left-turns, there is no significant difference in the control delays. This is because there is no significant difference in the length corresponding to guidelines and optimized lengths. For protected left-turns, and for a cycle length of 140 seconds and v/c ratio of 0.83 for left-turn lane, the corresponding delays for guidelines and optimum lengths are 54.83 and 56. 31 seconds per vehicle. For a v/c ratio of 1.04 for left-turn lane the corresponding delays for guidelines and optimum lengths are 71.61 and 71.90 seconds per vehicle. From these observations it could be seen that the control delays for guidelines are almost same to control delays corresponding to optimum lengths.

6.3. Recommendations

1. For the northbound approach of the intersection of S. Main Street and Charleston Boulevard, with a cycle length of 140 seconds and protected-permitted left-turn phasing and existing traffic volume, it is be recommended that existing length of 185 feet is not sufficient and it should be increased to 250 feet. For future, when the traffic volume varies for the northbound approach of the intersection, the optimum length of left-turn computed by this study should be used.
2. In this study, cycle lengths of 100, 120 and 140 seconds are used for evaluating the impact length of left-turn lane on control delays. However to ensure the proper working of the intersection a balance between the number of vehicles, green durations and cycle lengths should be achieved. In this study only the green durations are optimized, while cycle lengths are not. For future studies, the cycle lengths should be optimized and a balance between the traffic characteristic can be used to study the impact of lengths of left-turn lanes on control delay.

3. The results of this study are based on a single site-specific case study. The optimum lengths obtained from this study cannot be utilized for another site because the traffic conditions and geometric characteristics vary from site to site. Therefore, more sites should be studied in order to generalize the results and develop general guidelines that can be used for different intersection situations.

APPENDIX A

TRAFFIC COUNT DATA

Appendix A1.1 Traffic count data from silver state traffic for Main Street and Charleston Boulevard.

Silver State Traffic
1819 Quarley Place
Henderson, Nevada 89014
702-898-1968

File Name : CHE6FA~1
Site Code : 00007777
Start Date : 3/7/2006
Page No : 1

Groups Printed- 1 - Unshifted

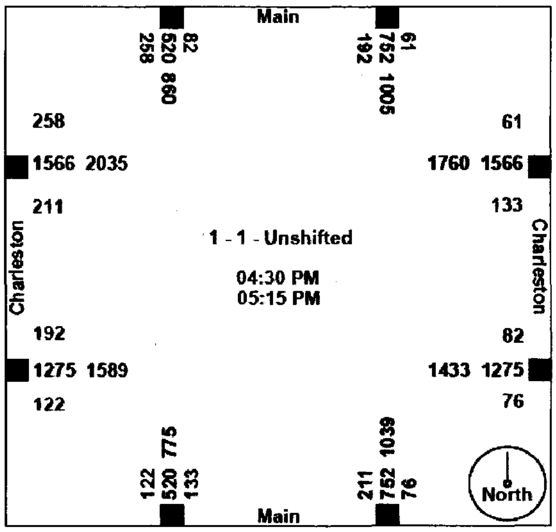
	Main Southbound				Charleston Westbound				Main Northbound				Charleston Eastbound				
Start Time	Right	Thru	Left	U-turns	Right	Thru	Left	Peds	Right	Thru	Left	Peds	Right	Thru	Left	Peds	Int. Total
Factor	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
07:00 AM	40	199	9	0	10	182	38	0	3	54	15	0	31	252	43	0	876
07:15 AM	37	187	12	0	5	271	34	0	7	50	16	0	55	320	32	0	1026
07:30 AM	38	213	14	0	9	259	45	0	5	60	33	0	38	281	38	0	1033
07:45 AM	37	214	12	0	9	255	38	0	7	81	29	0	38	351	38	0	1109
Total	152	813	47	0	33	967	155	0	22	245	93	0	162	1204	151	0	4044
08:00 AM	32	171	14	0	8	220	42	0	13	85	35	0	30	332	37	0	1019
08:15 AM	48	156	14	0	10	228	25	0	8	97	32	0	28	338	48	0	1026
08:30 AM	39	133	19	0	9	247	22	0	11	81	38	0	33	280	35	0	947
08:45 AM	33	121	15	0	14	236	32	0	14	73	30	0	27	268	37	0	900
Total	152	581	62	0	41	931	121	0	46	336	135	0	116	1216	155	0	3892
*** BREAK ***																	
04:00 PM	73	121	25	0	10	361	44	0	14	191	57	0	36	324	67	0	1323
04:15 PM	65	130	27	0	16	372	44	0	20	174	60	0	35	333	51	0	1327
04:30 PM	57	130	24	0	19	380	31	0	23	246	52	0	29	302	44	0	1337
04:45 PM	69	113	16	3	14	389	38	0	14	149	56	0	44	306	44	0	1255
Total	264	494	92	3	59	1502	157	0	71	760	225	0	144	1265	206	0	5242
05:00 PM	66	157	27	1	18	373	26	0	20	175	50	0	23	324	57	0	1317
05:15 PM	66	120	15	1	10	424	38	0	19	182	53	0	28	343	47	0	1344
05:30 PM	49	105	18	0	20	326	33	0	24	179	63	0	20	338	41	0	1216
05:45 PM	45	96	11	0	12	356	36	0	11	102	45	0	28	333	38	0	1113
Total	226	478	71	2	60	1479	133	0	74	638	211	0	97	1338	183	0	4990
Grand Total	794	2366	272	5	193	4879	566	0	213	1979	664	0	519	5023	695	0	18168
Apprch %	23.1	68.8	7.9	0.1	3.4	86.5	10.0	0.0	7.5	69.3	23.2	0.0	8.3	80.5	11.1	0.0	
Total %	4.4	13.0	1.5	0.0	1.1	26.9	3.1	0.0	1.2	10.9	3.7	0.0	2.9	27.6	3.8	0.0	

