Characterization of Arterial Traffic Congestion Through Analysis of Operational Parameters (Gap Acceptance and Lane Changing)

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University Transportation Center for Alabama
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16. Abstract

This project monitored an urban arterial highway to characterize recurring congestion. There were two major initiatives in the project. The first one focused on observed variations in gap acceptance and lane changing in relation to traffic flow rates on signalized urban arterials. The second one was a sensitivity analysis of observed lane change parameters compared to embedded parameters in current microscopic traffic simulation models.

Despite the robustness and wide spread use of microsimulation models for this type of analysis, gaps and limitations exist that can affect the accuracy of the results. Also, changes in driver behavior such as lane changing and gap acceptance under different traffic conditions are not well understood. One of the aims of this research was to offer enhancements to lane changing and gap acceptance models to improve the accuracy of microscopic simulation, particularly while simulating saturated traffic conditions.

Several general findings were produced during the study: traffic flows at signals approaching saturation are still complex to analyze; interactions between traffic parameters are not well understood; drivers take higher risks when flow on a signalized arterial approaches saturation (accept smaller gaps); statistical distributions obtained for gap acceptance and lane changes confirmed what is suspected intuitively, when the traffic flow is heavy the probabilities of drivers accepting smaller gaps and changing lanes rapidly are higher than during moderate flow; existing microscopic traffic simulation tools simplify some of the traffic parameters in simulation models, which may be recoded or recalibrated for better accuracy of simulation results. In addition to these general findings, multiple specific findings and recommendations were recorded for lane changing, gap acceptance, and simulation model parameters.

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Executive Summary

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1.0 Introduction

Project Scope

The objective of this project was to monitor an urban arterial highway that experienced frequent saturation and periodic oversaturation, for the purposes of characterizing recurring congestion, and if possible to distinguish the changes in traffic parameters between under-saturation and saturation, and between recurring and non-recurring congestion.

Specifically, the project collected and analyzed field measurements of the operational parameters gap acceptance and lane changing. Analysis of these two operational characteristics was intended to insight into traffic flow uncertainty (predictability) along the oversaturated arterial. A third aspect of the research was a comparison and analysis of field data collected for the two parameters with similar embedded parameters in simulation models.

The project directly supports the management of traffic flow and mitigation of congestion theme of the University Transportation Center for Alabama (UTCA). Of equal importance, the project is directly responsive to national surface transportation research needs and goals. By addressing current needs (and initiatives) established by the Federal Highway Administration (FHWA), the project was intended to position UTCA researchers to contribute to congested-related research on the national level. The data and findings associated with activities proposed in this project will enhance the understanding of congestion in Alabama and the results will be transferable and of interests to other researchers in other states.

The Study Site

UTCA maintains an Intelligent Transportation Systems/Traffic Management Center (ITS/TMC) lab on the University of Alabama campus. The lab is a satellite facility of the Tuscaloosa Department of Transportation (TDOT) and receives live feed of real-time traffic by closed-circuit television (CCTV) cameras placed along the study road (McFarland Boulevard, Tuscaloosa, AL).

The study segment is 2.3 miles long on a six-lane congested facility between two major arterials (13th Street and Skyland Boulevard). It includes an Interstate interchange (I-20/59) with two associated signalized junctions. There were nine intersections, three major and six minor, all of which are controlled by actuated and coordinated signals. Most of the segments between the intersections are long enough (1,000 to 3,000 feet) to facilitate lane changes.

This corridor experiences recurring congestion on a daily basis and exhibits severe non-recurring congestion events due to local incidents on McFarland, major incidents on the intersecting Interstate, and special events (e.g., University of Alabama football games). The Alabama Department of Transportation (ALDOT) provided data showing an average daily traffic (ADT) for McFarland Boulevard as 58,000, and a speed limit of 55 mph.

A sketch of the study road is given in Figure 1-1. TDOT cameras cover the major intersections along this route, and a snap shot of a typical camera view is given in Figure 1-2.

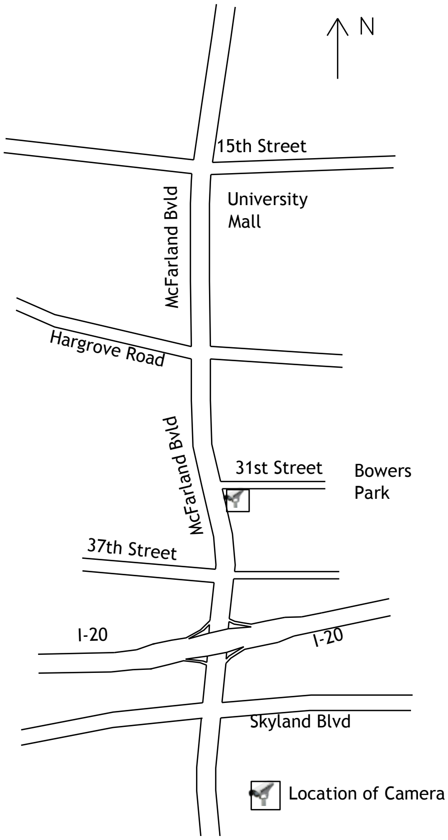


Figure 1-1. Study road (McFarland Boulevard).

Overview of the Project

There were two major initiatives in this project. The first research initiative focused on observed variations in gap acceptance and lane changing in relation to traffic flow rates on urban streets. It is summarized in Section 2 of this report.

The second research effort conducted a sensitivity analysis of lane change parameters observed on McFarland Boulevard in saturated and free flow traffic conditions as compared to similar parameters in microscopic traffic simulation models. This information may be found in Section 3 of this report.

Section 4 includes the findings and recommendations that emerged from the project. The references consulted during this project are recorded in Section 5.

Figure 2-2. Snap shot of an approach to a signal on the study road.

