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EMPIRICAL VERFICATION OF MODELED QUEUE LENGTHS

BY

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THESIS

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Requirements for the Degree of

Master of Science
Civil Engineering

The University of New Mexico
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DEDICATION

To my parents, whose moral and emotional support has brought me this far.

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I would like to thank God for bringing me this far. He has been my source of encouragement through it all.

My sincerest thanks go to Dr. James Brogan, my advisor, who encouraged me and motivated me through my program. With his guidance and editing skills, I am able to complete this project.

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ABSTRACT

The purpose of left turn lanes is to separate left turning vehicles from the through traffic stream; this tends to increase capacity by adding another lane to the approaches of an intersection and also improves safety and reduces delay. Capacity, delay and operational issues are usually related to a single shared lane between left turning vehicles and through vehicles which are expected to be eliminated with an exclusive left turn lane. If left turn queues are not accurately estimated, they may be the source of these safety issues counteracting the benefits of the left turn lane.

The accurate determination of left turn queues is very critical for the safety and efficient operation of an intersection. If a left turn lane is not adequately estimated to store the longest expected queue during a signal cycle with a high probability, left turning vehicles may back up into the adjacent through lane or the through traffic may block the entrance to the left turn lane preventing left turning vehicles from entering their lane. These effects may lead to additional intersection delay and also rear-end collisions which compromise the safety of the intersection.

Currently, the state-of-art in left turn lane modeling is the use of various software packages which are either analytically or simulation based. A survey carried out as part of this study indicated that traffic engineers are not very confident in the results reported by these methods. Some traffic engineers surveyed stated that they felt the models reported shorter queue lengths than those actually observed in the field while others stated that they felt the models reported longer queues than actual queue lengths. The survey also indicated that most of the engineers surveyed did not compare model queue lengths to any field values to ascertain the performance of the models.

The objective of this study is to determine the most reliable traffic software package used in left turn modeling.

Several models have been developed and are available to the traffic engineer for estimating left turn lane lengths; the engineer is thus faced with selecting the most reliable model. Several studies have been conducted to determine the performance of models. The results have shown that microscopic models which are simulation based are the more reliable and report queue lengths comparable to observed field queue lengths.

To add to the knowledge of model reliability, this study evaluated the most frequently used models in traffic analysis-Synchro, TEAPAC, HCS+ (all macroscopic models) and SimTraffic (a microscopic model). These models were selected based on results from the survey carried out as part of the study. Four intersections operating under varying traffic conditions were modeled. Results showed that SimTraffic, a simulation based model, was the most accurate in estimating left turn queues.

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CHAPTER 1

INTRODUCTION

1.1 Background

Left turn lanes are provided to separate left turning vehicles from the through traffic stream, to increase the capacity of an intersection, and to reduce delay and safety issues associated with a single shared lane containing both left turning vehicles and through vehicles.

Research conducted by Agent (1) showed that crash rates at signalized intersections with a dedicated left turn lane experienced only 46% of crash rates of those intersections with no dedicated left turn lanes. Other research by Gluck et. al. (2) showed that dedicated left turn lanes reduce crashes by 50% on average and also reduce rear-end collisions by between 60% and 88%. These two studies confirm that the provision of a dedicated left turn lane reduces crash rates at an intersection.

The required physical length of a left turn lane is the sum of the distance required for the driver to move laterally into the left turn lane and decelerate to a stop plus the required storage as shown in the figure below.

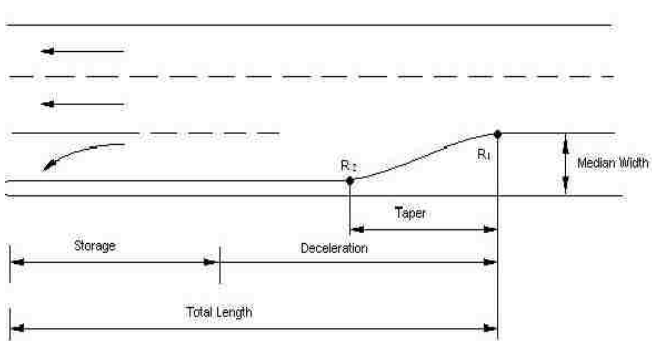

Figure 1-1: Single Left Turn Lane (3)

Thus, the provision of a turn lane of sufficient length will improve intersection flow and the overall capacity of the intersection. Therefore, left turn lanes should be of adequate length to allow left turning vehicles to laterally move into the left turn lane without excessive deceleration in the through lane and also sufficient to provide the required length to store the longest queue expected during a critical period.

The accurate determination of left turn queues is very critical to the safety and efficient operation of an intersection. If a left turn lane is not adequately estimated to store the longest expected queue during a single cycle with a probably of 90-95%, left turning vehicles may back up into the adjacent through lane. The through traffic may block the entrance to the left turn lane depending on the through volume thereby preventing left turning vehicles from entering their lane. This may lead to additional intersection delay and also causes rear-end collisions compromising the safety of the intersection.

Several methods and procedures have been developed and are available to the traffic engineer in estimating the length of a left turn lane. These methods are grouped in three categories: rule of thumb methods, macroscopic methods (analytically based) and microscopic methods (simulation based).

The concepts pertaining to each method are similar except for assumptions and differences unique to the specific models. Consequently, for the same data input, models developed based on a particular method will report different queue lengths. In addition, several different definitions exist for left turn queues resulting in the difficulty of determining how these models vary from one another.

Currently, the state-of-art in left turn lane modeling is the use of software packages which are either analytically or simulation based. The survey carried out as part of this study showed that traffic engineers are not very confident in the left turn queue lengths reported by the traffic models they use. A summary of the survey results indicated that the models either overestimated or underestimated queue lengths when compared to actual field queue lengths. Some of the respondents said that they were simply not confident in the reported queues without providing any further explanation. The survey also showed that most of the engineers did not compare the model reported queue lengths to field values to ascertain the performance of the models used. There is a need for a procedure that provides an explanation on how these estimated queue lengths vary from one another and from actual field observed queues.

This study evaluated several of the most frequently used models - Synchro, TEAPAC, HCS+ (macroscopic models) and SimTraffic (a microscopic model). These models were selected based on results of the survey. The queues reported by these models were compared with field observed queues.

1.2 Problem Statement

Although traffic software models of a particular method are based on similar concepts, each reports different queue lengths given the same data input. Coupled with different definitions describing left turn queues in the literature, the determination of exact left turn queue lengths is difficult. Given the safety and operational issues associated with the accurate determination of left turn lanes, every effort must be made to ensure that left turn lanes be of sufficient length to accommodate the longest expected queue with a high probability.

Several researchers have attempted to determine the performance of traffic software in estimating left turn queue lengths. The reliability of these models is determined by comparing the reported queues with actual field queue lengths; the model that reports queue lengths which compares best with field values is assumed to be the most reliable model. Most studies conducted on model performance have shown that microscopic based models are the most reliable in estimating queue lengths.

The following questions still exist:

1. Are left turn lanes designed sufficiently long enough to store the longest expected queue during the critical period?
2. Are left turn lanes of insufficient length made up for by increasing signal cycle timing which may subsequently increase travel delay?
3. Is excessive overflow of the left turn lane resulting in safety and delay issues?

Though the accurate estimation of left turn lane length allows for a small probability of occasional failures, traffic engineers should be confident in the model reported queues so that they are more familiar and aware of the operational conditions of the site.

This research attempts to address these questions by evaluating four traffic software packages commonly used by traffic engineers in left turn lane design- three macroscopic models and one microscopic model. Four intersections operating under varying traffic conditions were modeled.

1.3 Research Objectives

The focus of this research is in two parts:

1. Compare the left turn queues estimated by traffic models to the observed field queue. Synchro and TEAPAC are based on Highway Capacity Manual

procedures and HCS+ is a direct replication of the procedures and methodology outlined in the Highway Capacity Manual. SimTraffic is a simulation based model which models traffic based on car following, lane change and driver and vehicle characteristics.

2. Determine any relationships that may exist between predicted left turn queues among HCS+, Synchro and TEAPAC by statistical analysis. A null hypothesis that there is no significant difference between left turn queues estimated by HCS+, Synchro and TEAPAC will be tested.

1.4 Organization of the Thesis

The thesis contains six chapters. Chapter 2 reviews existing knowledge and research conducted on left turn lane design and the performance of traffic models in left turn lane modeling. Chapter 3 discusses the survey that was sent to state and local engineers to ascertain the most frequently used traffic models for left turn queue estimation. A copy of the survey is shown in Appendix A. Chapter 3 also gives an overview of the selected traffic models evaluated in this research. Chapter 4 describes the criteria and methods followed in selecting the study locations; also discussed is the data collection process. The analysis of the data and results are then discussed in Chapter 5. Also included in Chapter 5 is a summary of statistical comparisons made between the left turn queues estimated by the traffic models. Chapter 6 contains conclusions, recommendations and recommendations for future work.

CHAPTER 2

LITERATURE REVIEW

The purposes of a left-turn lane are to expedite the movement of through traffic, to control the movement of turning traffic, to increase the capacity of the intersection, and to improve safety characteristics. Therefore, the determination of an adequate left turn lane at a signalized intersection is a very critical issue in intersection design. Insufficient design of the lane length may compromise the safety and efficient operation of a signalized intersection. Left turn lanes are designed to accommodate left turning vehicles as their volumes increase and result in introducing unacceptable delays at the intersection. The determination of the numbers of left turning vehicles is difficult as traffic volume varies for a given time period, hence in estimating left turn storage length, traffic engineers select a queue length with a high probability of not being exceeded for a given signal cycle. In addition, to better understand vehicular interaction, traffic engineering professionals have developed various statistical analyses to describe traffic patterns to estimate the number of vehicles that may arrive within a certain time interval.

In general, three methods have been developed to determine left turn storage lengths; these are:

1. Rule of thumb methods
2. Analytical methods
3. Simulation based methods

The following sections present a detailed discussion of each of these methods.

2.1 Rule of thumb

A rule of thumb method is the simplest method for estimating left turn lane lengths based on average number of vehicles that arrive per signal cycle.

Queue length estimated by the rule of thumb method is given by the equation below:

$$Q=V/N_c * (t) \qquad \text{(Eq. 2-1)}$$

Where:

Q = Storage length (vehs)

V = Peak hour left turn volume (vph)

N_c= Number of cycles per hour

t = variable dependent on probability of storing the longest expected queue per cycle.

Typically, t ranges between 1.5 and 2.0 thus increasing the average arrival rate depending on the threshold probability. The table below indicates the corresponding threshold probability for various t values.

Table 2-1: Suggested Values of t

t value	Approximate Probability of Storing all Vehicles
2.0	>0.98
1.85	0.98
1.75	0.95

Source: Discussion paper, Oregon State University (4)

To determine the queue length in feet, rather than the number of vehicles, the above formula is multiplied by an average vehicle length, $L_{v,}$ in the traffic mix. The average length is dependent on the percentage of trucks in traffic stream. Typically, a value of

25ft is used for traffic streams with less than 2% trucks. For traffic streams with greater than 2% truck volume, different values are used as indicated in Table 2-2.

Table 2-2: Suggested Values of Average Vehicle Lengths for Different Truck Compositions

Percent of Trucks in Traffic Stream	Average Vehicle Length
<2%	7.6 m (25ft)
5%	8.0 m (27ft)
10%	9.0 m (29ft)

Source: Discussion paper, Oregon State University (4)

2.1.1 Guidelines Based on Rule of Thumb Method

AASHTO's Green Book (5) provides a guideline for determining left turn lane length at signalized intersections which depends on signal cycle length, signal phasing plan, and the rate of arrivals and departures of left turning vehicles. The Green Book suggests a left turn lane of length equal to one and one half to two times the average arrival rate per signal cycle.

A similar method based on the rule of thumb method is outlined in the Canadian Highway Capacity Manual (6). This procedure uses different 't' variables based on the probability that a given queue length will be exceeded. The Canadian manual includes a chart for different average queue lengths which can be interpolated based on an hourly left turn flow rate to determine the required left turn storage length.

The Texas Department of Transportation uses twice the average number of left turning vehicles that arrive per signal cycle (7) while the Delaware Department of Transportation (DelDOT) uses 1.5 times the number of left turning vehicles that arrive per signal cycle. To get the length in feet, DelDOT suggests a vehicle length of 20 ft for passenger vehicles (8).

Finally the California Department of Transportation (CALTRANS) uses cycle length, signal phasing and arrival and departure rates to determine a left turn length based on a 1.5 to 2 times the average arrival rate per signal cycle (9).

2.2 Analytical Based Models

Analytical based methods include queuing theory and are probability-based, where vehicle arrivals are assumed to follow a Poisson arrival distribution and departure rates follow an exponential service distribution. Most analytical models share concepts with some unique characteristics that distinguish one from the other. The Poisson distribution is used to estimate the probabilistic occurrence of events. Thus, to determine the occurrence of any number of vehicles for a given time period such as signal cycle, an average number of vehicles expected to arrive for that signal cycle is estimated. Based on this average vehicle occurrence, the probability of any number of vehicles arriving is determined with the formula below:

$$P(x) = \frac{e^{-\lambda} * \lambda^{x}}{x!} \qquad \text{(Eq. 2-2)}$$

Where:

P(x) = probability of exactly x left-turning vehicles,

λ = average number of left-turning vehicles per cycle,

x = 0, 1, 2...

e = Napierian base of logarithms (2.71828. . .)

An earlier work on estimating left turn lane lengths based on queuing theory was developed by J.E Leish (10) who, based on Poisson arrivals and an exponential service rate, developed a nomograph. The graph gives the required left turn lane length for two

probabilities (90% and 95%) of storing the longest expected queue with the 90th percentile indicating a minimum required lane length and the 95th percentile being the desirable lane length.

The City of Irvine, CA in its Transportation Procedures (11), has adopted Leish's nomograph in estimating left turn lanes. They recommend that the truck mix be explicitly stated and that all left-turning vehicles be accommodated 95% of the time. It is also recommended, however, that engineering judgment be applied in cases where the required left turn length is longer than that suggested by the nomograph.

Other research conducted by Oppenlander et. al. (12) developed a model for estimating left turn storage lengths at signalized intersections. Like Leish, Oppenlander assumed a vehicle arrival rate based on Poisson arrivals and a departure rate following an exponential service distribution. The model was evaluated for different signal phases.