Appendix A1.2 Traffic count data with traffic movements from Silver State Traffic for Main Street and Charleston Boulevard.

Silver State Traffic
1819 Quarley Place
Henderson, Nevada 89014
702-898-1968

File Name : CHE6FA~1
Site Code : 00007777
Start Date : 3/7/2006
Page No : 3

	Main Southbound					Charleston Westbound					Main Northbound					Charleston Eastbound					
Start Time	Right	Thru	Left	U-turns	App. Total	Right	Thru	Left	Peds	App. Total	Right	Thru	Left	Peds	App. Total	Right	Thru	Left	Peds	App. Total	Int. Total
Peak Hour From 12:00 PM to 05:45 PM - Peak 1 of 1																					
Intersection	04:30 PM																				
Volume	258	520	82	5	865	61	1566	133	0	1760	76	752	211	0	1039	122	1275	192	0	1589	5253
Percent	29.8	60.1	9.5	0.6		3.5	89.0	7.6	0.0		7.3	72.4	20.3	0.0		7.7	80.2	12.1	0.0		
05:15 Volume	66	120	15	1	202	10	424	38	0	472	19	182	53	0	254	26	343	47	0	416	1344
Peak Factor																					0.977
High Int.	05:00 PM					05:15 PM					04:30 PM					05:15 PM					
Volume	66	157	27	1	251	10	424	38	0	472	23	246	52	0	321	26	343	47	0	416	
Peak Factor					0.862					0.932					0.809					0.956	



Appendix A2.1: Field traffic count data sheet for left-turn

Traffic Count			
Location: **S. Main Street @ Charleston Blvd.**		City: **Las Vegas**	
Approach: **North Bound S. Main Street**		Movement: **Left-turning Traffic**	
Time: 4: 30:00 pm to 5: 31:30 pm		Date: **30/01/08**	
Observer: Upendera			
Cycle #	**# of vehicles**	**Cycle #**	**# of vehicles**
1	12		
2	7		
3	9		
4	7		
5	9		
6	6		
7	7		
8	7		
9	10		
10	11		
11	7		
12	8		
13	7		
14	8		
15	6		
16	8		
17	7		
18	8		
Total left-turning traffic count: 144			