2.0 Observed Variations in Gap Acceptance and Lane Changing in Relation to Traffic Flow Rates on Urban Streets

Introduction

Traffic congestion is a common concern on urban streets. During peak hours, traffic demand at a signalized intersection increases and often exceeds the capacity of the intersection when the length of the green signal indication is insufficient to clear the vehicles waiting to pass through the intersection. In this event, the intersection is said to be saturated. Driver behavior varies during the transition from undersaturated to saturated flow. Understanding the changes in driver behavior may help us understand the underlying contributors to congestion and thereby help devise solutions for it. Among the many operational parameters related to driver behavior, lane changing and gap acceptance appear to be the most strongly related to the increase in congestion.

Lane changing refers to drivers changing roadway lanes without interfering with vehicles in the destination lane. Gap acceptance is the minimum size of gap (seconds) in traffic flow that drivers are willing to accept when entering or crossing a traffic stream, or while changing lanes. Over the years, these two driver behavior parameters have attracted attention from researchers. However much of the existing research has been done on lane changes on freeways, not on urban streets. This study is an attempt to enhance traffic operations by improving our understanding of lane changing and gap acceptance parameters on urban streets under different levels of traffic flow.

Objective of this Research Step

This research step contributed explored the changes in lane changing and gap acceptance parameters on urban streets under different levels of traffic flow. It contributes to the broad objective of the overall research project, which investigated changes between under-saturated and oversaturated traffic conditions in terms of performance measures (delay) and operational parameters (gap acceptance and lane changing).

Review of Prior Lane-Changing Studies

Historically, there has been great interest in parameters related to driver behavior. Past research on these parameters has mainly focused on freeways rather than urban streets. The reason could be that traffic operations on urban streets are more complex than on freeways due to the presence of traffic signals and the lack of sufficient access management on urban streets.

Previous research has shown that gap acceptance and lane changing on freeways depend on driver parameters like aggressiveness, urgency, and impatience (Goswami and Bham, 2007). It is known that drivers behave differently under diverse traffic, geometric, and environmental conditions. Similarly, the same driver can behave differently under varying traffic and control conditions (Goswami and Bham, 2007). The authors studied driver behavior in terms of gap acceptance and critical gaps (the minimum value of an accepted gap) for mandatory lane changes in congested and uncongested traffic conditions. Data collected by the Next Generation Simulation (NGSIM) project on I-80 was used for this study. The authors proposed a gamma distribution for accepted time gaps for mandatory lane change maneuvers under both uncongested and congested traffic flow conditions. They also found that drivers were more sensitive to trailing critical gaps (between the subject vehicle and the following vehicle) than to leading critical gaps (between the subject vehicle and the following vehicle).

Modeling the lane changing process has attracted interest among researchers. One such study done by Toledo and Zohar (2007), focused on modeling the duration of lane changes. The authors used vehicle trajectory data at a high time resolution collected from cameras mounted on I-80. They found that lane changes were not instantaneous events as modeled by most microscopic traffic simulation software models. They have durations in the range of 1.0 to 13.3 seconds, with a mean of 4.6 seconds. They also indicated that the lane change durations for passenger cars differed significantly from that of heavy vehicles. However, with both vehicle types, lane change durations were longer when the maneuver was riskier or when the task was complicated by the relationship of the subject vehicle to other vehicles.

Earlier studies also focused on risk taking behavior of drivers with respect to congested traffic conditions. One of the studies conducted by Mahlavat and Zhang (2008) on I-35 determined the safe headway adopted by drivers during different levels of traffic flow. The authors attempted to identify the relationship between increasing congestion levels and drivers' willingness to adopt unsafe headways. They found that at all traffic flow levels there were vehicles traveling at unsafe headways, but more drivers seemed to adopt unsafe headways as the flow level increased.

A pilot study was conducted by Coifman et al. (2006), on the effects of lane change maneuvers on freeway delays. The authors proposed a method to estimate delays caused by a lane change maneuver within a given lane, relative to the situation in which no lane change occurred. The authors used vehicle trajectory data from I-405. Their methodology was to determine the difference between the measured and estimated travel times. The measured travel time was obtained from trajectory data and the estimated travel time was found by an algorithm which reflected conditions in the lane if there had been no lane changes. The authors showed that the method was feasible, but further research was needed to evaluate the impact of some of the assumptions made in the study.

Data Acquisition

The UTCA ITS/TMC lab was used extensively for collecting the required data for this study, using live feed from real-time traffic by closed circuit television cameras placed along

McFarland Boulevard, the study road shown previously in Figure 1-1. One of the cameras was adjusted to view the intersection of McFarland Boulevard and 37th Street, including about 1000 feet of southbound approach of McFarland Boulevard to the signal. This view was shown previously as Figure 1.2.

Methodology

Real time traffic flow was recorded using WinTV® software available in the ITS/TMC lab. The data collection protocol captured data from the AM peak (7:00 AM to 9:00 AM), midday (11:00 AM to 1:00 PM), and the PM peak (4:00 PM to 6:00 PM) on a normal working day (February 2008), thus covering both undersaturated and saturated traffic conditions.

Field measurements were collected in time intervals corresponding to the green phase for the southbound traffic at the signalized intersection. Data was collected for the number of lane changes and gap acceptances per cycle of green time. For each lane change and gap acceptance, the duration of the change maneuver (in seconds) and the size of the accepted gap (in seconds) were collected.

Data Collection Procedure The recorded videos were viewed in Windows Movie Maker® due to its editing capabilities. For instance, the video can be observed as slowly as one frame for every one-fifteenth of a second and can move forward and backwards as necessary. This improves accuracy of data collection and reduction.

In this study, gap acceptance refers to accepting a gap during a lane change maneuver. Hence the gap acceptance and lane change duration parameters are related to each other. Figure 2-1(a) shows all the lane change maneuvers possible within a three-lane road and Figure 2-1(b) shows the process of vehicles accepting gaps while changing lanes.