Oppenlander's model, which yields left turn lane storage length in vehicle units, is given by the equation below:

$$v \text{ (vehs)} = \frac{[\log Pn - \log(1-(\lambda/\mu))]}{\log(\lambda/\mu)} \qquad \text{(Eq. 2-3)}$$

Where:

v = number of vehicles in the queue

Pn = probability of n vehicles in the queue

λ = arrival rate, equivalent passenger cars per second (pcps)

μ = service rate, equivalent passenger cars per second (pcps)

λ and μ are estimated by following equations:

$\lambda = 1.1 \times V/3600$

$\mu = S \times (G/C)/3600$

Where:

"1.1" = adjustment factor for the equivalence of left-turn vehicles with a separate phase

V = left-turn volume, equivalent passenger cars per hour (pcph)

S = lane saturation flow, equivalent passenger cars per hour of green (pcphg)

G/C = ratio of green time to cycle length (cycle split) for the turning-lane

Oppenlander's final results were summarized in the form of reference tables for 50th, 85th and 95th percentile left turn storage lengths for different turning volumes, green ratio and saturation flows.

Kikuchi et al. (13) employed a probabilistic approach for determining the length of left turn lanes. Two main criteria were employed: first, minimizing the probability of overflow of left turning vehicles into adjacent through lanes and second, minimizing the probability of through vehicles blocking the entrance to the left turn lane while queued during a red interval. The main analytical approach was to derive the probability that a vehicle approaching the intersection toward the end of the red phase will not encounter lane overflow or lane blockage.

A threshold probability was assumed in both cases. The threshold probability was defined as the frequency of occurrence of both problems. Selection of the threshold probability depended on several factors such as economy, capacity, safety and site-specific conditions.

Assuming a threshold probability of 0.02 for the overflow case, a Markov chain model was developed to estimate the required left turn lane length (number of vehicles). The left turn lane length was determined to be dependent on left turn volume, the protected phase

duration, cycle length, opposing through volume, and layout of the intersection. The required left turn lane length was summarized in a set of tables for different green time ratios for various left turn volumes.

Modeling from the left turn lane blockage perspective, with a threshold probability (τ_i = 0.1) for blockage, the required left turn storage length (in vehicles) was calculated by the following equations:

$P_B(N)$ = Prob {number of through vehicle ≥ N, and the number of left-turning vehicles already in the lane < N, and a left-turn vehicle arrives} (Eq.2-4)

$$N^{**} = \min \{N \mid P_B(N) \leq \tau_i\} \quad \text{(Eq.2-5)}$$

Where:

τ_i = threshold probability of left turn lane blockage

Other research by Kikuchi et al (14) also employed probabilistic methods in determining dual left turn lane lengths. Similar to the above discussion, the determination of a dual left turn lane length also was based on the probability of left turn lane spillover into an adjacent through lane and blockage of the left turn by an adjacent through lane queued during the red interval. A threshold probability was specified which was defined as the minimum probability that all arriving left turning vehicles can enter the dual lanes without encountering either spillover or blockage.

Vehicle arrival patterns were assumed to follow a Poisson distribution. Other factors, such as signal timing and vehicle mix were also considered. The probability of a left turning vehicle arriving during the red and not encountering blockage or spillover was

determined as a function of the left turn lane length and the arrival rate of the through and left turning vehicles.

The required left turn lane length was determined as the length for which the probability that all arriving left turning vehicles can enter the left turn lanes without blockage or spillover was greater than the threshold probability.

2.3 Simulation Based Methods

Simulation based methods evaluate system performance and network capacity by utilizing fundamental traffic flow, speed, and density relationships.

An early study on determining left turn lane length at signalized intersections by simulating traffic conditions was by Oppenlander et. al. (15). This simulation was designed to model the interaction between vehicles arriving at an intersection, signal operation, and movement of vehicles at the intersection and was based on a Poisson probability distribution. In this study, the departure rate was assumed to be a triangular probability distribution and was based on headway field values which were divided into average, lower and upper departure times depending on the extent of waiting queues. Vehicles arriving on the green proceeded through the intersection while those arriving on red were placed in a queue to await a green signal.

A range of traffic volumes between 50 and 800 vph were simulated in intervals of 50 for different green times of 60, 75, 90,120,150 and 180. The study resulted in a series of reference tables with 50th, 85th and 95th percentile queue lengths.

2.4 Traffic Software Packages

Traffic simulation packages have been developed based on analytical and simulation based methods that basically utilize traffic flow, speed and density in estimating network capacity and system performance. There are basically two types of simulation packages, micro-simulation and macro-simulation models. Micro-simulation models incorporate specific car-following, vehicle performance, and lane changing algorithms to model individual vehicle behavior. On the other hand, a macro-simulation model uses continuum equations to model traffic as a whole and not as individual vehicles. Thus performance measures are estimated based on aggregate traffic. Macro-simulation models usually require less data input and simpler coding efforts but provide a corresponding lower level of output detail.

2.4.1 Micro-simulation Models

Most micro-simulation models use various algorithms and driver behavior models to simulate the movement of individual vehicles on a network. Each vehicle is modeled as a unique entity with a vehicle type and vehicle performance characteristics. Any vehicle that enters the road network is either assigned a car, bus, truck or a carpool with corresponding performance characteristics in terms of acceleration, deceleration, speed and turning characteristics. In addition, driver characteristics are assumed for each vehicle in the traffic stream. A driver may be assumed as aggressive, conservative or a characteristic between these extremes. Data on vehicle performance, driver characteristics, interaction between vehicles and the overall performance of the roadway system are collected and updated once per second. Once a vehicle is assigned

performance and driver characteristics, its movement through the network is determined by three primary algorithms (16):

• Car following

• Lane changing

• Gap Acceptance

Car following algorithms basically determine the headway or spacing and the interactions between vehicles on the roadway which subsequently determines the distribution of vehicles on the network. In SimTraffic, the average headway is about 1.2 seconds but generally varies based on speeds, driver and vehicle characteristics. Conservative drivers are assigned higher headways at higher speeds while the aggressive drivers are assigned shorter headways at the same high speeds as reflected in the real world.

Lane changing algorithms determine how vehicles on a network make lane changes, merge or weave into traffic streams. Making a lane change maneuver involves driver behavior, vehicle characteristics and characteristics of the surrounding traffic stream. Drivers may make mandatory lane changes, positional lane changes, or discretionary lane changes depending on prevailing conditions and the destination of the driver. SimTraffic models these three lane changes and allows the user to modify selected parameters to replicate site specific conditions. Some of the lane changing characteristics assigned to drivers in the model includes maximum acceptable deceleration rates in order to make a lane change, average distance over which to make a lane change, minimum acceptable gap in adjacent traffic stream, distance at which to begin a mandatory lane change, and thresholds for making a discretionary lane change.

With gap acceptance algorithms, the manner in which the simulated traffic turns into or crosses conflicting traffic streams is determined.

2.4.2 Macro-simulation Models

Unlike micro-simulation models, macroscopic models simulate traffic flow by aggregating traffic flow characteristics such as speed, flow and density and the relationship between them.

Macroscopic models are deterministic and analytical in nature; the same results are obtained each time for the same input data. Macro-simulation models usually require relatively shorter analysis time than micro-simulation models. Data pertaining to geometric, traffic, and signal and phasing data are required.

2.5 Comparison of Queue Lengths Estimated by Traffic Models

Numerous studies have been conducted to evaluate and compare the performance of traffic models with observed queue lengths. Model outputs are difficult to compare directly however, because of the different queue lengths reported by the traffic models and the different terminology and definitions found in the literature. Basically, four different definitions of left turn queues are estimated by the myriad of models available; these are defined below:

Maximum queue length – number of vehicles in the queue at the beginning of a green interval.

Average queue length – the average number of vehicles in the queue based on estimates over some time interval. Almost all the models estimate average (50th percentile) queue lengths.

Average maximum queue length – average of maximum queue lengths over a number of cycles.

Maximum back-of-queue – the number of vehicles in the queue at the start of green, plus those that join the queue after the start of the green.

The most recent study to compare predicted traffic model queue lengths with observed field queue lengths was by Qi et. al. (17) where seven intersections in Houston, Texas operating under varying traffic conditions were modeled. The selected models evaluated in this study were HCS+ (version 5.1), Synchro (version 6), SimTraffic (version 6), and VISSIM. HCS+, and Synchro are macroscopic models, while SimTraffic and VISSIM are microscopic models.

HCS+ is a macroscopic model that implements the concepts and procedures outlined in the Highway Capacity Manual 2000 (18), published by the Transportation Research Board. It is basically used for capacity analysis and determining the quality of service of signalized intersections, unsignalized intersections, urban streets, freeways, weaving areas, ramp junctions, multilane highways, two lane highways, and transit. HCS+ is sectioned into modules and it is used in computing delay and level of service at an intersection. In its queuing module, it provides five different percentile back-of-queues including the 50th and 95th percentile queues. In Qi's evaluation, the 95th percentile queue was compared.

Synchro is a macroscopic model developed by Trafficware. It is an analytical model whose signal analysis is based on the concepts of Chapter 16 of the Highway Capacity Manual 2000 (19). Its capabilities include capacity analysis, actuated signal modeling, coordination and time space diagrams. Synchro computes average 50th and 95th percentile

queue lengths and can indicate queue spillback. Synchro's 95th percentile queue was used in this study.

SimTraffic is a microscopic model that emulates real world traffic conditions. It fully simulates signals, unsignalized intersections (including roundabouts) and the interactions that occur between vehicles. SimTraffic cannot be used for optimizing purposes and requires more time for modeling (19). SimTraffic is integrated with Synchro and thus imports its geometry, traffic and signal parameters from Synchro. SimTraffic reports average maximum queue length, maximum queue length and 95th percentile queue lengths. SimTraffic's 95th percentile queue length was used in this study.

VISSIM is a multi-modal microscopic, time-step and behavior based simulation model developed at the University of Karlsruhe, Germany (20). Its capabilities include intelligent transportation system control strategies modeling such as ramp metering, transit signal priority, and time-space diagram outputs. VISSIM, compared to other micro simulation models, provides more flexibility in specifying model outputs. VISSIM's 95th percentile queue was compared in this study.

The researchers developed an evaluation criterion 'Accuracy level' for determining the most accurate model. The accuracy level criterion was used to determine the level of precision of each model compared to the observed queue length. The accuracy level is determined by the following equation:

$$\text{Accuracy} = 1\text{-ave}\left(\frac{L_m - L}{L}\right) * 100\% \qquad \text{(Eq. 2-6)}$$

Where:

L_m = queue length predicted by traffic model

L = observed queue length

Their results showed that SimTraffic outperformed the rest of the selected models with an accuracy level of 85%. That is 85% of SimTraffic's queue estimates closely matched field values. Synchro was the next best model with an accuracy level of 83.0% followed by HCS+ with an accuracy level of 79.6% and VISSIM, a microscopic model, with a 61.2% accuracy level. VISSIM overestimated in six of the cases modeled. The researchers reasoned that VISSIM was the least accurate because of its tendency to overestimate due to the queue counter in VISSIM, which tends to count adjacent through vehicles when both left turn lane overflow and blockage conditions exist.

Another study by the same researchers compared Synchro, SimTraffic, VISSIM and their developed TSU Model (3) an analytical model developed based on a discrete Markov time chain. The researchers claim that their model accounts for limitations that are present in some existing models.

In addition to the accuracy level discussed earlier, the researchers in this study utilized a second evaluation criterion - 'Score'. The score basically indicated the number of times a model predicted queue lengths that best matched the observed queue lengths relative to the other models being evaluated.

Overall, the TSU model produced the most accurate estimates using the accuracy level criterion with 90.6% accuracy, followed by SimTraffic with 85% accuracy. Synchro and VISSIM produced 83.9% and 57.3 % accuracy levels respectively. In terms of score, Synchro produced only 1 queue length comparable with an observed queue length while SimTraffic, VISSIM and TSU models each produced 3 comparable queue lengths.

An earlier study conducted by Mystowski and Khan (21), compared observed queue lengths with selected model predictions. Signal94 (version 1.22), Synchro3, TRANSYT-

7F (version 7), Passer II-90 (version 2) and CORSIM (version 4) were evaluated for six intersections in Denver, Colorado.

This study compared observed average maximum queue lengths with Passer II-90, CORSIM, Synchro3 (50%) and TRANSYT-7F. Also, observed maximum queue lengths were compared with Signal94 and Synchro3.

PASSER II-90 is a macroscopic deterministic model developed by the Texas Transportation Institute in the early 1980s (22). The Progression Analysis and Signal System Evaluation Routine model is used for traffic analysis and also for optimizing signal timing. It models only through and left turn movements and not right turn movements. It reports maximum queue per cycle.

CORSIM (CORridor SIMulation) was developed by the Federal Highway Administration and is one of the most widely used simulation packages in the United States (23). It is used for analyzing signal systems, freeway systems, or a combined signal and freeway system. Some of its capabilities include signal analysis, coordination, pre-emption and queuing studies involving turn pockets and queue blockage. CORSIM is one of the most widely acceptable simulation packages and hence is mostly used in verification and validation of other traffic simulation packages.

TRANSYT, which is an acronym for TRAffic Network StudY Tool, is another of the most widely available signal timing tools (24). TRANSYT-7F is a traffic signal timing optimization software package for traffic networks, corridors, or single intersections. Its strength lies in its ability to simulate traffic conditions in detail. It predicts maximum back of queue.

Study results showed that both Synchro3 and TRANSYT-7F predicted maximum back of queue lengths greater than or equal to the field measurements and the estimates of maximum queue lengths from Passer II-90 and CORSIM in 66% of the cases.

Selinger et. al. (25) evaluated SimTraffic and CORSIM at three different highway facilities which comprised an isolated intersection with considerable pedestrian activity, an arterial corridor with closely spaced intersections and a freeway. The purpose of the research was to provide guidance to traffic engineers regarding the model that best simulates a particular highway facility.

In all three studies, SimTraffic and CORSIM were calibrated as deemed necessary to replicate existing field conditions. In modeling the isolated intersection with considerable pedestrian activity, it was realized that CORSIM did not account for pedestrian volumes of less than 100 per approach while SimTraffic accounted for pedestrian activity irrespective of the volume. CORSIM assumed that pedestrian volumes less than 100 do not cause excessive delay and hence ignores pedestrian volumes of less than 100. However, though the pedestrian volume was only 95, the researchers realized it affected the intersection operation by causing additional delay to right turning and left turning vehicles on the approaches that conflicted with pedestrian movement. Since SimTraffic accounts for pedestrian volume irrespective of the volume, it produced more realistic results than CORSIM.

The second case study modeled was an arterial with closely spaced intersections in which CORSIM produced better results than SimTraffic. Due to the closely spaced intersections, SimTraffic limited the number of vehicles that could queue across (or be present at a link at a point in time) and hence reduced the number of vehicles that were

served within an hour. This was due to the fact that SimTraffic has a grid avoidance feature which will not allow vehicles to queue into an intersection. The researchers, however, also mentioned that if the intersections were not closely spaced, SimTraffic may have produced comparable results to CORSIM.

The third case study was a major weave section on a freeway facility. Results showed that CORSIM produced better results than SimTraffic in this evaluation.