Appendix A2.2: Field traffic count data sheet for through vehicle

Traffic Count			
Location: **S. Main Street @ Charleston Blvd.**		City: **Las Vegas**	
Approach: **North Bound S. Main Street**		Movement: Through Traffic	
Time: 4: 30:00 pm to 5: 31:30 pm		Date: **30/01/08**	
Observer: Avinash			
Cycle #	**# of vehicles**	**Cycle #**	**# of Vehicles**
01	23		
02	25		
03	23		
04	28		
05	22		
06	28		
07	26		
08	25		
09	28		
10	27		
11	29		
12	28		
13	32		
14	25		
15	31		
16	24		
17	27		
18	27		
Total through traffic count: 478			

Appendix A2.3: Field traffic count data sheet for right-turning vehicle

Traffic Count			
Location: **S. Main Street @ Charleston Blvd.**		City: **Las Vegas**	
Approach: **North Bound S. Main Street**		Movement: Right Turning Traffic	
Time: 4: 30:00 pm to 5: 31:30 pm		Date: **30/01/08**	
Observer: Ancilla			
Cycle #	**# of vehicles**	**Cycle #**	**# of vehicles**
1	2		
2	3		
3	3		
4	2		
5	1		
6	2		
7	3		
8	5		
9	3		
10	2		
11	3		
12	2		
13	3		
14	5		
15	3		
16	2		
17	2		
18	2		
Total right-turning traffic count: 48			

Appendix A3.1: Field data sheet for determining the control delay for left-turn vehicles

1

Intersection Control Delay Study				
Location: **S. Main Street @ E. Charleston Blvd.**		City: **Las Vegas**	Cycle Length: 140 Sec	
Approach: **North Bound S. Main Street**		Movement: **LEFT LANE**	**Date: 30/01/08**	
Time: 4:30:00 **pm to** 5:11:30 pm		Free flow speed (mi/h): 30 mph	Observer: Swarup	
Time (Minute Starting at)	Total Number of vehicles stopped in the approach at Time		Number of cycles: 18	
	0 sec	**30 seconds**	**60 seconds**	**90 sec**
	Lane 1	**Lane 1**	**Lane 1**	**Lane 1**
4:30:00	12	10	5	8
4:32:00	10	3	5	7
4:34:00	9	10	5	4
4:36:00	8	10	12	12
4:38:00	0	4	7	10
4:40:00	2	4	5	6
4:42:00	18	4	3	8
4:44:00	9	12	5	3
4:46:00	8	10	0	5
4:48:00	8	10	11	2
4:50:00	4	6	7	8

2

Intersection Delay Study				
Location: **S. Main Street @ E. Charleston Blvd.**		City: **Las Vegas**		Cycle Length: 140 Sec
Approach: **North Bound S. Main Street**		Movement: **LEFT LANE**		Date: **30/01/08**
Time:		Free flow speed (mi/h): 30		Observer: Swarup
Time (Minute Starting at)	Total Number of vehicles stopped in the approach at Time			Number of cycles:
	0 sec	**30 seconds**	**60 seconds**	**90 sec**
	Lane 1	**Lane 1**	**Lane 1**	**Lane 1**
4:52:00	3	1	5	6
4:54:00	0	3	6	12
4:56:00	12	5	6	12
4:58:00	13	14	6	7
5:00:00	1	7	0	6
5:02:00	8	9	11	8
5:04:00	10	11	12	13
5:06:00	5	8	10	10
5:08:00	6	~~6~~ 7	4	7
5:10:00	7	5	4	5
	8			

Appendix A3.2: Field data sheet for determining the control delay for through vehicles