In the figure, gap refers to the time gap available to the subject vehicle in the target lane and accepted gaps are those gaps accepted by the subject vehicle. The accepted gaps were collected as follows:

- The time (T1) and location of the leading vehicle in the target lane were noted at the instant the subject vehicle first began changing its alignment in the present lane.
- After the subject vehicle changed lanes, the time (T2) was noted when the following vehicle crossed the same spot as that noted in the first step.
- The difference between times T1 and T2 gives the accepted gap size (in seconds).

Similarly, the duration of the lane change maneuver was calculated as the time taken by the subject vehicle to completely change from one lane to another.

Past studies have indicated that a leading gap or a trailing gap of 200 feet or more will result in vehicles not interacting with each other (Goswami and Bham, 2007). In this study, gaps are defined as the time between the leading and trailing vehicles (see Figure 2-1(b)). So a gap size of 400 feet was taken as the limit for vehicles to be in interaction. Assuming the speed of vehicles as 35 mph, about 8 seconds is needed to clear 400 feet. In other words, when a vehicle changed lanes, there should be 200 feet between it and the leading vehicle, and between it and the following vehicle. Thus, gap sizes equal to or more than eight seconds were not counted in the data collection process.

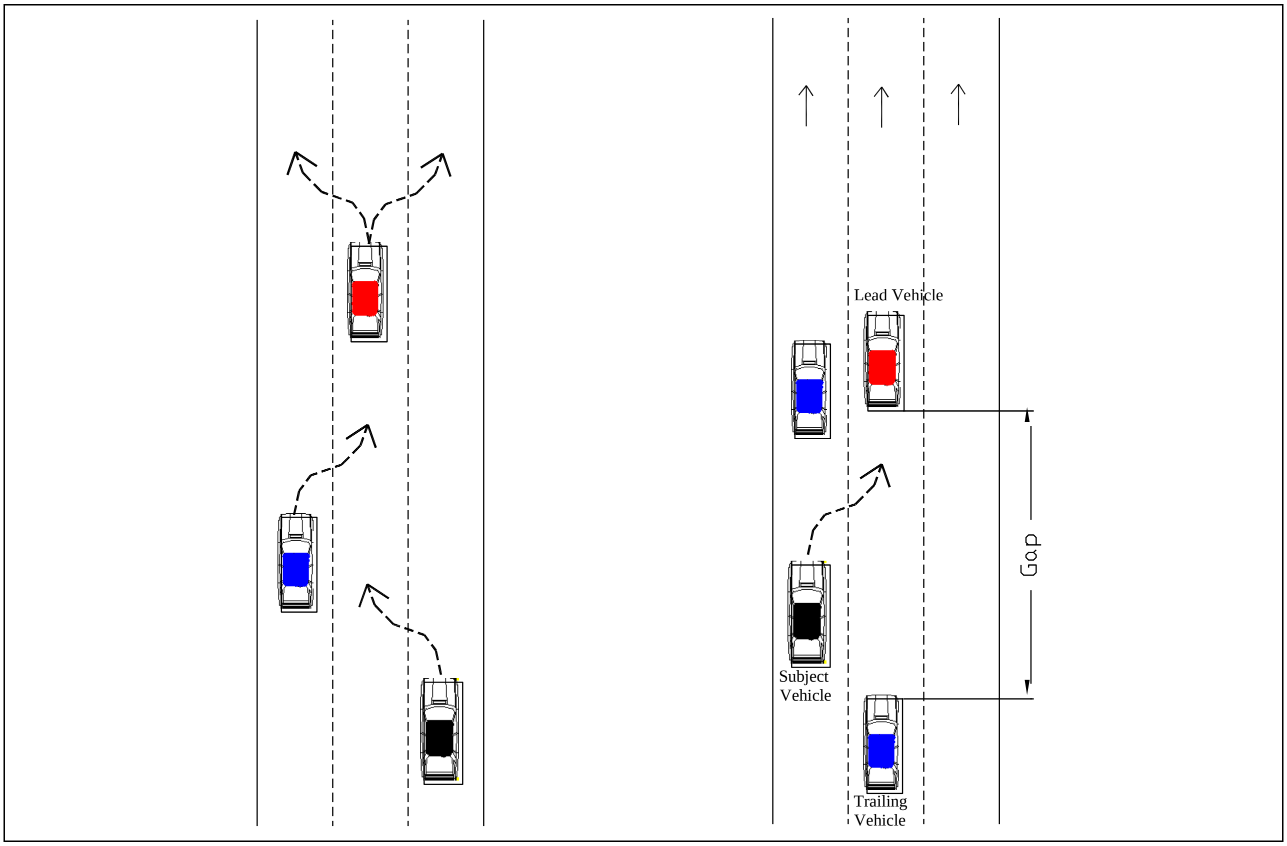


Figure 2-1(a). Possible lane changes on a three-lane road.

Figure 2-1(b). Gap acceptance while changing lanes.

The approach under consideration has three through lanes. Lane changes and gap acceptances occurring only within these three lanes were collected for the study. The data form used to collect duration of lane changes and accepted gaps is shown in Table 2-1. Sample data is shown on the form. As mentioned earlier, if the gap sizes were equal to or more than eight seconds they were not taken into account. This explains the blank spaces corresponding to accepted gaps in Table 2-1.

Creation of Flow Rate Bins and Categorizing Data The flow rate of each cycle of green time was obtained by dividing the volume of traffic clearing the intersection during green with the green time (in minutes). The flow rate is expressed as the number of vehicles per minute of green time. Hence, each cycle has a flow rate associated with it. The lane changes and gap acceptances occurring in a particular cycle correspond to the flow rate of that cycle. For analysis purposes, four different flow rate bins were created to cover the range of traffic flow:

- 10 – 30 vehicles per minute of green
- 30 – 50 vehicles per minute of green

- 50 – 70 vehicles per minute of green
- 70 – 90 vehicles per minute of green

After creating the flow rate bins, each lane change and accepted gap was recorded in the appropriate bin. As a result, each flow rate bin contained a considerable number of lane changes and accepted gaps. To ensure a valid statistical analysis of the grouped data, the minimum sample requirement of each bin was calculated.