The researchers concluded by recommending SimTraffic in modeling queue lengths with considerable pedestrian activity and CORSIM for freeway facilities and closely spaced intersections.

Viloria et al, (26) compared several software packages under a wide range of traffic conditions. The purpose of their research was to establish conversion equations to translate selected traffic model queue length output to HCM 2000 queue equivalents. The researchers were of the opinion that HCM 2000 provided a comprehensive treatment for left turn queue modeling by accounting for factors such as controller type, progression quality, random and overflow effects associated with traffic flow and, thus, was analytically defensible. Selected models included Signal 97/TEAPAC, NETSIM/ CORSIM, Oppenlander's method, TRANSYT-7F, and Teply's model, (Canadian Highway Capacity Manual). Each model was evaluated for different volumes under several cycle lengths and for a varying range of under-saturated conditions. Regression analyses were performed to establish the relation and the reliability that existed between the proposed HCM model and the selected models. Queues generated by each model were plotted against HCM's 50th, 90th and 95th percentile confidence level. The researchers concluded that HCM 2000 generally produced higher queues than all the

other models. This is because the models report only average queue values without applying any queue expansion and secondly, those that apply queue expansion factors do not reflect the possibility of overflow from a previous cycle. The researchers concluded that 90th percent confidence maintained in the past for left turn storage may not be adequate enough for conditions approaching saturation.

2.6 Summary of Background Literature

A summary of available literature indicates the wide variation in left turn queue definition and methods available for their estimation. Due to this, the traffic engineer is still faced with determining the most reliable method for estimating left turn lane.

Most research conducted into determining the performance of available models indicates that micro-simulation models are more reliable than the macro-simulation models. These micro-simulation models however must be calibrated to reflect site specific conditions.

At this stage of left turn modeling, no one model can be said to be the most reliable in designing left turn lanes. Users should, however, compare model outputs with field values in order to be certain of the performance of the models being used.

CHAPTER 3

METHODOLOGY

The objectives of this study were achieved by carrying out the following tasks:

1. Selection of candidate traffic model(s)
2. Site identification and selection
3. Data collection
4. Data processing and analysis
5. Left turn modeling
6. Comparison of left turn queues

The sections that follow discuss in detail the processes carried out under each task.

3.1 Selection of Traffic Software Packages

In order to determine the most widely used software packages for left turn queue modeling at signalized intersections, a survey was sent to all 50 states as well as to local traffic engineers. The state engineers were those serving on the Subcommittee on Traffic Engineering of AASHTO's Standing Committee on Highways and the local traffic engineers were identified using the Institute of Transportation Engineer's membership directory. The survey (see Appendix A) contained eight questions relating to the respondents' traffic modeling experience. A total of 100 surveys were electronically sent and 35 responses were received.

3.1.1 Summary of Survey

The following summarizes the responses to the survey questions:

The survey asked which software packages were used for left turn queue modeling. Responses indicate respondents use more than one traffic model.

The survey asked which software packages were used for left turn queue modeling. Responses indicate respondents use more than one traffic model. The responses are shown in Figure 3-1.

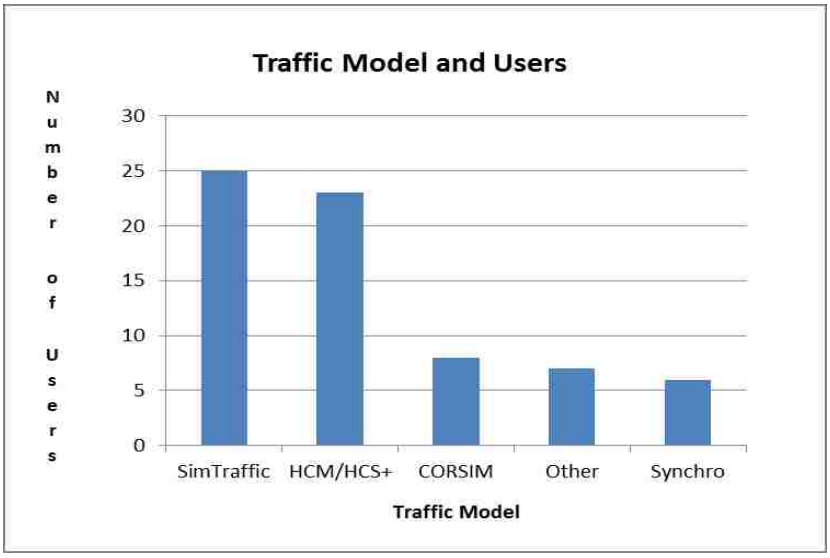

Figure 3-1: Responses to Methods of Left turn Modeling

About 71% of the 35 respondents use SimTraffic (a microscopic model) while 17% use Synchro. Synchro/SimTraffic is a complete analysis package developed by Trafficware. 65% of the respondents use HCS+ and 20% use some other types of models such as CORSIM or some other model not listed in the survey.

The second question attempted to determine the level of confidence respondents had in the queues reported by the respective packages used. Their responses indicated that, although traffic engineers may use more than one traffic model in their design and capacity analyses, a large percentage of them do not trust the output of the models. About 6% of the

respondents were very confident with model output while 90% of them were not confident with the model reported queue length. The figure below indicates the respondents' responses.

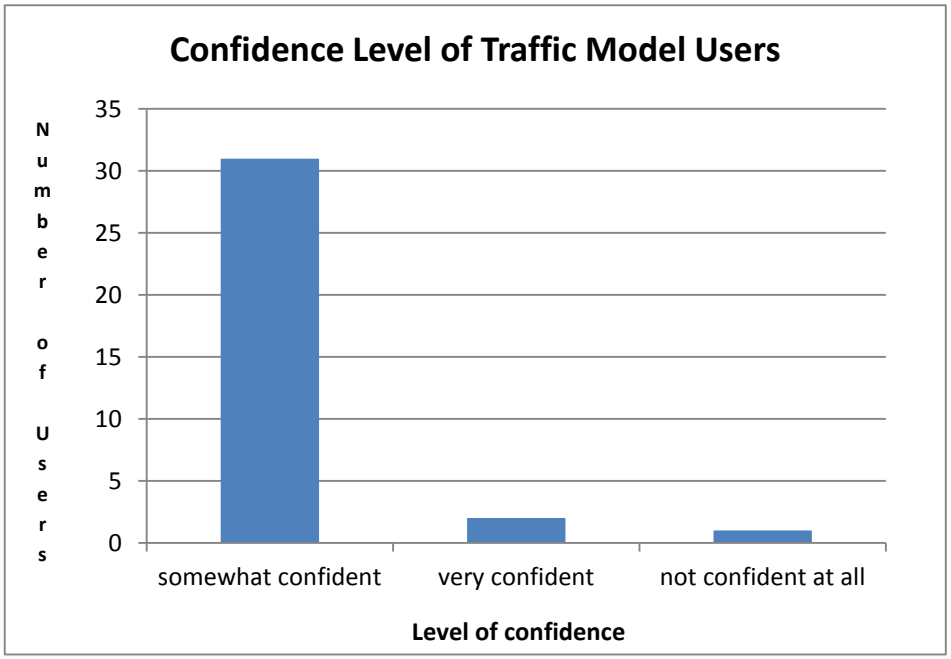

Figure 3-2: Estimated Left Turn Queues Confidence Levels

The third question asked respondents to state how the reported queues compare with actual field queues; the following are the responses:

- 17 out of the 35 respondents responded they had not compared estimated lengths to actual lengths.
- 9 responded that they felt the estimated lengths were quite close to the actual lengths.
- 2 respondents felt that the tools estimated lengths that were too short.
- 1 respondent felt that the tools consistently overestimated queue lengths.

The following questions were based on ascertaining from the respondents the parameter which best defined left turn queue and also the treatment given to left turn lanes operating under oversaturated conditions.

The table below shows the parameter and the number of respondents that selected a parameter. Some of the respondents selected multiple responses.

Table 3-1: Parameters that Describe Queue Length

Left turn queue parameter	Number of responses	Percent
Average maximum queue length over a number of signal cycles	11	31%
Percentile queue length (95%)	9	26%
Maximum queue length at the beginning of the green interval	10	29%
Maximum back of queue -vehicles in queue at the beginning of green plus vehicles that join during the green interval	9	26%

The responses indicate more than one definition for left turn queues and thus no one standard way of defining left turn queues.

Respondents were also asked to indicate their preferred treatment for a backed up queue. Table 3-2 summarizes the responses. Respondents could select more than one treatment.

Table 3-2: Treatment for a Backed-up Left Turn Lane

Left turn treatment	Number of responses
Install dual left turn lane	28
Lengthen the protected green interval	27
Extend left turn lane	25
Other	9

Again, from the responses, traffic engineers have different methods of dealing with left turn overflow and the treatment may depend on the prevailing conditions at the site.

The next question asked the respondents to state when they considered that a vehicle has joined the back of a queue. Twenty of the 35 respondents responded that they do not conduct queue studies. Of the ones that do, nine defined a queued vehicle in terms of speed and stated that they consider a vehicle queued when it is travelling at a speed less than five mph. Four agencies defined a queued vehicle in terms of its distance from a stopped vehicle and stated the vehicle queued when it was within 40 feet from a stopped vehicle.

3.2 Selected Software Packages

The response from the survey indicated that a large percentage of respondents use SimTraffic and HCS+ for left turn queue modeling, hence these two were selected for further study. SimTraffic is integrated with Synchro and imports its geometric, traffic and signal parameters from Synchro and therefore Synchro was subsequently added to the evaluation package. A fourth package, TEAPAC, was also added to the evaluation models. The following sections give an overview of the characteristics of the selected packages, the left turn estimated by each and the differences between the models.

3.2.1 SimTraffic (version7)

SimTraffic 7 is a micro-simulation model integrated with Synchro 7 and developed by Trafficware Corporation, Sugar Land, Texas (19).

The model is run directly from Synchro data input and requires data related to mapping, links, geometry, lanes, volume, timing and signal actuation. It has the ability to simulate a wide variety of traffic signal controls, including a network with traffic signals operating on different cycle lengths or operating under fully actuated conditions.

As a microscopic simulation model, SimTraffic models vehicle performance and driver behavior using various algorithms including car following, lane changing, and gap acceptance. Each vehicle that enters the network is assigned a vehicle type (auto, bus, truck or carpool) with a corresponding vehicle performance characteristic such as acceleration rate, deceleration rate, turning speed, and free flow speed. Each driver is also assigned a level of behavior on a scale of one to ten ranging from aggressive to cautious. This behavioral assignment determines the performance profile on the road network. SimTraffic tracks each individual vehicle in the traffic stream and collects comprehensive operational measures such as delay, stops, queues, average speeds and fuel consumption for every 0.1 second of the simulation time. The variation of each vehicles behavior is simulated in a manner reflecting real-world operations. Based on these vehicle and driver characteristics, SimTraffic computes individual vehicle performance and overall network performance. SimTraffic considers a vehicle queued when it is traveling at less than 10 feet per second (7mph).

SimTraffic reports average queue length, maximum queue length and 95th percentile queue length for each lane during the analysis period. It also records the maximum queue observed for each two minute simulation interval. Average queue is computed as the average of two minutes of maximum queue observed during the analysis period. Maximum queue is the longest queue observed for two minutes of the analysis period for any lane. The 95th percentile queue is calculated as the average queue plus 1.65 standard deviations; it is a calculation and not simulated.

The following are some of the differences that exist between SimTraffic and the three macroscopic models evaluated in this study.

- SimTraffic must be calibrated to emulate the prevailing traffic conditions at the site.
- SimTraffic must be seeded with traffic in order to run the analysis. The time needed for seeding should be long enough to allow a vehicle to traverse the road network that is being modeled.
- SimTraffic is integrated with Synchro and therefore SimTraffic imports geometric, traffic, and signal timing parameters from Synchro.
- SimTraffic assumes a vehicle length of 19.5 ft while Synchro, HCS+, and TEAPAC all assume a vehicle length of 25 ft. Vehicle length is the length of the vehicle plus the space between it and the vehicle in front of it.

3.2.2 Synchro (version 7)

Synchro 7, also developed by TrafficWare, is a macroscopic, deterministic and analytical model and replicates the signalized capacity analysis as specified in the 2000 Highway Capacity Manual (19). Unlike SimTraffic, which is a microscopic model, Synchro represents traffic in terms of aggregate measures for each movement at an intersection. Synchro is used for capacity analysis and is capable of optimizing cycle lengths, splits and offsets and in determining network coordination. The procedure provides output that includes delays, stops, fuel consumption, average (50th) and 95th percentile back of queues, and the percent of time that queues exceed the available storage. Average (50th) percentile is the maximum back of queue for a cycle with average vehicle arrivals while the 95th percentile queue is calculated by increasing the arrival rate to account for fluctuations in traffic.

In the estimation of queues, Synchro does not consider vehicles delayed for less than 6 seconds as part of the queue because it assumes they are slowed but not stopped.

Synchro's maximum back of queue is calculated below:

$$Q = \frac{v}{3600} * (R-6) * \left[1 + \frac{1}{s/v - 1}\right] * \frac{L}{n * fLU} \qquad \text{(Eq. 3-1)}$$

Where:

R= Red time

s = Saturation flow rate (vphgpl)

v = Arrival rate (vph)

L = Length of vehicles including space between them (ft)

n = Number of lanes

fLU = Lane utilization factor

The above model is for unsaturated conditions (v/c<1).

For saturated conditions (v/c>1), Synchro calculates queue length as the maximum queue after two cycles given by the formula below:

$Q' = (v* (C - 6) + ((v - s)* g/C)) * C / 3600$

(Eq.3-2)

The 95th percentile queue is computed by increasing the arrival rate to account for fluctuations in traffic volume; this volume is not adjusted for the Peak Hour Factor (PHF) because the adjustments account for traffic fluctuations usually accounted for by the PHF.

3.2.3 HCS+ (version 5.4)

HCS+ is a macroscopic model that implements the concepts and procedures outlined in the Highway Capacity Manual 2000, published by the Transportation Research Board (18). HCS+ is maintained and sold through the McTrans Center at the University of Florida in Gainesville. Its primary use is for capacity analysis and determining the quality of service of signalized intersections, unsignalized intersections, urban streets, freeways, weaving areas, ramp junctions, multilane highways, two lane highways, and transit. Appendix G of Chapter 16 of the Manual outlines procedures and methodologies for estimating back of queue at a signalized intersection.

HCM 2000 defines back of queue as the number of vehicles queued depending on the arrival pattern and on the number of vehicles that do not clear the intersection during a green interval (overflow). HCS+ computes maximum back of queue and outputs average, 70th, 85th, 95th, and 98th percentile back of queue per lane per movement. The average back of queue comprises two terms: Q_1 and Q_2. In addition to maximum back of queue, HCS+ outputs a queue storage ratio, which compares the average queue length to the available storage distance. The purpose of this procedure is to determine if blockage will occur.