Intersection Delay Study (QUEUES)								
Location: **S. Main Street @ E. Charleston Blvd.**				City: **Las Vegas**			Cycle Length: 140 Sec	
Approach: **North Bound S. Main Street**				Movement: **THROUGH LANE**			Date: **30/01/08**	
Time: 4:30:00 pm to 5:11:30 pm				Free flow speed (mi/h): 30			Observer: Vidhya	
Time (Minute Starting at)	Total Number of vehicles stopped in the approach at Time							
	0 sec		**30 seconds**		**60 seconds**		**90 sec**	
	Lane 1	**Lane 2**	**Lane 1**	**Lane 2**	**Lane 1**	**Lane 2**	**Lane 1**	**Lane 2**
4:30:00	8	10	0	0	1	4	5	8
4:32:00	8	11	9	13	0	0	6	8
4:34:00	12	14	14	16	9	8	0	0
4:36:00	8	9	10	12	14	16	0	0
4:38:00	3	3	8	9	13	11	14	13
4:40:00	0	0	2	5	6	6	8	11
4:42:00	1	1	0	0	4	5	8	7
4:44:00	9	11	1	2	4	5	6	8
4:46:00	8	9	10	11	0	0	5	4
4:48:00	7	7	9	12	3	4	0	0
4:50:00	5	4	7	7	9	12	0	0

Intersection Delay Study								
Location: **S. Main Street @ E. Charleston Blvd.**				City: **Las Vegas**			Cycle Length: 140 Sec	
Approach: **North Bound S. Main Street**				Movement: **THROUGH LANE**			Date: **30/01/08**	
Time: 4:30:00 pm to 5:11:30 pm				Free flow speed (mi/h): 30			Observer: Vidhya	
Time (Minute Starting at)	Total Number of vehicles stopped in the approach at Time							
	0 sec		**30 seconds**		**60 seconds**		**90 sec**	
	Lane 1	**Lane 2**	**Lane 1**	**Lane 2**	**Lane 1**	**Lane 2**	**Lane 1**	**Lane 2**
4:52:00	1	3	7	9	9	10	14	13
4:54:00	0	0	3	4	7	9	13	11
4:56:00	2	3	0	0	4	4	9	10
4:58:00	11	13	0	0	5	7	8	11
5:00:00	4	15	13	12	0	0	8	10
5:02:00	9	12	13	13	6	4	0	0
5:04:00	7	8	9	11	14	16	0	0
5:06:00	5	6	8	8	10	9	12	13
5:08:00	0	0	8	7	10	11	14	14
5:10:00	2	3	0	0	7	9	10	9
5:12:00	8	12						

Appendix A4.1: Field data sheet for stopped and not stopped vehicles for left-turn lane

Intersection Delay Study / STOPPED / NOT STOPPED					
Location: **S. Main Street @ Charleston Blvd.**			City: **Las Vegas**		
Approach: **North Bound S. Main Street**			Movement: Left Turning Traffic		
Time: 4: 30:00 pm to 5: 31:30 pm			Date: **30/01/08**		
Observer: Nitin			Free Flow Speed (mi/h): 28mph		
Cycle Number	**Vehicles Stopped**	**Vehicles Not Stopped**	**Cycle Number**	**Vehicles Stopped**	**Vehicles Not Stopped**
1	10	2	12	6	2
2	7	0	13	6	1
3	8	1	14	7	1
4	7	0	15	6	0
5	7	2	16	5	3
6	4	2	17	6	1
7	7	0	18	7	1
8	5	2			
9	9	1			
10	9	2			
11	4	3			
Total Number of Vehicle Stopped: 120			**Total Number of vehicles not Stopped:** 24		

Appendix A4.2: Field data sheet for stopped and not stopped vehicles for through and shared right lanes

STOPPED / NOT STOPPED					
Location: S. Main Street @ Charleston Blvd.			City: Las Vegas		
Approach: North Bound S. Main Street			Movement: Through and Right Turning Traffic		
Time: 4: 30:00 pm to 5: 31:30 pm			Date: 30/01/08		
Observer: Dinesh			Free Flow Speed (mi/h): 30		
Cycle Number	**Vehicles Stopped**	**Vehicles Not Stopped**	**Cycle Number**	**Vehicles Stopped**	**Vehicles Not Stopped**
1	20	5	12	22	8
2	22	6	13	28	7
3	23	3	14	22	8
4	24	6	15	25	9
5	20	3	16	20	6
6	23	7	17	25	4
7	22	7	18	24	5
8	20	10			
9	23	8			
10	23	6			
11	29	9			
Total Number of Vehicle Stopped: 409			**Total Number of vehicles not Stopped:** 117		

APPENDIX B

NETSIM DESCRIPTION

Appendix B1.1: Network Simulation (NETSIM) description taken from the Corridor Simulation (CORSIM) user Manual Version 1.01 (FHWA, 1996)

CORSIM is a microscopic simulation and modeling component of the Traffic Software Integrated System (TSIS) tool suite.