Table 2-1. Data Collection Form and Sample Data

Green Time					Accepted Gap						Duration of Lane Change						Volume
Start	hr	min	sec	ms	time	min	sec	ms	sec	diff	time	min	sec	ms	sec	diff	# of veh
	4	6	40	40	T1	6	40	47	40.47	4.86	T1	6	40	47	40.47	4.13	78
					T2	6	45	33	45.33		T2	6	44	60	44.60		
					T1	6	43	07	43.07	5.00	T1	6	43	07	43.07	3.93	
					T2	6	48	07	48.07		T2	6	47	0	47.00		
											T1	6	52	13	52.13	3.60	
											T2	6	55	73	55.73		
					T1	7	2	40	2.40	3.47	T1	7	2	40	2.40	5.33	
					T2	7	5	87	5.87		T2	7	7	73	7.73		
					T1	7	9	53	9.53	3.00	T1	7	9	53	9.53	3.47	
					T2	7	12	53	12.53		T2	7	13	0	13.00		
					T1	7	11	20	11.20	8.47	T1	7	11	20	11.20	2.93	
					T2	7	19	67	19.67		T2	7	14	13	14.13		
					T1	7	27	27	27.27	4.00	T1	7	27	27	27.27	4.93	
					T2	7	31	27	31.27		T2	7	32	20	32.20		
											T1	7	44	73	44.73	3.14	
End	4	7	51	87							T2	7	47	87	47.87		

Note: T1 and T2 for accepted gaps and lane changing are defined separately in methodology.

Sample Requirements

The minimum sample size was calculated using the standard procedure for this type of study (Currin, 2001). A confidence level of 95%, a sample standard deviation(s) of 0.5 for six samples and a permitted error of the estimate of 5% were assumed. The number of required samples was obtained as 64. This number was taken as the number of lane changing or gap acceptance maneuver required for statistical validity.

The number of samples available in each bin is shown in Table 2-2. It should be noted that for an accepted gap both the lead and following vehicle must be present in the target lane. This explains the difference in the number of lane changes and accepted gaps in Table 2-2 for each flow rate bin.

Table 2-2. Available Number of Samples

Flow Rate bins	Number of Samples Available	
	Accepted Gaps	Lane Changes
10 – 30 veh/min of green	63	156
30 – 50 veh/min of green	171	322
50 – 70 veh/min of green	139	230
70 – 90 veh/min of green	65	106

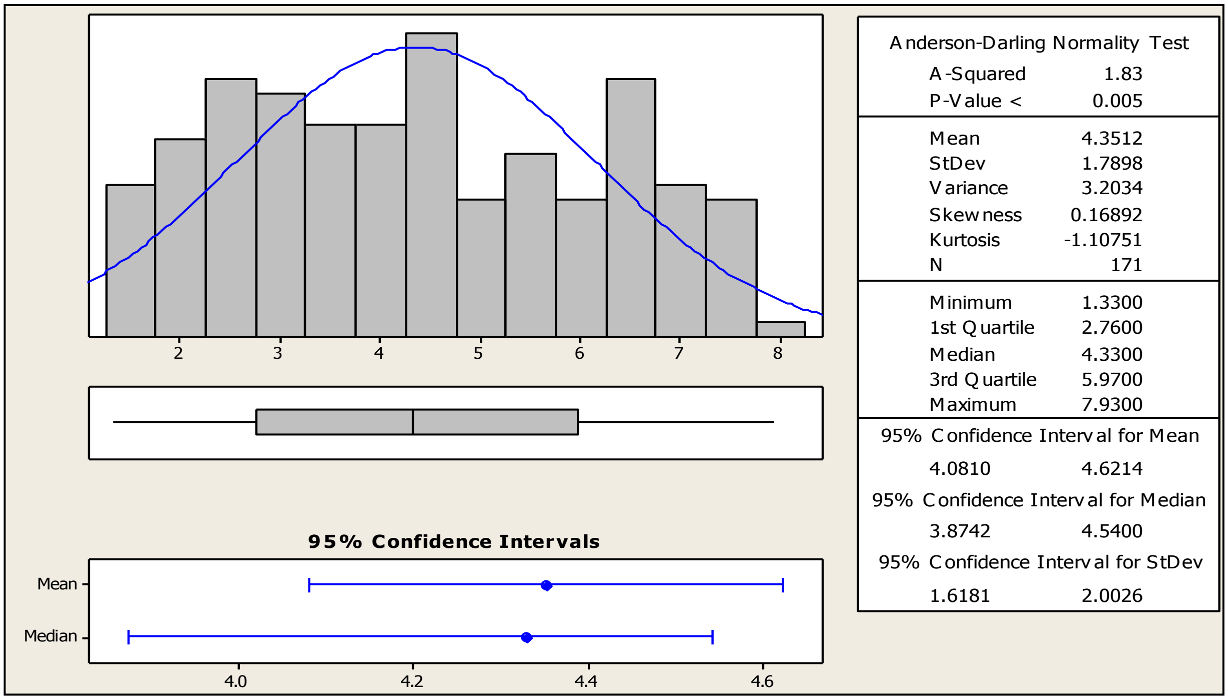
Analysis of Data

Descriptive Statistics for Accepted Gaps

The accepted gaps corresponding to each flow rate bin were analyzed to obtain basic statistics such as mean, median, standard deviation, and skewness. Table 2-3 shows the basic statistics obtained using Minitab. Examples of two such analyses are shown in Figures 2-2 and 2-3.