The first term in the calculation (Q_1) is computed based on uniform arrivals adjusted for progression. Q_2 (the second term) is an increment of queued vehicles to account for flow randomness and overflow. These two terms are summed to calculate the maximum distance (in vehicles) over which the queue extends from the stop line for an average signal cycle length. The percentile back-of-queue values are calculated by applying

empirically-developed factors based on signal type (pretimed vs. actuated) to the average value described above.

HCS+ computes average queue length by the formulas below:

$$Q = Q_1 + Q_2 \qquad \text{(Eq. 3-3)}$$

Where:

Q = maximum back of queue on an average signal cycle (veh)

Q_1 = average back of queue assuming uniform arrivals and adjusting for the effects of progression (veh)

Q_2 = incremental term due to randomness and cycle failures (veh)

Q_1 is computed as follows:

$$Q_1 = PF_2 * \frac{(v_L C/3600)(1 - g/C)}{1 - [\min(1.0, X_L) * g/C]} \qquad \text{(Eq. 3-4)}$$

Where:

Q_1 = number of vehicles that arrive during the red interval and during the green interval until the queue has dissipated

PF_2 = adjustment factor for effects of progression

v_L = lane group flow rate (veh /h)

C = cycle length (s)

g = effective green time (s)

X_L = ratio of flow rate to capacity

$$PF_2 = \frac{\left(1 - Rp\frac{g}{C}\right)\left(1 - \frac{v_L}{s_L}\right)}{\left(1 - \frac{g}{C}\right)\left[1 - Rp\left(\frac{v_L}{s_L}\right)\right]} \qquad \text{(Eq. 3-5)}$$

Where:

PF_2 = adjustment factor for effects of progression

v_L = lane group flow rate (veh /h)

s_L = lane group saturation flow rate per lane (vphgpl)

C = cycle length (s)

g = effective green time (s)

R_p = platoon ratio P(C/g)

The incremental queue due to randomness and overflow, Q_2, is given by the following formula:

$$Q_2 = 0.25 c_L T\left[(X_L - 1) + \sqrt{(X_L - 1)^2 + \frac{8 k_b X_L}{c_L T} + \frac{16 k_B Q_{bL}}{(c_L T)^2}}\right] \qquad \text{(Eq. 3-6)}$$

Where:

Q_2 = average overflow queue (veh)

c_L= lane group capacity per lane (veh/h)

T = length of analysis period (h)

X_L = flow rate to capacity ratio

Q_{bL} = initial queue at start of analysis period (veh)

C= cycle length (sec)

k_B = adjustment factor for early arrivals

$$k_B = 0.12\ I \left(\frac{s_L g}{3600}\right)^{0.7} \quad \text{for pretimed signals} \qquad \text{(Eq 3-7)}$$

$$k_B = 0.10\ I \left(\frac{s_L g}{3600}\right)^{0.6} \quad \text{for actuated signals} \qquad \text{(Eq.3-8)}$$

I = upstream metering for platoon arrivals

To estimate percentile back of queue, the formula below is applied:

$$Q_{\%} = Qf_{B\%} \qquad \text{(Eq.3-10)}$$

Where:

$Q_{\%}$ = percentile back of queue (veh)

Q = average back of queue (veh)

$f_{B\%}$ = percentile back of queue factor

$f_{B\%} = p_1 + p_2 e^{-Q/p_3}$

p_1, p_2 and p_3 values are dependent on the type of signal control and percentile values and are empirically developed.

3.2.4 SIGNAL2000/TEAPAC (version 8.10)

TEAPAC is an acronym for Traffic Engineering Application PACkage, developed by Strong Concepts (27). TEAPAC provides a quick and integrated analysis and design for transportation and traffic engineering problems. TEAPAC complete consists of more than a dozen integrated applications for performing signal analysis, traffic impact analysis, progression analysis, and count analysis. The program is a macroscopic model based on the procedures outlined in the Chapter 16 of the Highway Capacity Manual 2000 and is used for capacity analysis, signal timing/phasing optimization, and intersection design and also for determining level of service for current projects. SIGNAL2000's capacity analysis allows for easy determination of capacity problems and identifies the cause of

the capacity problems. It computes queue lengths by four different basic model structures: the 2000 HCM, ARRB model, MBQ model, and SIGNAL97 model. Several variations of these models are calculated, therefore eight models are computed.

The 2000 HCM model computes queue length based on the maximum back of queue model defined in the Highway Capacity manual. Two models are computed under the 2000 HCM model structure; the first model computes the percentile queue for the worst lane in a lane group and the second computes the average queue for the worst lane in a lane group.

The ARRB model is based on the maximum back of queue model defined by the Australian Road Research Board (ARRB) and as implemented in the SIDRA5 model. It computes 95th percentile queue for the worst lane in a lane group.

The MBQ model applies the maximum back of queue model from standard queuing theory. It computes the average queue for the average lane in a lane group.

SIGNAL97 computes maximum queue length, i.e. the number of vehicle arrivals during the red time for each cycle. It follows the standard queuing theory commonly referred to as "red time formula". There are four variations of this model; Models 7, 8, 9, and 10.

SIGNAL97 models 9(S97E) and 10(S97A) apply an adjustment factor of 2.0 in estimating the 90th percentile queue.

Models 7(S97E+) and 8(S97A+) are the enhanced versions of models 9 and 10 respectively indicated by the "+" sign. These models compute percentile queue based on the percentile specified by the user which is based on actual cumulative Poisson arrivals probabilities and not based on a 2.0 factor.

SIGNAL2000 computes maximum queue length (MQL) based on standard queuing theory (also called the 'red time formula') and is given by the formula below:

$$Qn = 2.0 * q * r / N \qquad \text{(Eq.3-11)}$$

Where:

Qn = number of vehicles in queue per lane (veh)

2.0 = 90th percentile randomness factor (a Poisson distribution estimate)

q = arrival rate (vehicles per second) v/3600

r = adjusted volume (vph)

N = number of lanes in lane group

For over saturated conditions (v/c > 1), queue length is calculated by the formula below:

$$Qn = [2.0*q*r + T*V*(X-1)/[X*N]] \qquad \text{(Eq.3-12)}$$

Where:

Qn = number of vehicles in queue per lane

2.0 = 90th percentile randomness factor (Poisson distribution estimate)

q = arrival rate (vehicles per second) v/3600

r = adjusted volume (vph)

N = number of lanes in lane group

T = length of analysis period (minutes)

V = volume during analysis period (veh/h)

X = v/c ratio

3.3 Summary of Software Packages

A detailed comparison of the four selected packages is presented in the following tables. The purpose of the comparison is to highlight the characteristics of the model as well as differences among the packages. A brief comparison of the characteristics for the four packages is provided in Table 3-3. The differences that exist between the four models and the queue length estimated are provided in Table 3-4.

Table 3-3: Software Characteristics

Model	Method/Assumption	Estimated Queue Length
Synchro (version 7)	Analytical, deterministic and macroscopic model. Assumes no initial queue for v/c operating conditions. Considers initial queue from previous cycle for v/c conditions.	50th and 95th percentile maximum back of queue
SimTraffic (version 7)	Microscopic and stochastic model	Average, Maximum and 95th percentile back of queue
HCS+ (version 5.4)	Analytical, deterministic and macroscopic model. Assumes no initial queue for v/c operating conditions. Considers initial queue from previous cycle for v/c conditions.	Average, 70th , 85th, 90th, 95th, and 98th percentile maximum back of queue
TEAPAC (version 8.10)	Analytical, deterministic and macroscopic model. Uniform arrivals on red. No initial queue. Adjustment factor of 2 is used to provide a 90th percentile randomness factor.	Maximum queue

Table 3-4: Software Differences

	Synchro	HCS+	TEAPAC	SimTraffic
Actuated Signals	Internally calculates actuated green time	User must specify average green time	User must specify average green time	Depends on Synchro dataset
Queue Length Calculation	Assumes vehicle queued when stopped or delayed for more than 6 seconds.	Queue length includes all vehicles queued until they clear the intersection	Considers vehicles queued on red interval only	Assumes vehicle is queued when stopped behind a queued vehicle, stopped to make a mandatory lane change or travels at less than 7m/s
Progression Factor	Calculates progression factor from arrivals from upstream intersections	User must specify progression factor	User must specify progression factor	Depends on Synchro dataset
Vehicle Length	25 ft	25 ft	25 ft	19.5 ft

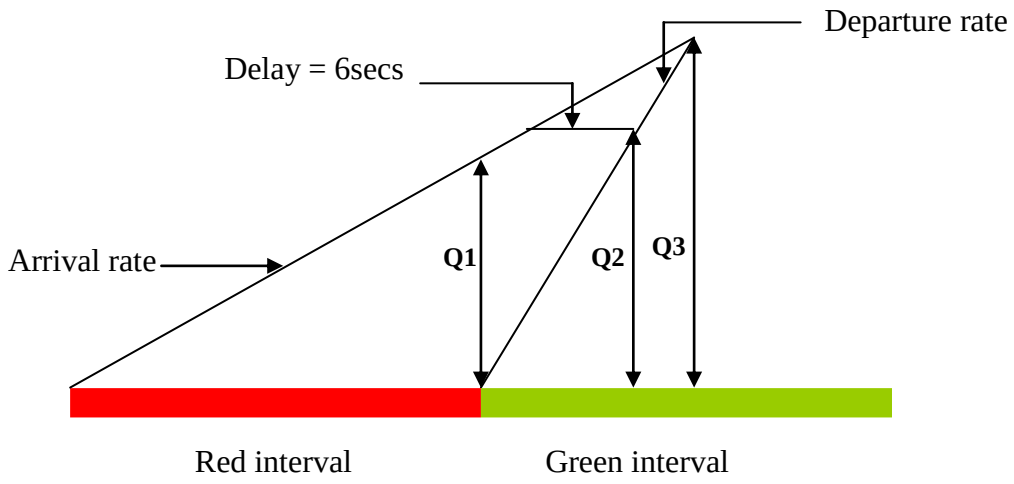

Figure 3-3: Queue Length Estimated by Traffic Models (26)

Q1 = Maximum queue calculated by TEAPAC

Q2 = Maximum queue calculated by Synchro (vehicles delayed less than 6 seconds are not considered)

Q3 = Maximum queue calculated by HCS+ (Maximum back of queue)

CHAPTER 4

SITE SELECTION AND DATA COLLECTION

In order to evaluate the selected models for their ability to replicate actual left turn queues in the field, intersections operating under varying traffic and geometric conditions were identified and selected. Comparing model performance under varying traffic conditions was critical in software evaluation as some models, for example HCS+, may not perform well under over saturated conditions (18).

4.1 Initial Data Collection Plan

The initial data collection plan was to employ hand-held video cameras to record turning data on each approach but, after several trials, it was realized that it was not feasible as it was difficult to find a suitable height to mount the camera. In addition, it was impossible to tilt the camera at the correct angle to obtain a good view of the full length of the left turn lane. Having a good view of the approaches and the full left turn lane length was very important in determining the phasing plan and verifying the signal timing.

The study sites were thus selected according to the following criteria in order to fully evaluate the capacity of the software to model traffic under varying operating conditions.

- Study sites should vary in the number of left turn lanes. Thus, the intersections selected consisted of both single and dual left turn lanes.
- Study sites should operate under different degree of saturation, therefore study sites ranging from v/c < 1 to v/c >1 were selected.
- Study sites should have mounted video cameras on each approach.

4.2 Selected Study Sites

The City of Albuquerque, as of the time of data collection, did not have intersections with video cameras; intersections in the City of Rio Rancho which met the criteria were thus identified and selected. Rio Rancho is the largest city in Sandoval County and is the third largest and fastest growing city in the state and was the only jurisdiction at the time of the data collection which was collecting acceptable traffic camera data.

Four intersections were identified and selected. Three of the intersections are actuated coordinated along NM528, and are identified in Figures 4-1 through Figures 4-4. The three intersections that were modeled are:

1. NM528 & Southern
2. NM528 & Sara
3. NM528 & Westside

The fourth intersection modeled is an actuated uncoordinated location shown in Figure 4-5.

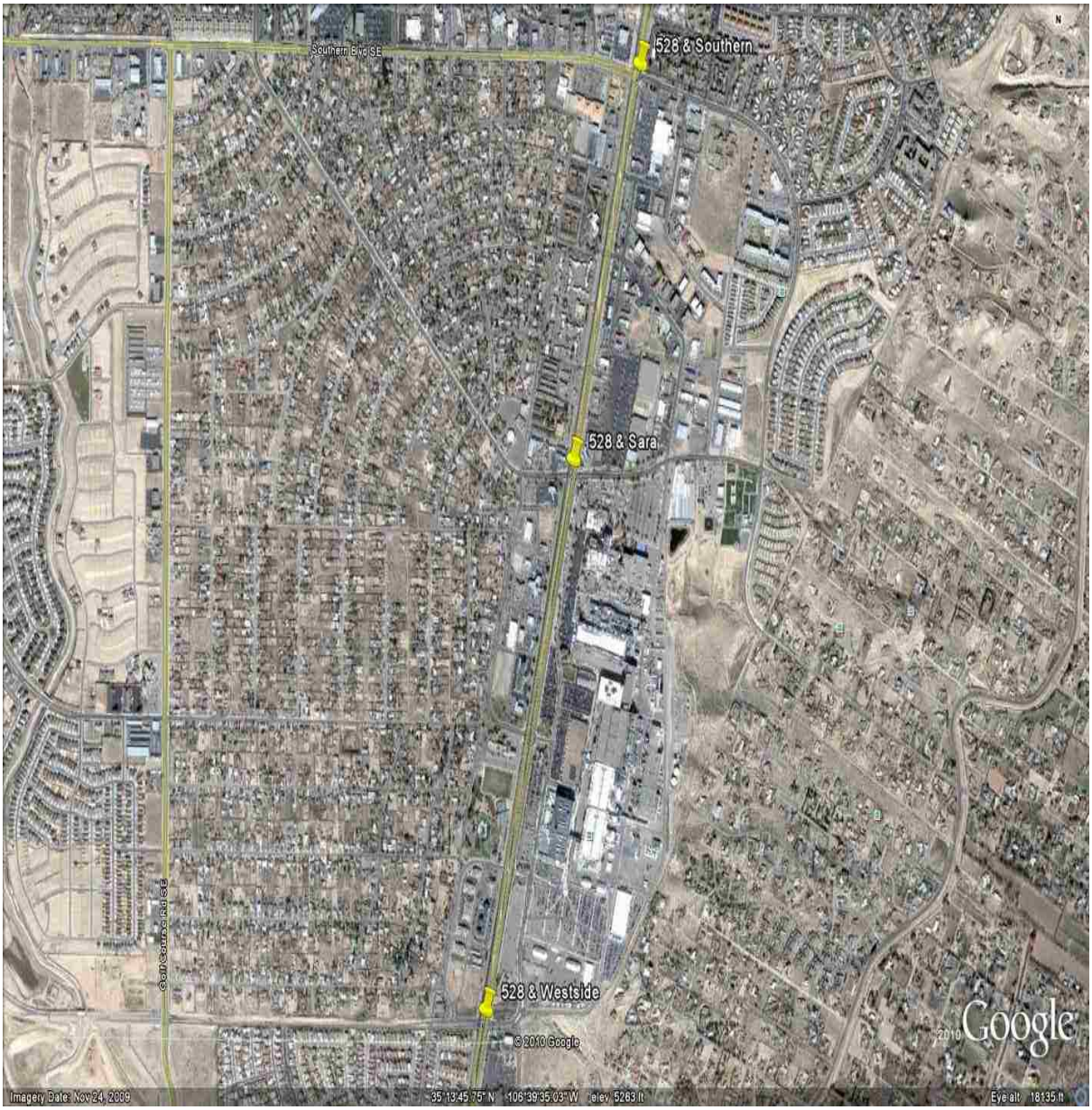

Figure 4-1: Selected Intersections Along NM528
Source: Google Earth

4.2.1 NM528 & Westside Boulevard

NM528 & Westside is an actuated cordinated four-legged intersection. The North and South approaches have dual left turn lanes, four through lanes and one right turn lane. The East approach has a dual left turn lane, one through lane and one right turn. The West approach has a dual left turn lane, two through lanes and one right turn lane. The intersection operates on a 108 second cycle length during the morning peak and a 126 second evening peak cycle length. The left turns move on a protected phase and right turns are permitted through the entire cycle.