"NETSIM applies interval-based simulation to describe traffic operations. Each vehicle is a distinct object that is moved every second. Each variable control device (such as traffic signals) and each event are updated every second. In addition, each vehicle is identified by category (auto, car-pool, truck, or bus) and by type. Up to 16 different types of vehicles (with different operating and performance characteristics) can be specified, thus defining the four categories of the vehicle fleet. Furthermore, a "driver behavioral characteristic" (passive or aggressive) is assigned to each vehicle. Its kinematic properties (speed and acceleration) as well as its status (queued or free flowing) are determined. Turn movements are assigned stochastically, as are free-flow speeds, queue discharge headways, and other behavioral attributes. As a result, each vehicle's behavior can be simulated in a manner reflecting real world processes."

"Each time a vehicle is moved, its position (both lateral and longitudinal) on the link and its relationship to other vehicles nearby are recalculated, as are its speed, acceleration, and status. Actuated signal control and interaction between cars and buses are explicitly modeled. Vehicles are moved according to car-following logic, response to traffic control devices, and response to other demands. For example, buses must service passengers at bus stops (stations); therefore, their movements differ from those of private vehicles. Congestion can result in queues that extend throughout the length of a link and block the upstream intersection, thus impeding traffic flow. In addition, pedestrian traffic can delay turning vehicles at intersections."

“The following list summarizes the major features of the NETSIM simulation model. Most of these microscopic treatments are transparent to the user, whose prime concern is the description of traffic operations provided by the model:

- Fleet Components (buses, carpools, cars, and trucks)
- Load Factor (the number of passengers/vehicle)
- Turn Movement
- Bus Operations (paths, flow volumes, stations, dwell times, and routes)
- HOV Lanes (buses, Carpools, or both)
- Queue Discharge Distribution
- Detailed Approach Geometry
- Stop and Yield Signs
- Pretimed Signal Control
- Signal Ring-actuated Control
- Dual Ring-actuated Control
- Number of Lanes per Approach (a maximum of 7)
- Incidents and Temporary Events”

There are several CORSIM inputs that can be used for calibration of the model. These inputs allow users to alter and modify the CORSIM model to match local real-world traffic conditions. These calibration parameters include driver behavior parameters and vehicle performance parameters. The driver behavior parameters for NETSIM include queue discharge headway and start-up lost time, distribution of free flow speed by driver type, mean duration of parking maneuvers, lane change parameters, maximum left and right turning speeds, probability of joining spillback, probability of left turn jumpers and laggers, gap acceptance at stop signs, gap acceptance for left and right turns, pedestrian delays and driver familiarity with their path.

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VITA

Graduate College
University of Nevada, Las Vegas

Nitin Kalsi

Local Address:
1555 E Rochelle Ave., Apt # 245
Las Vegas, Nevada 89119

Home Address:
5513/1, Modern Housing Complex, Manimajra
Chandigarh, India 160101

Degrees:
Bachelor of Engineering, Civil Engineering, 2005
Punjab Engineering College, Chandigarh, India

Thesis Title:
Analysis and Evaluation of the Impact the Length of Left-Turn Lane on Signalized Intersection Delays

Thesis Examination Committee:
Committee Chair, Dr. Mohamed Kaseko, Ph. D.
Committee Member, Dr. Hualiang Teng, Ph. D.
Committee Member, Dr. Dave James, Ph. D.
Graduate College Representative, Dr. Ashok K Singh, Ph. D.