Table 2-3. Basic Statistics of Accepted Gaps for Different Flow Rates

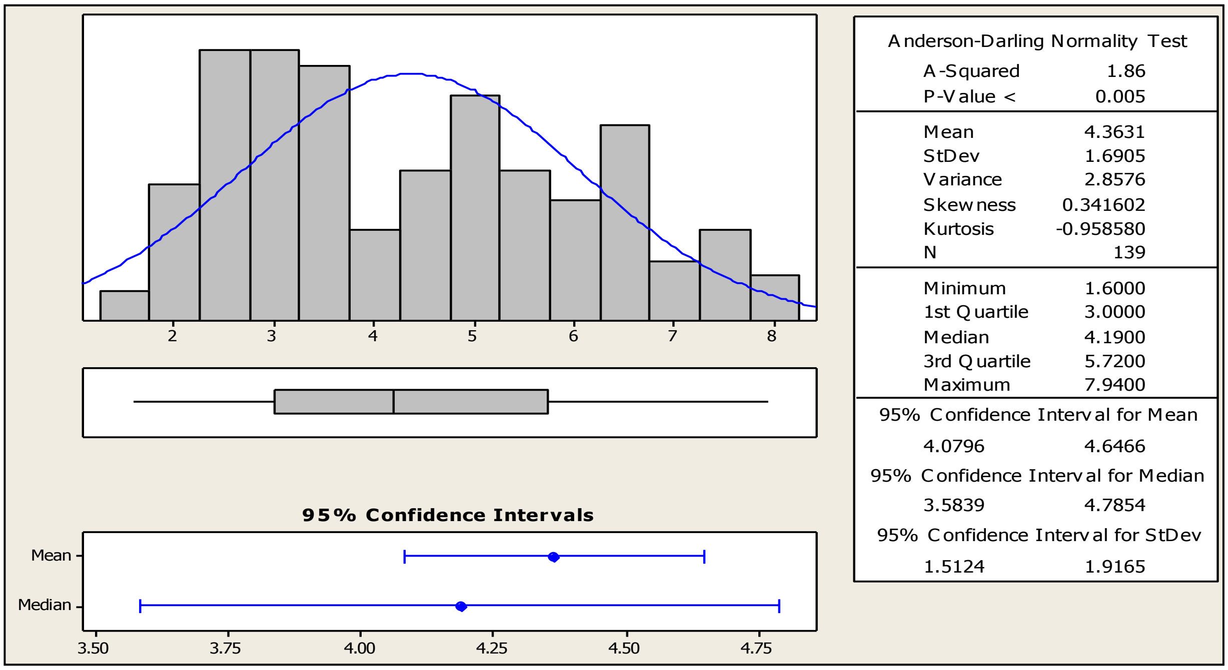
Flow Rate	Mean	Standard Deviation	Median	Skewness
10 to 30 veh/min	4.33	1.65	4.33	0.104
30 to 50 veh/min	4.35	1.79	4.33	0.169
50 to 70 veh/min	4.36	1.69	4.19	0.342
70 to 90 veh/min	4.04	1.61	3.74	0.635



Anderson-Darling Normality Test	
A-Squared	1.83
P-Value <	0.005
Mean	4.3512
StDev	1.7898
Variance	3.2034
Skewness	0.16892
Kurtosis	-1.10751
N	171
Minimum	1.3300
1st Quartile	2.7600
Median	4.3300
3rd Quartile	5.9700
Maximum	7.9300
95% Confidence Interval for Mean	
4.0810	4.6214
95% Confidence Interval for Median	
3.8742	4.5400
95% Confidence Interval for StDev	
1.6181	2.0026

Figure 2-2. Statistics of accepted gaps for flow rate 30–50 veh/min.

Before drawing inferences from Table 2-3, the differences in the mean values of the accepted gaps for different flow rates were checked by conducting a hypothesis test. The methodology adopted to conduct the test is given in the following text.



Anderson-Darling Normality Test

A-Squared	1.86
P-Value <	0.005
Mean	4.3631
StDev	1.6905
Variance	2.8576
Skewness	0.341602
Kurtosis	-0.958580
N	139
Minimum	1.6000
1st Quartile	3.0000
Median	4.1900
3rd Quartile	5.7200
Maximum	7.9400

95% Confidence Interval for Mean

4.0796 4.6466

95% Confidence Interval for Median

3.5839 4.7854

95% Confidence Interval for StDev

1.5124 1.9165

Figure 2-3. Statistics of accepted gaps for flow rate 50–70 veh/min.

<u>Hypothesis Test for Difference between Means of Accepted Gaps</u> The hypothesis test was performed at a 90% confidence interval to check whether the mean values of accepted gaps were different for different flow rates. Minitab was used to conduct the hypothesis test. The results are given in Table 2-4. The null and alternative hypotheses are stated below:

H_0: *The mean values of accepted gaps obtained from two different flow rates are the same.*
H_1: *The mean values of accepted gaps obtained from two different flow rates are different.*

Table 2-4. Hypothesis Test for Accepted Gaps (Mean)

Flow Rate Bins	Z-Statistic	Z-Critical	Hypothesis (H_0/H_1)
10-30 & 30-50 veh/m	0.11	1.28	Do not Reject H_0
10-30 & 50-70 veh/m	0.17	1.28	Do not Reject H_0
10-30 & 70-90 veh/m	1.39	1.28	Reject H_0
30-50 & 50-70veh/m	0.09	1.28	Do not Reject H_0
30-50 & 70-90 veh/m	2.49	1.28	Reject H_0
50-70 & 70-90 veh/m	2.33	1.28	Reject H_0

The results of the hypothesis test indicate that the mean value of the accepted gap for the highest flow rate (70 to 90 veh/minute) is smaller than that obtained for all the other flow rates: 10 to 30 veh/m, 30 to 50 veh/m, and 50 to 70 veh/minute.

<u>Best Fitted Distributions for Accepted Gaps under Different Flow Rates</u> The samples collected for accepted gaps for different flow rates were used to find the corresponding fitting distribution. Arena®, a software used for statistical design and analysis, was used to fit the distributions. In order to overlay the fitted distributions of accepted gaps of four different flow rates, the shape, scale and location parameters obtained from Arena were used to recreate the distributions. The parameters of the best fitted distributions and their square errors are given in Table 2-5, and the fitted distributions are shown in Figure 2-4.