Figure 4-2 below shows the geometry of the intersection.

Figure 4-2: NM528 & Westside Boulevard Intersection
Source: Google Earth

4.2.2 NM528 & Southern Boulevard

NM528 & Southern Boulevard is also an actuated cordinated intersection which operates on a 108 second cycle during the morning peak and a 126 second cycle during the evening peak period. The North approach has one left turn lane, three through lanes, and one right turn lane and the South aprroach has three through lanes, a dual left turn lane and a channelized right turn lane. The East approach has two through lanes, a dual left turn lane and one right turn lane while the West approach has one through lane, a dual left turn lane and one right turn lane. The left turning vehicles move on protected-permitted phasing and right turns are permitted throughout the cycle. The geometry of the intersection is shown in the figure below.

Figure 4-3: NM528 & Southern Boulevard Intersection
Source: Google Earth

4.2.3 NM528 & Sara

This intersection is also an actuated cordinated intersection along NM528 which operates on a cycle length of 108 seconds during the morning peak and 126 seconds during the evening peak. Sara Road, the East-West street, has one through lane, a dual left turn lane and one channelized right turn on the East approach. The West approach has one through, one left and one channelized right turn. Both the North and South approaches have three through lanes, one long left turn lane and one channelized right turn lane. The figure below shows the geometry of the intersection.

Figure 4-4: NM528 (N/S) & Sara Rd Intersection
Source: Google Earth

4.2.4 Broadmoor & High Resort

Broadmoor & High Resort is an actuated, uncoordinated signal-controlled intersection with a 96 second cycle length. The North approach has three lanes with one through, one left turn and one right turn lane while the South approach has one shared through and right turn lane and one left turn lane. The East approach has one through lane, one left turn lane, and one right turn lane and the West approach has one shared lane for through, left and right turns. The geometry showing the layout is in the figure below.

Figure 4-5: Broadmoor (N/S) & 7 Falls Dr. /High Resort Blvd Intersection
Source: Google Earth

4.3 Data Collection

To accomplish the objectives of this thesis, data were collected for the purpose of evaluating the selected packages in terms of their ability to replicate observed queue lengths. This section discusses the data to be collected and the determination of maximum observed queues.

4.3.1 Data Required

Data required for the left turn modeling included the number of vehicles queued at the end of the red time (maximum observed queue), geometric data, traffic data, and signal timing/phasing data. The following describes the variables that were collected each for of the data parameters required.

Geometric data

- Lane type (shared or exclusive)
- Number of lanes
- Lane width and lane length
- Left turn storage length

Traffic data

- Lane volume
- Percent of heavy vehicles

Signal phasing and timing data

- Left turn phasing (protected, permitted, protected-permitted)
- Splits and phasing
- Cycle length

4.3.2 Data Collection Procedure

The City of Rio Rancho has video cameras installed at the selected intersections for basic traffic detection purposes. Though most of the cameras were fixed, some had pan/tilt/zoom (PTZ) capabilities, allowing for a better view of queue lengths. Data were collected by attaching a multi-channel video recorder to the video-out feed in each intersection's controller box. A simple plug-in and an identification of the desired time period allowed the simultaneous recording of all four approaches at each selected intersection location. Data at successive intersections were collected by simply unplugging the recorder and moving it to the next intersection. With the exception of the intersection at Broadmoor and High Resort, data were collected at the three sites along NM528 for seven consecutive days.

Time stamps on the video camera made it possible to obtain the phasing and timing data and the actual green and yellow intervals were recorded. Since the signal control was actuated, the average timings recorded over several cycles were used in the analysis. Some geometric data information was obtained through the video but a field visit was also made to measure left turn storage lengths. Lane width was assumed to be 12 feet.

For traffic data information, each approach was divided into lane groups. Exclusive left and right turn lanes were treated as separate lane groups. Shared lanes were treated as one lane group. Traffic volume counts were obtained by manually counting the left turn volume while watching the video camera in the UNM traffic engineering lab. For the purposes of the study, only the left turn volume was counted. The number of lanes, in addition to the amount of through volume, made it is difficult to count other movements. Since the analysis of each lane group did not impact the result of the other lane groups, it was not

necessary to use the prevailing current volume of all the lane groups. Therefore, through volumes used were those from 2008 obtained from the traffic management center of the Department of Public Works in Rio Rancho, the jurisdiction responsible for managing the study sites. The 2008 volume data were the most current available.

Data were extracted from the recorder at the three intersections for morning and afternoon/evening peak periods between 6:00-10:00 am and 3:00-8:00 pm, respectively. For the analysis, only data collected between 7:00-9:30 am and 4:00-6:30 pm were analyzed.

The setup of Broadmoor and High Resort did not allow for video data to be collected utilizing a video camera and recorder, hence data were manually collected. In addition to the data needs mentioned earlier, data collected at this intersection included turning movement counts on all approaches for morning (6:00-8:30 am) and afternoon (2:00-3:30 pm) peak periods. The turning movement counts were collected using a Jamar counter. Maximum queue lengths were also collected. The intersection has a school located on its southbound approach; this influenced the time period for the data collection.

4.4 Data Reduction

The recorded data were reviewed in the traffic laboratory for the best quality video on all approach lanes as well as for the full extent of the left turn lane. This was very important in order to count the total number of left turning vehicles queued during any given period. The approaches that offered the best images were selected. The table below summarizes the selected approaches of the intersections along NM528.

Table 4-1: Intersection Approaches and Times for Analysis

Location	Times	Approaches
NM528& Westside	6:00-8:30 AM	SB LT
		WB LT
	4:00-6:30 PM	WB LT
		NB LT
NM528 & Sara	6:00-8:30 AM	SB LT
		NB LT
	4:00-6:30 PM	SB LT
		NB LT
NM528& Southern	6:00-8:30 AM	EB LT
		SB LT
	4:00-6:30 PM	EB LT
		SB LT

The selected approaches were critically examined for the various traffic items outlined below:

- The number of left turning vehicles in the lane at the beginning of green (end of red interval).
- The number of left turning vehicles arriving after the start of green (this volume, in addition to the vehicles in the queue at the end of the red interval, was used to calculate the peak hour volume and the peak hour factor (PHF).
- The effective green time (a time stamp on video made it possible to calculate this item).
- The number of vehicles remaining, if any, at the end of effective green time.
- The phasing and split information for each movement.

The volume data were summed in 15 minute intervals in order to calculate the peak hour volume and PHF. An Excel spreadsheet was used for processing the data collected at the various selected approaches. An example of the Excel program developed is shown in the table below for one of the intersection approaches.

Table 4-2: Processed Data for NM528 & Southern

Location:	NM528 & Southern							
Approach:	EB Left AM							
Time @ Start of LT Green	Number in Queue		Time @ End of LT Green	Effective green time	Number in Queue at the end of green(Spillover)		Number that arrive after start of Green	Total number that pass on green
	Lane 1	Lane 2			Lane 1	Lane 2		
	(shoulder)	(median)			(shoulder)	(median)		
7:00:09	4	3	7:00:29	0:00:20	0	0	1	8
7:01:57	4	2	7:02:16	0:00:19	0	0	0	6
7:03:44	4	4	7:04:03	0:00:19	0	0	0	8
7:05:33	2	1	7:05:47	0:00:14	0	0	1	4
7:07:20	5	6	7:07:46	0:00:26	0	0	0	11
7:09:08	4	1	7:09:30	0:00:22	0	0	0	5
7:10:58	6	6	7:11:17	0:00:19	0	0	0	12
7:12:45	5	5	7:13:05	0:00:20	0	0	0	10
7:14:33	3	4	7:14:52	0:00:19	0	0	1	8

TABLE 4-2 shows that for NM 528 and Southern EB left turning vehicles, when the signal turned green at 7:00:09, there were 4 vehicles in the shoulder lane and 3 vehicles in the median lane as indicated in columns 2 and 3. At the end of the green time at 7:00:29 (an effective green time of 20 seconds), column 5 shows there were 0 vehicles in both shoulder and median lanes implying that all vehicles queued during the red interval went through the intersection. In addition, one vehicle arrived after the start of green and went through the

intersection after the start of green. A total of 8 left turning vehicles were thus served during this movement.

The table also indicates lane utilization by comparing the number of vehicles in the lanes was determined from columns 3 and 4 and the total number of vehicles that cleared the intersection determined from column 9; the 15 minute volume, peak hour volume and peak hour factor may thus be computed. Queue carryover was also determined from columns 6 and 7. Maximum queue lengths were determined from either column 2 or 3; for a dual left turn lane, the longer of the two lanes was selected. The maximum queue observed on the field was used as a benchmark for comparing model queues.

4.4.1 Data Processing

The maximum observed queues (MOQ) were determined for each of the approaches for the morning and evening peak periods. Maximum queue length (MOQ), as defined in Chapter 2, is the number of vehicles queued at the beginning of the green time (end of red interval). For approaches with dual left turn lanes, the queue length was for the lane with the longer queue. Queue carryovers and volume to capacity (v/c) ratios were also computed for each of the approaches for both peak periods. Queue carryover is the proportion of cycles within the analysis period for which queues did not clear in one cycle and had to be carried over to the next cycle.

Table 4-3 on the next page shows queue carryover for the different periods analyzed and its associated movement type.

Table 4-3: Maximum Observed Queue (MOQ)

Intersection	LT Movement/Period	MOQ (vehicles)	Queue Carryover (%)	Movement Type	Peak Hour v/c
NM528 & Southern	EB/AM	12#	1.5	Protected	0.83
	SB/AM	15	41.17	Protected	0.85
	EB/PM	13#	18.0	Protected	1.04
	SB/PM	12	11.1	Protected	0.94
NM528 & Sara	SB/AM	2	0	Protected/ Permitted	0.17
	NB/AM	8	1.0	Protected/ Permitted	0.82
	SB/PM	3	0	Protected/ Permitted	0.23
	NB/PM	24	1.3	Protected/ Permitted	1.12
NM528 & Westside	SB/AM	4#	0	Protected	0.32
	WB/AM	3#	0	Protected	0.31
	WB/PM	5#	0	Protected	0.51
	NB/PM	14#	2.8	Protected	0.73

#: Longer queue of the two lanes

On both single and dual left turn approaches operating under free flowing and stable traffic conditions i.e. v/c ≤ 0.34 (LOS A) and v/c ratios between 0.35 and 0.51(LOS B), there are no queue carryovers which is consistent with the level of service that is expected under such conditions (29). For v/c ratios ranging between 0.74 and 0.89, which depicts unstable conditions and occasional cycle failures (LOS D), the queue carryovers are consistent with the prevailing conditions. However the carryover at NM528 & Southern SB/AM was very

high in relation to its degree of saturation. A review of the recorded video indicated a stalled vehicle at the beginning of the left turn queue. For that cycle, this stalled vehicle was the only vehicle that went through the intersection causing the rest of the vehicles to wait to be served in the next cycle. This led to a spillover of the previous cycles to the subsequent cycles through the analysis period hence the high percentage of queue carryover. For approaches with v/c between 0.94 and 0.99 (LOS E), there was a queue carryover, as expected, as well as for approaches operating over capacity i.e. v/c >1.0.

With the exception of a high queue carryover which occurred on NM528 & Southern SB/AM, due to the stalled vehicle, the percentage of queue carryovers are consistent with the degree of saturation on the approaches.

NM528 & Sara NB/PM, which has a high v/c ratio of 1.12, had a carryover as low as 1.3. This may be due to the movement type which is protected / permitted and therefore permits vehicles to move on both green arrow and green ball. In addition to the movement type, this left turning movement had a long effective green time which may explain why it seems to have a low queue carryover.

4.5 Left Turn Modeling

Each of the intersections was modeled with the selected traffic models by entering data pertaining to their respective geometry, signal timing, and traffic parameters.

For TEAPAC, HCS+ and Synchro, which are macroscopic models, left turn queues were obtained immediately after the coding. For SimTraffic, Synchro's data input formed the basis for analysis. Thus data pertaining to the geometry, signal phasing and timing, and traffic data were not coded but obtained from Synchro data input. Default parameters in

SimTraffic were used; no calibration was done in this study. SimTraffic data were run 10 times and results averaged to obtain left turn queues.

4.5.1 Determination of Model Queue Lengths

The geometric, signal, and traffic data items were coded into each software to determine the left turn queues. A sample calculation of the left turn queue for EB and SB approaches on NM528 & Southern using HCS+ is shown in Table 4-4. For these approaches, all left turning vehicles move on a protected phase. The EB approach is a dual left turn with an AM peak hour volume of 403 vehicles per hour and the SB approach is a single left turn lane with an AM peak hour volume of 147 vehicles per hour.

4.5.2 Comparison of Left Turn Queues

Traffic model outputs from each of the models were compared with the maximum observed queue lengths. Comparisons were made by pairing model output with corresponding observed queue lengths. Absolute differences in the observations were obtained and t-tests were performed on these differences. Comparisons were also made between the macroscopic model outputs using regression analysis. The details of the comparisons made and the results of the statistical tests are discussed in detail in chapter 5.

Table 4-4: Sample of HCS+ Back-of-Queue Worksheet - NM528 & Southern AM Peak

BACK-OF-QUEUE WORKSHEET												
General Information: NM528 & Southern												
Project Description: Left Turn Queue Modeling												
Average Back of Queue: AM Peak												
	EB			WB			NB			SB		
	LT	TH	RT	LT	TH	RT	LT	TH	RT	LT	TH	RT
Lane Group	L	T	R	L	T	R	L	T	R	L	T	R
Initial Queue/Lane	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Flow Rate/Lane Group	537	152	241	44	88	109	203	1084	2	167	1624	255
Satflow/Lane	1770	1863	1583	1770	1863	1583	1770	1862	1583	1770	1862	1583
Capacity/Lane Group	649	492	690	127	209	287	369	1560	696	172	2250	1082
Flow Ratio	0.2	0.1	0.2	0.0	0.0	0.1	0.1	0.3	0.0	0.1	0.3	0.2
v/c Ratio	0.83	0.31	0.35	0.35	0.42	0.38	0.55	0.69	0.00	0.97	0.72	0.24
I Factor	1.000	1.000	1.000	1.000	1.000	1.000	0.942	0.942	0.942	0.839	0.839	0.839
Arrival Type	3	3	3	3	3	3	3	5	6	3	4	5
Platoon Ratio	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.67	2.00	1.00	1.33	1.39
PF Factor	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.67	0.22	1.00	0.87	0.17
Q1	8.0	3.7	4.8	0.6	2.5	2.9	3.0	9.3	0.0	5.0	12.8	0.5
Kb	0.4	0.5	0.6	0.2	0.3	0.4	0.3	1.1	1.0	0.3	1.1	0.8
Q2	1.6	0.2	0.3	0.1	0.2	0.2	0.3	2.4	0.0	2.1	2.7	0.2
Q Average	9.5	3.9	5.1	0.7	2.7	3.1	3.3	11.7	0.0	7.1	15.5	0.7
Percentile Back of Queue (95th percentile)												
fB%	1.9	2.0	2.0	2.1	2.0	2.0	2.0	1.7	2.6	1.9	1.6	2.1
Back of Queue	17.6	7.7	10.0	1.5	5.4	6.2	6.6	19.8	0.0	13.5	25.4	1.5
Queue Storage Ratio												
Queue Spacing	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0
Queue Storage	252	0	0	135	0	0	512	0	800	233	0	260
Average Queue Storage Ratio	0.9			0.1			0.2		0.0	0.7		0.1
95% Queue Storage Ratio	1.8			0.3			0.3		0.0	1.4		0.1

CHAPTER 5

DATA ANALYSIS

This chapter compares the model estimated queues to the field measured maximum observed queues (MOQ). Tables 5-1, 5-2, 5-3 and 5-4 show the comparison between queues estimated by HCS+, Synchro, TEAPAC and SimTraffic. Each table shows the queue estimated by the specific model, the MOQ, and the difference, in number of vehicles, between model estimates and MOQ. V/c ratios are also shown in the tables. One case, NM528 & Sara, NB PM, will not be analyzed because the MOQ does not represent the exact number of vehicles queued during the evening peak period due to poor video quality at that time. It was observed, however, that this left turn approach was filled to capacity and overflowed into the adjacent through lane.

5.1 HCS+ Queue Estimates

HCS+ estimates maximum back of queue. Maximum back of queue is the number of vehicles queued at the beginning of the green in addition to the number of vehicles that join the queue after the start of the green. Thus, HCS+ queue estimates include slowing vehicles in addition to stopped vehicles until the vehicles fully clear the intersection. It was therefore expected that HCS+ queue estimates would be longer than the maximum observed queue-the number of vehicles queued at the beginning of green. HCS+ 95th percentile queues are shown in Table 5-1.

Table 5-1: HCS+ vs. Maximum Observed Queues

Intersection and Approach	v/c	95th HCS+ (vehicles)	MOQ (vehicles)	Veh. Diff.
NM528 & Southern, EB AM	0.83	18	12	+6
NM528 & Southern, SB AM	0.85	14	15	-1
NM528 & Southern, EB PM	1.04	23	13	+10
NM528 & Southern, SB PM	0.94	22	12	+10
NM528 & Sara, SB AM	0.17	2	2	0
NM528 & Sara, NB AM	0.82	9	8	+1
NM528 & Sara, SB PM	0.23	2	3	-1
NM528 & Sara, NB PM	1.12	34	24#	+10
NM528 & Westside, WB AM	0.31	3	3	0
NM528 & Westside, SB AM	0.32	2	4	-2
NM528 & Westside, WB PM	0.51	6	5	+1
NM528 & Westside, NB PM	0.73	17	14	+3

As shown in the table, the estimated queue lengths compared favorably with the observed queue lengths for approaches operating under low congestion (v/c < 0.5). Under these conditions, HCS+ underestimated queue lengths by a maximum of 2 vehicles and overestimated by a maximum of 1 vehicle while it estimated queue lengths exactly in two cases.

HCS+, however, performed poorly under high to over saturated (v/c = 0.85 to > 1.0) traffic conditions where, in some cases it overestimated queue lengths by up to 10 vehicles.

5.2 Synchro Queue Estimates

Synchro also estimates maximum back of queue but, unlike HCS+, it considers vehicles that are delayed 6 seconds or more that join the queue after the start of green in addition to the vehicles queued at the beginning of green. Synchro estimates both 50th and 95th percentile queues. Table 5-2 compares Synchro 95th percentile queues to the MOQ and also shows the difference in vehicles between Synchro's estimated queues and observed queue lengths. Also shown in the table are the v/c ratios for each of the approaches.

Table 5-2: Synchro vs. Maximum Observed Queues

Intersection and Approach	v/c	95th Synchro (vehicles)	MOQ (vehicles)	Veh. Diff.
NM528 & Southern, EB AM	0.83	8	12	-4
NM528 & Southern, SB AM	0.85	9	15	-6
NM528 & Southern, EB PM	1.04	13	13	0
NM528 & Southern, SB PM	0.94	13	12	+1
NM528 & Sara, SB AM	0.17	1	2	-1
NM528 & Sara, NB AM	0.82	7	8	-1
NM528 & Sara, SB PM	0.23	1	3	-2
NM528 & Sara, NB PM	1.12	30	24#	+6
NM528 & Westside, WB AM	0.31	2	3	-1
NM528 & Westside, SB AM	0.32	2	4	-2
NM528 & Westside, WB PM	0.51	4	5	-1
NM528 & Westside, NB PM	0.73	10	14	-4

Synchro underestimated queues in both under-saturated and near-saturated conditions, that is v/c ratios ≤ 0.85. However, it did estimate an exact queue length for NM528 & Southern EB during the evening peak period with v/c = 1.04 and overestimated for the SB approach during the evening peak period by only 1 vehicle. Overall, Synchro both overestimated and underestimated queue lengths up to by a maximum of 6 vehicles. Unlike HCS+, where there was a clear relationship between queue lengths and traffic congestion level, there is no such relationship with the Synchro results.

5.3 SIGNAL2000/TEAPAC Queue Estimates

Table 5-3 compares SIGNAL2000/TEAPAC's 90th percentile queue lengths with the observed queue lengths. Also shown in the table are the differences (in vehicles) between SIGNAL2000/TEAPAC's estimates and observed queue lengths and the v/c ratio for the approaches.

Table 5-3: TEAPAC vs. Maximum Observed Queues

Intersection and Approach	v/c	90th TEAPAC (vehicles)	MOQ (vehicles)	Veh. Diff.
NM528 & Southern, EB AM	0.83	13	12	+1
NM528 & Southern, SB AM	0.85	9	15	-6
NM528 & Southern, EB PM	1.04	15	13	+2
NM528 & Southern, SB PM	0.94	16	12	+4
NM528 & Sara, SB AM	0.17	2	2	0
NM528 & Sara, NB AM	0.82	8	8	0
NM528 & Sara, SB PM	0.23	1	3	-2
NM528 & Sara, NB PM	1.12	33	24#	+9
NM528 & Westside, WB AM	0.31	2	3	-1
NM528 & Westside, SB AM	0.32	2	4	-2
NM528 & Westside, WB PM	0.51	5	5	0
NM528 & Westside, NB PM	0.73	15	14	+1

For five of the cases operating under low saturated conditions, i.e. v/c $\leq$ 0.50, SIGNAL2000 underestimated queue lengths by a maximum of 2 vehicles in three of the cases while comparing favorably with the other two approaches operating under low saturated conditions. For conditions approaching saturation i. e. v/c > 0.85, TEAPAC overestimated queues by a maximum of four vehicles except for one case where it reported same queue lengths as the observed and underestimated by a maximum of six vehicles. However, under oversaturated conditions, TEAPAC overestimated by a maximum of 2 vehicles.

On the whole, all of the macroscopic models overestimated under oversaturated conditions.

5.4 SimTraffic Estimated Queues

SimTraffic is a microscopic model and differs from HCS+, Synchro, and TEAPAC which are macroscopic models. Unlike macroscopic models, which reproduce the same results each time when coded with the same input data, SimTraffic, a microscopic model, will produce different results with the same input each time it is run. This is due to the fact that a microscopic model, while emulating real world conditions, assigns different driver and vehicle characteristics each time the model is run. Driver characteristics includes driver aggressiveness and vehicle characteristics which include the type and percentage of vehicle types created each time the model is run. Microscopic models, therefore, need to be run a number of times and the results averaged.

In queue length modeling with SimTraffic, the manual suggests two possible ways of running the analysis that may replicate observed queues:

1. The analyst adjusts traffic volumes to 95th percentile volume and simulates the model for a time interval such as the cycle length, or

2. The analyst runs the model for an hour without any volume adjustment. The assumption with this second scenario is that traffic volume will peak to a 95th percentile within the one hour period.

Both scenarios were modeled in this research. In addition to the above scenarios outlined in the SimTraffic manual, a third scenario was studied in which SimTraffic was run with an unadjusted traffic volume either for the PHF or the 95th percentile for 10 minutes as suggested by the default settings in SimTraffic.

The results of these three scenarios are shown in Table 5-4. The table shows the estimated queue length for each of the scenarios run, the MOQ and the v/c ratios on each approach. A comparison was also made between the 95th percentile queues and the observed queue length.

The estimated queues shown in the table are average queues reported over 10 separate runs.

Table 5-4: SimTraffic Queues vs. Observed Queues

Intersection and Approach	v/c	95th SimTraffic Queue (vehicles)			MOQ (vehicles)	Best SimTraffic Analysis
		Unadjusted Volumes, (10 minutes) (1)	95th %ile adjusted volume,(2 minutes) (2)	Unadjusted Volumes, (1hour) (3)		
NM528 & Southern, EB AM	0.83	10	12	10	12	(2)
NM528 & Southern, SB AM	0.85	9	16	9	15	(2)
NM528 & Southern, EB PM	1.04	16	15	16	13	(2)
NM528 & Southern, SB PM	0.94	13	14	13	12	(1), (3)
NM528 & Sara, SB AM	0.17	3	2	3	2	(1), (2), (3)
NM528 & Sara, NB AM	0.82	10	11	8	8	(3)
NM528 & Sara, SB PM	0.23	5	5	5	3	(1), (2), (3)
NM528 & Sara, NB PM	1.12	34	33	48	24#	(2)
NM528 & Westside, WB AM	0.31	3	4	3	3	(1), (3)
NM528 & Westside, SB AM	0.32	2	3	2	4	(2)
NM528 & Westside, WB PM	0.51	6	5	4	5	(1), (2)
NM528 & Westside, NB PM	0.73	12	17	12	14	(1), (3)

Column 3 shows the 95th percentile queues reported for traffic volumes unadjusted for the PHF or the 95th percentile volume and simulated for 10 minutes (the SimTraffic default simulation time). Running the model under this scenario produced 6 overestimated queues, 5 underestimated queues and 1 exact queue when compared to actual queue lengths.

Column 4 shows the 95th percentile queue reported for traffic volumes adjusted for the 95th percentile volume and simulated for a 2 minute time interval. The 2 minute simulation time interval is approximately the cycle length of the intersections modeled in this study. The AM and PM peak periods operate for cycle lengths of 108 and 126 seconds respectively. Estimated queue lengths for this scenario produced better queue lengths. It estimated 3 queues which are as observed in the field and overestimated in the rest of the cases by a maximum of 3 vehicles.

Column 5 shows SimTraffic's 95th percentile queues for traffic volume unadjusted for the peak hour factor or the 95th percentile volume and simulated for 1 hour. This is the second option suggested by Trafficware for modeling queue lengths. Queue estimates from this scenario compare favorably with queue lengths reported from the 10 minute simulation. This scenario reported exact queue lengths as observed in the field for 2 of the cases, underestimated queues in 6 of the cases and overestimated queue lengths in the remaining 3 cases.

Column 7 indicates the scenario that produced the best queue lengths when compared to the actual observed queues. In the queue lengths shown in columns 3 and 5, the simulation run for unadjusted traffic volume compares closely with each of the others in 8 out of the 12 simulations run.

The simulation results for the 2 minute time interval, on the other hand, compared favorably with the MOQ in 7 of the 12 cases, with a maximum of 3 vehicles overestimated. Queue lengths estimated under this scenario produced only one underestimated queue length.

5.5 Summary of Model Estimated Queue Lengths

A summary of the models used for estimating queue lengths is shown in Table 5-5. The bold numbers indicate the model queue lengths that most closely match actual queue lengths. In the table, SimTraffic's 95th percentile queue lengths estimated for a 2 minute time interval with 95th percentile adjusted volume is compared. In cases where there was no clear best estimated queue length, for example in the case one model overestimated by 1 or 2 vehicles while another model underestimated in the by 1 or 2 vehicles for the same approach, in relation to actual queue length, both queue lengths were considered best estimates.

Table 5-5: Queue Length Comparison -Models vs. MOQ (vehicles)

Intersection and Approach	v/c	Macroscopic			Microscopic	MOQ
		95th HCS+	95th Synchro	90th TEAPAC	95th SimTraffic (2)	
NM528 & Southern, EB AM	0.83	18	8	13	**12**	12
NM528 & Southern, SB AM	0.85	**14**	9	9	**16**	15
NM528 & Southern, EB PM	1.04	23	**13**	15	15	13
NM528 & Southern, SB PM	0.94	22	**13**	16	14	12
NM528 & Sara, SB AM	0.17	**2**	1	**2**	3	2
NM528 & Sara, NB AM	0.82	9	7	**8**	**8**	8
NM528 & Sara, SB PM	0.23	**2**	1	1	**5**	3
NM528 & Sara, NB PM	1.12	34	**30**	37	33	24
NM528 & Westside, WB AM	0.31	**3**	2	2	4	3
NM528 & Westside, SB AM	0.32	2	2	2	**3**	4
NM528 & Westside, WB PM	0.51	6	4	**5**	6	5
NM528 & Westside, NB PM	0.73	17	10	**15**	17	14
Score		4	3	4	5	
Accuracy		67.00%	69.36%	74.30%	75.61%	

Also included in the table are two criteria ‘Score’ and ‘Accuracy’, used in evaluating the performance of the models in replicating the observed queue. This method of evaluation is adopted from a study conducted by Yu et. al. (3) in evaluating traffic models in left turn queue modeling. In the table, each model is given a score basically indicating the number of times the model gives the best prediction relative to the other models. As can be seen from the table, Synchro predicted relatively close estimates in only three of the cases modeled, while HCS+, TEAPAC and SimTraffic (2) each predicted 4 queue lengths which closely matched actual field queue lengths.