Table 2-5. Parameters and Square Errors of Best Fitted Distributions for Gap Acceptance under Different Flow Rates

Flow Rate (veh/min)	Best Fitted Distribution	Parameters		Square Error
		Scale	Shape	
10 to 30	Weibull	2.140	3.75	0.0125
30 to 50	Weibull	1.950	3.78	0.0066
50 to 70	Gamma	0.948	3.55	0.0076
70 to 90	Gamma	0.862	3.53	0.0055

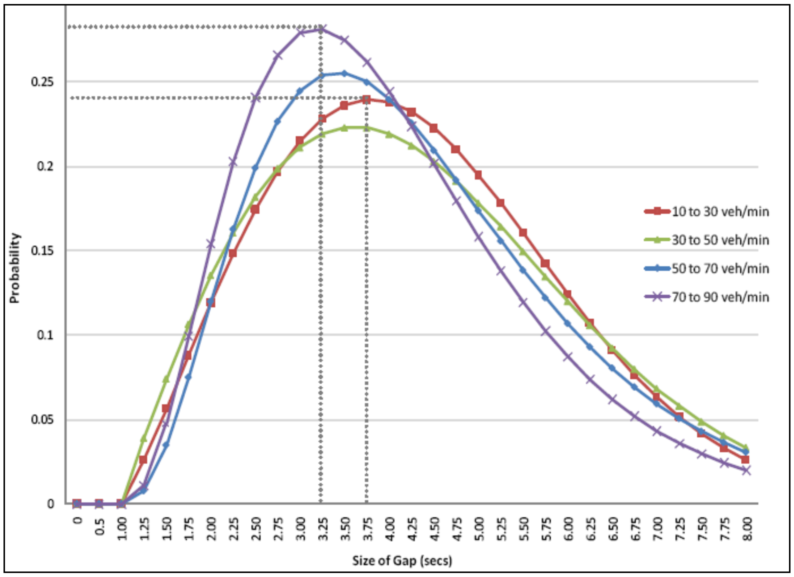


Figure 2-4. Best fitted distributions for gap acceptance under different flow rates.

From Figure 2-4, it can be observed that as the flow rate increases the accepted gap size corresponding to the highest probability decreases (the expected outcome). For instance, consider the flow rates of 10 to 30 veh/min and 70 to 90 veh/min. The accepted gap size corresponding to the highest probability (24%) in the former is 3.75 seconds, while that of the latter is 3.25 seconds (highest probability 28%). Similarly, the accepted gap size corresponding to the highest probability of the other two flow rates (30 to 50 and 50 to 70 veh/min) falls in between the two extremes. It can also be observed that the distributions are increasingly skewed to the right with increasing flow rate.

Findings for Accepted Gaps From the analysis of accepted gaps including basic statistics, hypothesis testing and best fitted distributions, the following observations can be drawn:

- Since the mean value of the accepted gaps during the highest flow rate (70 – 90 vehicles per minute of green time) was less than the other mean values of accepted gaps, it can be understood that average drivers accept smaller gaps when traffic flow is heavy.
- The steady decline in the median value of accepted gaps with increasing flow rates (4.33, 4.33, 4.19, and 3.74 seconds for 10-30, 30-50, 50-70, and 70-90 veh/m flow rates respectively) supports the first finding.
- The shape and skewness of the best fitted distributions showed that the probability of drivers accepting smaller gaps is higher when the traffic flow is heavy.
- From the above findings, it appears that drivers take higher risks to change lanes when congestion reaches higher conditions. On the same lines, it can be noted that drivers reduce their speed during congested traffic conditions and hence are willing to accept shorter gaps to change lanes.

Descriptive Statistics for Lane Change Durations

The mean, median, standard deviation and skewness were obtained for lane change durations of each flow rate bin. These statistics were obtained using Minitab and are given in Table 2-6.

Table 2-6. Basic Statistics of Lane Change Durations under Different Flow Rates

Flow Rate	Mean	Standard Deviation	Median	Skewness
10 to 30 veh/min	4.34	0.94	4.25	0.290
30 to 50 veh/min	4.33	0.93	4.31	0.149
50 to 70 veh/min	4.25	0.90	4.20	0.108
70 to 90 veh/min	4.19	0.81	4.20	0.016

Before drawing inferences from Table 2-6, the differences in the mean values of the change durations for different flow rates were checked by conducting a hypothesis test.

Hypothesis Test for Difference between Means of Lane Change Durations The hypothesis test was performed at a 90% confidence interval to check whether the mean values of lane change durations were different during higher flow rates. The results of the hypothesis test obtained using Minitab is given in Table 2-7.

The rejections of null hypothesis for the flow rates shown in Table 2-7 imply that the mean values of lane change duration of higher flow rates (i.e., 70 to 90 veh/min and 50 to 70 veh/min) are smaller than those obtained for lower flow rates (i.e., 10 to 30 and 30 to 50 veh/min). In other words, with increasing flow rates, time taken to change lanes decreases. However the decrease is relative less when compared with that obtained for accepted gaps.

Table 2-7. Hypothesis Test for Lane Change Duration (Mean)

Flow Rate Bins	Z-Statistic	Z-Critical	Hypothesis (H_0/H_1)
10-30 & 30-50 veh/m	0.06	1.28	Do not Reject H_0
10-30 & 50-70 veh/m	1.10	1.28	Do not Reject H_0
10-30 & 70-90 veh/m	2.13	1.28	Reject H_0
30-50 & 50-70veh/m	1.51	1.28	Reject H_0
30-50 & 70-90 veh/m	2.98	1.28	Reject H_0
50-70 & 70-90 veh/m	1.12	1.28	Do not Reject H_0

Best Fitted Distributions for Lane Change Durations under Different Flow Rates The procedure adopted to create the best fitted distributions for lane change durations is the same as that adopted for accepted gaps. The parameters of the fitted distributions and their square errors are given in Table 2-8, and the fitted distributions are shown in Figure 2-5.