The second criterion, ‘accuracy’, measures the level of precision of the model estimate to the actual queue length. Accuracy is calculated by the formula below:

$$\text{Accuracy} = 1\text{-ave}\left(\frac{L_m - L}{L}\right) * 100\% \qquad \text{(Eq.5-1)}$$

Where:

L_m = queue length predicted by traffic model

L = observed queue length

In terms of precision, SimTraffic (2), the simulation run for a 2 minute time interval with 95th percentile adjusted volume, predicted close estimates over 75% of the time, followed by TEAPAC’s 90th percentile queues. Synchro, which also calculates maximum back of queue similar to HCS+, was the next most accurate by predicting queues 69% of the time while HCS+ was 67% accurate.

Another evaluation measure was to determine the tendency of a selected model to over or underestimate queue lengths on average. The tables below show the comparison between the models and the number of cases in which they either over or underestimated queues. This evaluation is made for the total number of vehicles observed and estimated for each peak period on each approach. For example, the total number of vehicles observed during the AM peak period for NM528 & Southern is 27 and the total estimated by HCS+ for that same approach and same time period is 32. Each intersection is analyzed separately.

Table 5-6: Model Performance for NM528 & Southern Intersection

Intersection	Peak Period	MOQ	Macroscopic			Microscopic
			95th HCS+	95th Synchro	90th TEAPAC	95th SimTraffic (2)
NM528 & Southern	AM	27	32	17	22	28
			+5	-10	-5	+1
	PM	25	45	26	31	29
			+20	+1	+6	+4
Model performance			**+25**	**-9**	**+1**	**+5**

With the exception of Synchro, which underestimated queue lengths overall at this intersection, the other models all overestimated queue lengths with HCS+ reporting 25 more vehicles than the actual queue observed at this intersection. SimTraffic also overestimated but with only 5 more vehicles compared to the actual observed queue.

Table 5-7: Model Performance for NM528 & Sara Intersection

Intersection	Peak Period	MOQ	Macroscopic			Microscopic
			95th HCS+	95th Synchro	90th TEAPAC	95th SimTraffic (2)
NM528 & Sara	AM	10	11	8	10	11
			1	-2	0	1
	PM	3	2	1	1	5
			-1	-2	-2	2
Model Performance			**0**	**-4**	**-2**	**+3**

At NM528 & Sara, as shown in Table 5-8, the models predicted results comparable to actual queues for the AM peak. TEAPAC reported exact queue lengths while HCS+ and SimTraffic overestimated by 1 vehicle. Synchro, however, underestimated by two vehicles. The PM peak was not analyzed for this intersection due to poor video quality hence the actual number of left turning vehicles could not be accurately estimated.

Table 5-8: Model Performance for NM528 & Westside Intersection

Intersection	Peak Period	MOQ	Macroscopic			Microscopic
			95th HCS+	95th Synchro	90th TEAPAC	95th SimTraffic (2)
NM528 & Westside	AM	7	5	4	4	7
			-2	-3	-3	0
	PM	19	23	14	20	23
			+4	-5	+1	+4
Model Performance			**+2**	**-8**	**-2**	**+4**

For the AM Peak period at NM 528 & Westside, all the models, with the exception of SimTraffic, underestimated queue lengths. Synchro was the only model to underestimate queue lengths during the PM peak period. On the whole, HCS+ underestimated during the AM peak and overestimated during the PM peak, Synchro underestimated in both

AM and PM peak periods, TEAPAC underestimated during the AM peak and overestimated during the PM peak period while SimTraffic overestimated during the PM peak and estimated exact queue lengths during the AM peak period.

Table 5-9 below summarizes the overall performance of the models.

Table 5-9: Overall Model Performance

Intersection	Peak Period	MOQ	Macroscopic			Microscopic
			95th HCS+	95th Synchro	90th TEAPAC	95th SimTraffic (2)
NM528 & Southern	AM	27	32	17	22	28
			+5	-10	-5	+1
	PM	25	45	26	31	29
			+20	+1	+6	+4
NM528 & Sara	AM	10	11	8	10	11
			+1	-2	0	+1
	PM	3	2	1	1	5
			-1	-2	-2	+2
NM528 & Westside	AM	7	5	4	4	7
			-2	-3	-3	0
	PM	19	23	14	20	23
			+4	-5	+1	+4
Overall performance			**+27**	**-21**	**-3**	**+12**

Overall, HCS+ overestimates the three intersections along NM 528 by 27 vehicles and SimTraffic also overestimated but by 12 vehicles. Synchro and TEAPAC underestimated by 21 and 3 vehicles respectively. The overall model performance does not include vehicles estimated during the PM peak period for NM528 & Sara.

Tables 5-10 indicates, on average, the tendency of a model to under or overestimate at these intersections.

Table 5-10: Model's Ability to Under/Over-Estimate Queue Lengths

Measure	Macroscopic			Microscopic
	95th HCS+	95th Synchro	90th TEAPAC	95th SimTraffic (2)
Net Vehicles Estimated (all approaches)	+27	-21	-3	+12
No. of Queues Overestimated	7	1	4	8
No. of Queues Underestimated	2	9	4	1
No. of Queues Exact	2	1	3	2
Average No. of Vehicles Over/Underestimated	2.5	-1.9	-0.3	1.1

Overall, HCS+ overestimated 7 out of 11 cases modeled, underestimated in 2 cases and predicted 2 exact queue lengths. Synchro, on the other hand, overestimated in only 1 case while it underestimated in 9 cases and predicted exact queue length in 1 case. TEAPAC overestimated as much as it underestimated and estimated 3 exact queue lengths. SimTraffic, however, overestimated in 8 cases and underestimated in only 1 while it predicted the same observed queue lengths in 2 of the cases modeled.

On average, HCS+ overestimated 2.5 vehicles per approach modeled. Similarly, SimTraffic also overestimated but on a lower scale than HCS+ with an average 1.1 vehicles per approach. Synchro and TEAPAC, however, underestimated with an average 1.9 and 0.3 vehicles per approach modeled.

5.6 Broadmoor and High Resort Intersection

This section discusses the fourth intersection, Broadmoor and High Resort. This intersection also had an existing video camera but was fixed and therefore did not allow for data recording; data were manually collected at this intersection. This intersection is signalized with protected left turn lanes on the WB, SB, and NB approaches and a shared through /left turn lane on the EB approach. Data were collected manually in the morning (6:30 to 8:00 am) and afternoon (2:00 to 3:30 pm) peak periods. The main traffic generator for this intersection is a nearby school; this influenced the selection of the data collection times and subsequent analysis periods.

Turning movement count and delay studies were also conducted at this intersection. The turning count was done with Jamar electronic counter. A maximum queue length of 12 vehicles was observed SB during the afternoon peak period. The table below shows the estimated queues by the traffic models versus the maximum observed queue.

Table 5-11: Queue Comparison at Broadmoor and High Resort

MOQ	Macroscopic			Microscopic
	95th HCS+	95th Synchro	90th TEAPAC	95th SimTraffic (2)
12	11	5	8	11

All the models underestimated actual queue length with Synchro underestimating by 7 vehicles and HCS+ and SimTraffic by only 1 vehicle.

5.7 Local Technical Practices

Also as part of this research, two locally developed methods for estimating left turn queues were examined - Harmon's and Harwick's procedures.

5.7.1 Harmon's Procedure

Harmon's procedure was developed in 1990 by Dave Harmon who was then a traffic engineer with the City of Albuquerque. This procedure was extensively used for left turn lane design for both new and retrofitted city-funded projects. Harmon's procedure is based on the Poisson distribution and left turn queues are computed with a Microsoft Excel spreadsheet. The inputs required per approach include peak hour volume, signal cycle length, and an assumed vehicle length, typically 25 feet. The program then calculates the average number of left turning vehicles per cycle and computes individual and cumulative Poisson probabilities, i.e. the probabilities of 0, 1, 2, 3… vehicles turning until the selected probability is reached. The average number of vehicles corresponding to the closest design probability is selected and multiplied by the vehicle length (25 ft) to determine the left turn lane length.

5.7.2 Harwick's Procedure

Nevin Harwick, a local Albuquerque traffic engineering consultant, developed this procedure while working in Seattle, WA (30). The method is usually applied in local traffic impact studies and for private clients. The method modifies the negative exponential relationship used in developing a 95th percentile queue. An assumption made in Harwick's method is that if all left turn lanes are operating with a green time less than 15% the cycle length, i.e. $g/c < 0.15$, then all left turning vehicles will arrive on the red and the queue length is the 95th percentile queue. However, if the left turn lanes operate with a green time

greater that 15%of the cycle, then the 95th percentile is adjusted by one-half of the green time. It is assumed in this case that the left turning vehicles have a greater chance of arriving on a green signal indication and thus will not experience signal control delay. The left turn queue length is estimated by the equation:

$Q_{LT} = Q_{95} * [1.00-(g/C)/2]$ (Eq. 5-2)

Where:

Q_{LT} = left turn queue adjusted for green time

Q_{95} = 95th percentile queue

g/C = green ratio

The current study also compared Harmon and Harwick procedures to the Maximum Observed Queues for the twelve cases previously described. The results are shown in Table 5-12.

TABLE 5-12: Local Practices Comparison (Vehicles)

Intersection and Approach	v/c	Harmon Q_{95}	Harwick Q_{LT}	MOQ
NM528 & Southern, EB AM	0.83	18	16	12
NM528 & Southern, SB AM	0.85	8	6	15
NM528 & Southern, EB PM	1.04	20	20*	13
NM528 & Southern, SB PM	0.94	12	11	12
NM528 & Sara, SB AM	0.17	3	2	2
NM528 & Sara, NB AM	0.82	9	6	8
NM528 & Sara, SB PM	0.23	3	2	3
NM528 & Sara, NB PM	1.12	26	17	24
NM528 & Westside, WB AM	0.31	3	3*	3
NM528 & Westside, SB AM	0.32	2	2*	4
NM528 & Westside, WB PM	0.51	7	5	5
NM528 & Westside, NB PM	0.73	19	17	14

* (g/C) < 15%

Both Harmon's and Harwick's methods produced similar queue lengths for left turn lanes operating with g/C ratios less than 0.15 of the signal cycle length. However, in cases with left turn lane g/C ratios greater than 0.15 of the signal cycle length, Harwick's queue lengths were less than that of Harmon's which is consistent with the Harwick assumption. Harmon's method produced comparable results with field observed queue lengths in four of the cases while Harwick's method produced 3 exact queue lengths compared to field queues.

5.8 Model Analysis Time

The time required to perform an analysis is also an important aspect to be considered in selecting a traffic model. The following times were required in performing the previously described analyses.

HCS+

HCS+ requires an average of 15 minutes for modeling left turn queues. HCS+ is a deterministic model hence model output is obtained immediately after the volume, timing, phasing, geometric, and traffic parameters are coded.

Synchro

An average of 20 minutes is required using Synchro. Required parameters for the left turn lane modeling are also volume, timing, phasing, traffic and geometry. Similar to HCS+, the queue is obtained directly once the required parameters are coded.

TEAPAC

An average of 20 minutes is required in TEAPAC to model queue lengths. They are calculated directly after the volume, timing, geometric, and traffic parameters are entered.

SimTraffic

The amount of time required for modeling queue lengths in SimTraffic varies depending on the size of the roadway network being analyzed and the speed of the computer. Time is also required for calibration which may depend on the site and the number of simulation runs to be performed. On average, SimTraffic may require an additional 10 to 20 minutes required for data coding in Synchro when analyzing a single intersection.

5.9 Data Analysis Summary

The following discussion is based on model estimated queue lengths obtained for the coordinated intersections along NM528.

Based on the ability to most closely match observed left turn queues (MOQ) at three signalized intersections, SimTraffic seems to perform better than HCS+, Synchro, or TEAPAC.

SimTraffic has the ability to accurately replicate Maximum Observed Queues, and seems to predict closer queue lengths than HCS+, Synchro, and TEAPAC based on the score and accuracy criteria defined in section 4.5 in determining the most accurate results.

This observation is based on several factors:

- SimTraffic most closely matched MOQ in four of the eleven cases examined and has the second best matches in five other cases modeled. In evaluating the models based on 'score', SimTraffic, HCS+ and TEAPAC each produced four queue lengths with the best comparable queue lengths. In terms of "accuracy", which measures the level of precision as previously described in earlier sections,

SimTraffic reports more precise queue lengths as observed in the field for 75 percent of the cases evaluated.

- TEAPAC was the next most accurate and obtained more precise results in 74.3 percent of the cases, followed by Synchro with a score of 69.3 percent and HCS+ with 67.0 percent. Although HCS+ had the same score as SimTraffic, HCS+ was the least accurate due to the fact that it produced higher queue lengths compared to the rest of the models.

A review at the results at the fourth intersection, for which camera data were not available, showed that SimTraffic most closely matched the manually observed queue.

Most of SimTraffic comparable results were obtained from an adjusted 95th percentile volume simulated for a short period of time.

Generally, most of the models performed poorly on intersections operating with over-saturated conditions.

The local procedures, when compared with observed queue lengths, produced comparable results. Harmon's method was more accurate than Harwick's which tends to reduce queue length assuming left turning vehicles arriving on green.

5.10 Comparison of Model Queue Length Estimates

The results of the model outputs were further analyzed to determine if there were significant differences in estimated queues between the macroscopic models. This was accomplished by making statistical comparisons by pairing the queues of HCS+, TEAPAC and Synchro. A paired t-test and regression analyses were performed and are discussed below.

5.10.1 t-test

A paired t-test was done to compare the mean queue length at a level of significance of 0.05 with the null hypothesis that there is no significant difference in the queue length estimated between HCS+ and TEAPAC, HCS+ and Synchro and also between TEAPAC and Synchro. The null hypothesis was rejected when p-value was less than the 0.05 significance level. Tables 5-13, 5-14 and 5.15 summarize the results of the t–test.

Table 5-13: t-test Result for HCS+ and TEAPAC

Model	Queue Length		t-statistic	t-table	p-value
	Mean	Variance			
HCS+	12.67	108.24	-2.508	-2.200	**0.029**
TEAPAC	10.42	102.27			

The calculated t-statistic is greater than t-table (p-value = 0.029) hence, we reject the null hypothesis at the 0.05 level of significance. There is a difference in mean queue length estimated between HCS+ and TEAPAC.

Table 5-14: t-test Result for HCS+ and Synchro

Model	Queue Length		t-statistic	t-table	p-value
	Mean	Variance			
HCS+	12.67	108.24	-3.978	-2.200	**0.002**
Synchro	8.33	65.88			

The t-statistic is greater than t-table (p-value = 0.002) hence, we reject the null hypothesis at a 0.05 level of significance. There is a difference in mean queue length estimated between HCS+ and Synchro.

Table 5-15: t-test Result for TEAPAC and Synchro

Model	Queue Length		t-statistic	t-table	p-value
	Mean	Variance			
TEAPAC	12.67	102.27	3.017	2.200	**0.011**
Synchro	8.33	65.88			

The t-statistic is greater than t-table (p-value = 0.011) hence, we reject the null hypothesis at a 0.05 level of significance. There is a difference in mean queue length estimated between TEAPAC and Synchro.

5.10.2 Regression Analysis

A regression analysis was performed to determine the relation between the macroscopic models evaluated in this study. The graphs that follow show the relationship between HCS+ and Synchro, HCS+ and TEAPAC, and Synchro and TEAPAC.

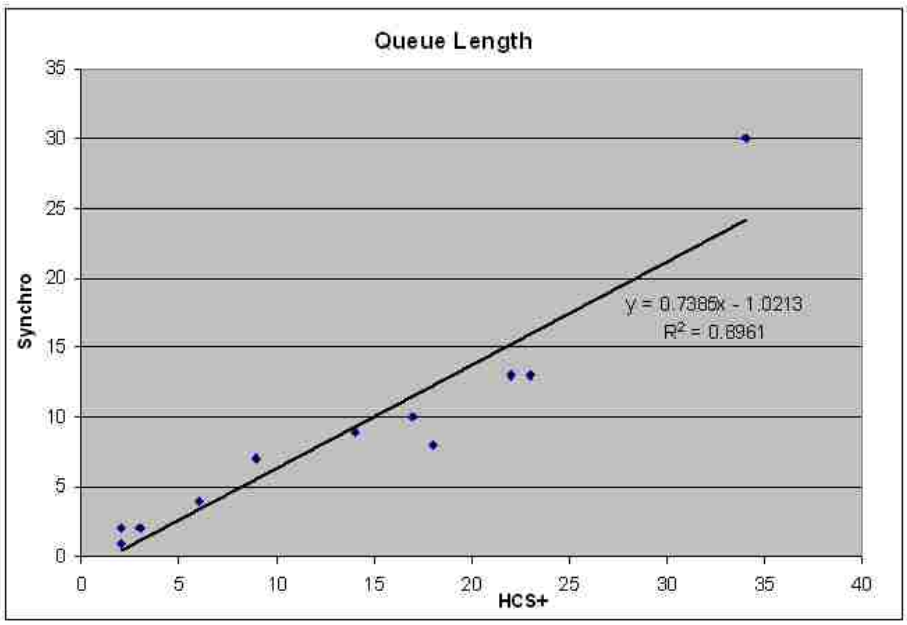

Figure 5-1: Comparison of Queue Lengths Estimated by HCS+ and Synchro.

Synchro underestimated queue length by 26% on average compared to HCS+.

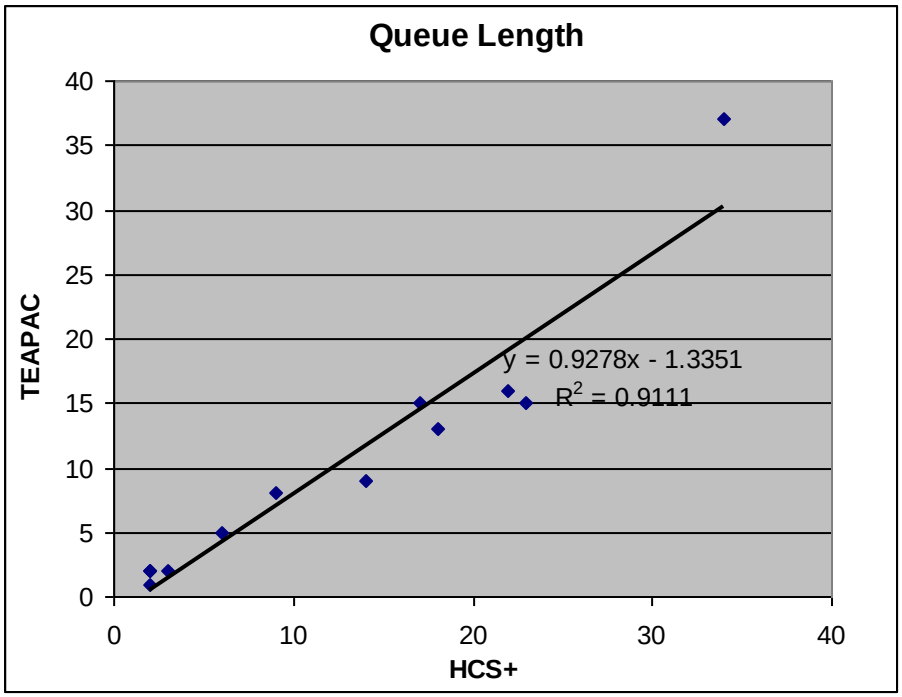

Figure 5-2: Comparison of Queue Lengths Estimated by HCS+ and TEAPAC.

TEAPAC underestimated queue lengths by 7% on average compared to HCS+.

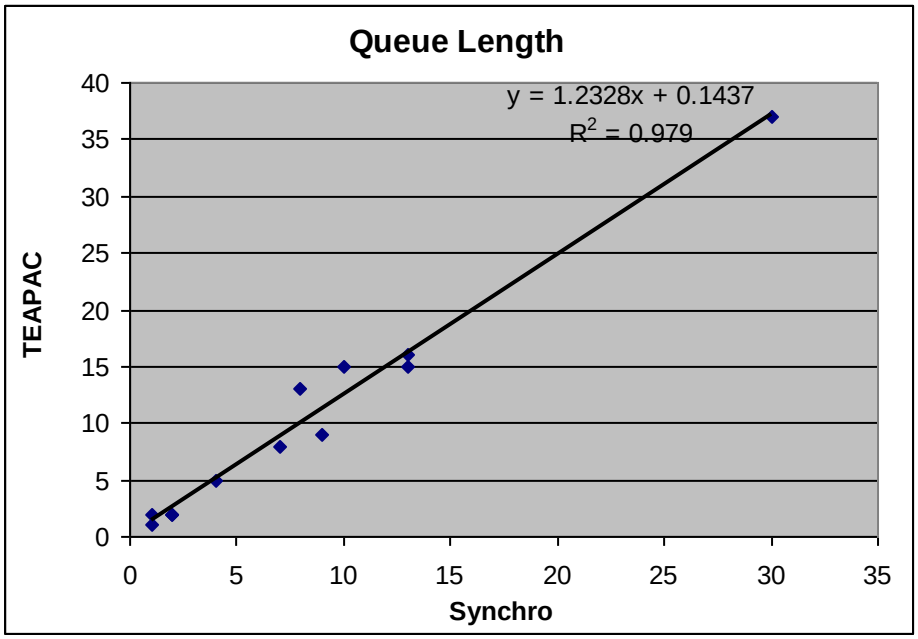

Figure 5-3: Comparison of Queue Length Computed by TEAPAC and Synchro.

From the graph, TEAPAC overestimated queue lengths by 23% on average compared to Synchro.

CHAPTER 6

CONCLUSIONS, RECOMMENDATIONS AND FUTURE WORK

6.1 Conclusions

Several software packages have been developed and are available to the traffic engineer for designing and estimating left turn queues. Little information is available, however, on how these models vary from each other and how they replicate observed field data.

The objective of this study was to evaluate several software packages and determine which best replicates left turn queues as observed in the field. This was carried out by modeling four different intersections operating under different traffic conditions. The macroscopic models evaluated were based on the procedures and methodology outlined in the Highway Capacity Manual with only some unique assumptions and minor differences. The study compared the estimated queue lengths from Synchro, SimTraffic, TEAPAC and HCS+ to actual queue lengths observed on the field. The observed queue length collected on the field was the maximum queue length, which reflects the number of vehicles queued at the beginning of green. Results showed that SimTraffic, which is a microscopic simulation model, produced the best results with a 76% precision level. TEAPAC, which also calculates maximum queue length, was the next best with a 74% precision level. Both Synchro and HCS+, which measure maximum back of queue, had precision levels of 69% and 67% respectively.

A paired t-test was performed to determine the level of significance of the mean queue length computed by HCS+, Synchro, and TEAPAC. This was done testing the null hypothesis that there is no significant difference between the estimated queues by these

models at a level of significance of 0.05. The results of the test showed that there is a significant difference between the queue lengths estimated by HCS+ when compared to both Synchro and TEAPAC.

Regression analysis was also performed to determine the relation between HCS+ and Synchro, HCS+ and TEAPAC, and TEAPAC and Synchro and to ascertain the variation in the queue lengths estimated between the models. Results show that HCS+ and Synchro, HCS+ and TEAPAC, and TEAPAC and Synchro are linearly related. On average, Synchro underestimated queue lengths by 26% compared to the HCS+ queues, and TEAPAC also slightly underestimated lengths by 7%.

It can be concluded that although TEAPAC and Synchro are patterned on the Highway Capacity Manual 2000, there is a difference in mean queue length estimated by these packages compared to that computed by HCS+. The difference could be due to the different assumptions of the models and the type of queue length estimated by HCS+, Synchro, and TEAPAC.

6.2 Recommendations

The following recommendations are made based on model's ability to replicate observed queue lengths and other traffic operational considerations:

SimTraffic performs best in modeling queue lengths with traffic volumes adjusted for the 95th percentile and simulated for a time period equal to the signal cycle length. This method compared best with the observed queue lengths in 3 of the 12 cases modeled relative to the other methods and had, overall, a higher precision level.

SimTraffic has the tendency to consistently slightly overestimate required queue lengths compared to the other three models which may over-and/or underestimate queue lengths.

Hence it may be a better model to use in left turn lane modeling because it has the tendency of overestimating in all cases modeled and its ability to overestimate is not as high as that of HCS+ and TEAPAC. It is better to overestimate than underestimate queue lengths in order to accommodate occasional overflows which may be caused by cycle failures, crashes, and special events. This ensures efficient intersection operation and reduces the frequency of blockages of both left turn lane and through lanes and delays associated with shorter queue lengths. Nevertheless, queue lengths should not be too far overestimated as in the case of HCS+. It may not be cost effective as the lane may not be fully utilized most of the time.

Although this study did not change any of the SimTraffic's default settings, it nevertheless produced relatively good results. Further calibration of SimTraffic to replicate field conditions might result in more precise queue lengths being estimated.

HCS+ could be used for analyzing isolated intersections and situations where time is of importance. However, it must be noted that HCS+ produces longer queue lengths as it includes slowing vehicles and stopped vehicles until they are entirely cleared through the intersection.

It must also be mentioned that the new Highway Capacity Manual 2010 procedure has been modified to consider only stopped vehicles in its back of queue estimation; shorter queue lengths thus may be obtained thereby increasing its accuracy.

6.3 Future Work

In reviewing the studies conducted to determine the performance of traffic software packages in estimating left turn queues, it is not clear how the actual field left turn queues are collected and compared; whether the number of left turning vehicles in the storage

bay is what is collected or if the total number of vehicles in the entire left turn bay, i.e. the storage bay plus the deceleration length are used. The determination of deceleration length is typically based on the speed limit of the roadway segment and is not dependent on the arrival, departure and signal timing and cycle length, which are the main factors that determine the length of the storage bay. Additionally, the function of deceleration lengths is to provide adequate distance for vehicles to gradually come to a stop without excessive deceleration. It is not supposed to provide storage for a queued vehicle. Traffic software packages model storage length whose actual function is to store vehicles required to stop at the signal until they have the right-of-way to clear the intersection. Therefore, the deceleration part of the left turn lane should be free of queued vehicle at any given time.

There is no clear distinction as to how the left turn queues are collected on all studies conducted and how the comparison is made with model outputs.

The benefits of the accurate determination of left turn lanes is important in ensuring safe and efficient operation of intersections, hence the actual field data compared with model output should be clarified for better understanding of the design of left turn queues.

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APPENDIX A)

SURVEY INSTRUMENT

Modeling Left-Turn Queue Lengths

1. Which, if any, of the following tools do you use to estimate future queue lengths in left-turn lanes? Check all that apply.
   - ☐ CORSIM
   - ☐ Highway Capacity Manual/Highway Capacity Software
   - ☐ Poisson analyses
   - ☐ SIGNAL2000/TEAPAC
   - ☐ SimTraffic
   - ☐ Other
2. Considering the technique(s) from question 1 that you use, how confident are you in the results they provide?
   - ☐ Highly confident
   - ☐ Somewhat confident
   - ☐ Not confident at all
   - ☐ Other
3. Based on the technique(s) that you use for queue length estimation, how do your estimates compare with actual, observed queue lengths at study locations?
   - ☐ Estimates are consistently higher than actual values.
   - ☐ Estimates are usually quite close to actual values.
   - ☐ Estimates tend to underestimate actual values.
   - ☐ Have not compared estimates to actual values.
   - ☐ Other
4. Based on your analyses and observations, which of the following is the most useful parameter describing queue length?
   - ☐ Maximum queue length at the beginning of the green interval.
   - ☐ Average queue length over some time period.
   - ☐ Average maximum queue length over a number of signal cycles.
   - ☐ Maximum back of queue, including vehicles that join during the green interval.
   - ☐ Percentile queue length
   - ☐ Other
5. In conducting field studies of queue lengths, when do you consider that a vehicle has joined the end of the queue?
   - ☐ When a vehicle has approached within ft of a stopped vehicle in the queue.
   - ☐ When an approaching vehicle has slowed to a speed of ☐ mph or ☐ ft/s.
   - ☐ Don't conduct queue length studies.
   - ☐ Other

6. Assume that you have a single, channelized left-turn lane that consistently backs up and blocks the adjacent through-traffic lane, what would be your preferred treatment? Check all that apply.
   - ☐ Extend the turn lane length, if possible.

- ☐ Lengthen the protected green interval for left-turning traffic, if possible.
- ☐ Install a dual left-turn lane, if possible.
- ☐ Other

7. Has your agency documented any queue length studies that might be helpful to the researchers on this project?
   - ☐ Yes
   - ☐ No
8. Can you offer any additional guidance to the researchers regarding queue length modeling?

Name of person providing this information:

Agency:

Email: Phone:

Please return this survey to:
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