Table 2-8. Parameters and Square Errors of Best Fitted Distributions for Lane Change Durations under Different Flow Rates

Flow Rate (veh/min)	Best Fitted Distribution	Parameters Scale	Shape	Square Error
10 to 30	Weibull	2.63	2.69	0.0082
30 to 50	Weibull	2.62	2.74	0.0043
50 to 70	Weibull	2.53	2.72	0.0040
70 to 90	Weibull	2.18	2.61	0.0073

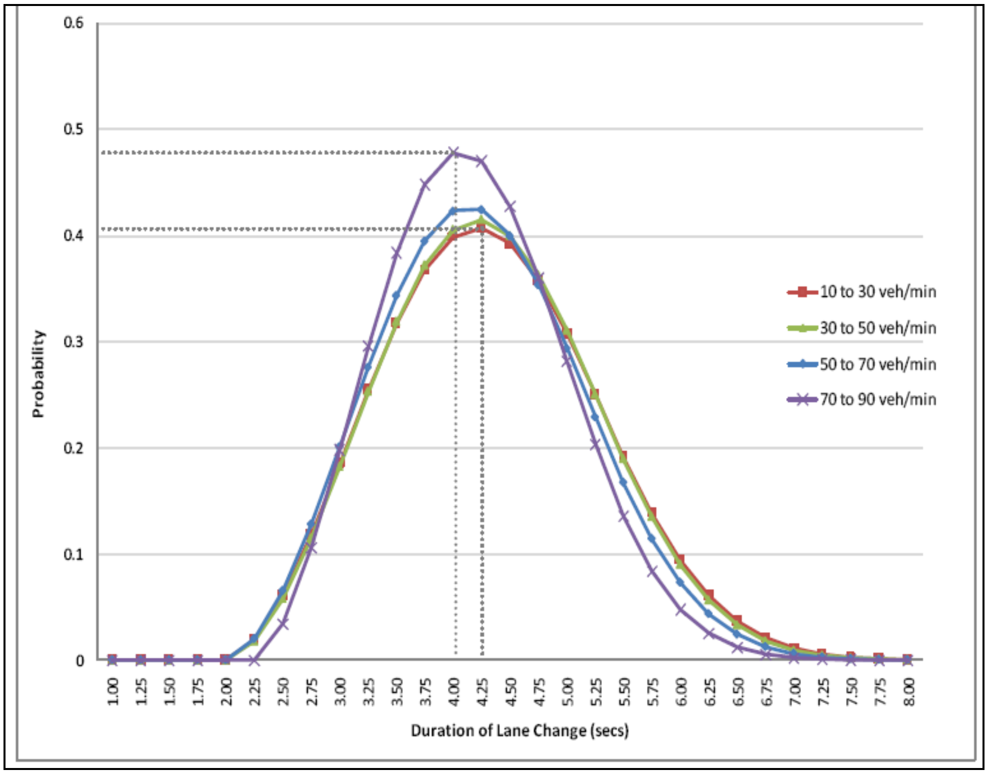


Figure 2-5. Best fitted distributions for lane change durations under different flow rates.

Figure 2-5 shows that with increasing flow rate the lane change duration corresponding to the highest probability decreases. For instance, for the flow rate of 10 to 30 veh/min, the lane change duration of 4.25 seconds corresponds to the highest probability of 41%, while for the flow rate of 70 to 90 veh/minute, a lane change duration of four seconds corresponds to its highest probability of 48%.

Findings for Lane Change Durations From the analysis of lane change durations including basic statistics, hypothesis testing and best fitted distributions, the following observations can be drawn:

- The mean values of the lane change duration show a decreasing trend with increasing flow rates (similar to the observation obtained for accepted gaps), but the change is relatively less when compared with that obtained for accepted gaps.
- The standard deviations of lane change durations from lower to higher flow rates were found to be 0.94, 0.93, 0.90, and 0.81 seconds. These values are much less than those obtained for accepted gaps, indicating that the variation of lane change duration values is less than that of accepted gaps.
- The shape and skewness of the best fitted distributions showed a higher probability that drivers change lanes more rapidly when traffic flow is heavy.
- By combining the above observations with that obtained for accepted gaps, it can be understood that during heavy traffic flow conditions considerably more drivers accept smaller gaps and change lanes a bit faster.

Rate of Lane Changes

In order to determine the trend in the rate of lane changes with increasing flow rates, the rate of lane changes was obtained by dividing the number of changes for each flow rate bin with the average flow rate. For instance, the average flow rate of the 10-30 flow rate bin was found to be 20 vehicles per minute. The rates of lane changes thus obtained for different flow rate bins are given in Table 2-9, and they are plotted on Figure 2-6.

Table 2-9. Rate of Lane Changes

Flow Rate Bins	No of Lane Changes	Rate of Lane Changes/veh/m
10-30 veh/m	144	7.2
30-50 veh/m	302	7.6
50-70 veh/m	223	3.7
70-90veh/m	103	1.3

The table and figure show that the rate of lane changes decreases with increase in traffic flow. This finding is reasonable because the available gaps decrease with increasing flow rates. It can be concluded that since there are fewer gaps during higher traffic flow or saturated flow, drivers accept smaller gaps.

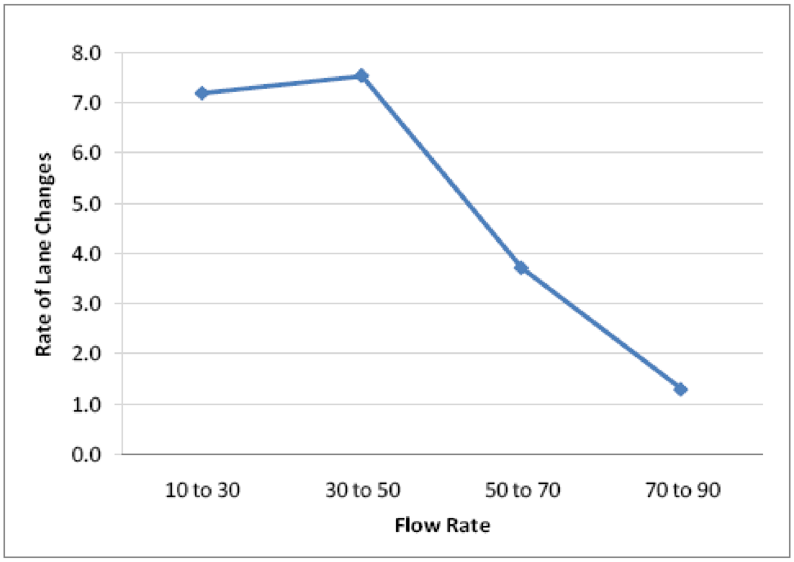


Figure 2-6. Trend of rate of lane changes.

Conclusions

There is a keen interest in changes in driver behavior parameters such as lane changing and gap acceptance under varying traffic flow conditions. This study explored the changes in gap acceptance and lane changing parameters on one urban street under different levels of traffic flow. The major finding of this research is that when traffic flow on a typical arterial approaches saturation, a considerable number of drivers accept smaller gaps and change lanes more rapidly. In other words, drivers take higher risks to change lanes during congested traffic flow. This finding is validated by the following observations:

- The mean values of accepted gaps ranged from 4.33 to 4.04 seconds for average flow rates of 20 to 80 vehicles per minute, and standard deviations were around 1.6 seconds. A hypothesis test proved that the extreme values (4.33 and 4.04) are indeed different.
- There was a steady decline in the median value of accepted gaps with increasing flow rates. The highest was 4.33 seconds and the lowest was 3.74 seconds, corresponding to flow rates of 10-30 and 70-90 veh/min, respectively.
- The shape and skewness of the best fitted distributions showed that the probability of drivers accepting smaller gaps is higher when the traffic flow is heavy.
- The mean values of lane change durations ranged from 4.34 to 4.19 seconds for average flow rates of 20 to 80 vehicles/minute, and the standard deviations were around 0.9 seconds. A hypothesis test proved that the extreme values (4.34 and 4.19) are indeed different.
- The variation of lane change durations is less than the variation of accepted gaps, which indicates that gap acceptance is more sensitive to changes in traffic volume than lane change duration.
- The best fitted distributions of lane change durations showed that the probability of drivers changing lanes more rapidly is higher when traffic flow is heavy.

- The rate of lane changes decreases with increasing traffic flow rates, probably because the number of available gaps decreases with increasing flow. It can be concluded that since there are less available gaps during higher traffic flow or saturated flow conditions, drivers accept smaller gaps.

All of these findings have direct implications upon the gap acceptance and lane changing parameters used in microscopic traffic simulation, particularly during model calibration. The default values of lane changing and gap acceptance parameters used in some of the common traffic simulation tools are indeed different from those obtained in this study. For instance, CORSIM has a default lane change duration value of three seconds, while the results obtained in this study show that the mean value of lane change duration varied from 4.19 to 4.34 seconds depending on the traffic flow rate. Also, the gap acceptance (while changing lanes) distributions obtained in this study may be used in lane change models in microscopic traffic simulation models.

Future Research

To further the current research, the following studies are suggested:

- Increase the sample size of data collection to reduce data-related variation.
- Instead of flow rates, driver behavior parameters should be compared with more representative parameters such as delay, speed or LOS of the arterial approach under consideration.
- Focus on how the driver behavior parameters, as currently used in microscopic traffic simulation models, relate to the field data obtained in this research. Both logical and statistical relationships can be examined.
- Perform similar research in other streets in other cities.

3.0 Sensitivity Analysis of Lane Change Parameters to Saturated and Free Flow Traffic Conditions in Microscopic Traffic Simulation Models

Introduction

Traffic simulation has been widely used as a traffic analysis tool in transportation analyses, particularly to analyze the operation of complex and congested transportation systems. However, despite the widespread use of traffic simulation software, there is still ongoing research to improve accuracy of simulation and model calibration. This paper focuses on the parameters used in lane change models (an integral part of microscopic traffic simulation models), namely, the duration of the lane change maneuver and the mean longitudinal distance to perform a lane change (look-ahead distance).

The broad objective of this research is to investigate the changes between undersaturated and saturated traffic conditions in terms of performance measures (delay) and operational parameters (gap acceptance and lane changing). This paper contributes to the research by exploring the sensitivity of lane changing parameters during undersaturated and saturated traffic conditions.

Background and Motivation

Driving is a highly complex task that requires continual integration of perception, cognition, and motor response; and lane changing is one subtask that incorporates many of these critical aspects of driving (Salvucci and Liu, 2002). Lane changes have a significant impact on the characteristics of traffic flow (Toledo and Zohar, 2007). It is suspected that lane change maneuvers could be one source of traffic delays (Coifman et al., 2006). Hence, sufficient care must be taken while modeling lane changes.

Lane change models form an integral and important part of microscopic traffic simulation. The functioning of these models is usually governed by driver behavior parameters such as duration of lane changes and longitudinal distance to perform a lane change. With increase in the usage and popularity of microscopic traffic simulation, the quest for accurate and reliable lane change models emerged.

Existing models of lane changing behavior emphasize the decision-making aspects of the task, but generally neglect the detailed modeling of the lane changing action itself and only model it as an instantaneous event (Toledo and Zohar, 2007). Some of the commonly used simulation software packages, such as SimTraffic and AIMSUN, do not explicitly state the duration of lane changes (SimTraffic, User Guide, Version 6.0, 2003 and AIMSUN User Manual, Version 5.1, 2006). CORSIM has a three second default value as the duration of lane change (CORSIM

User's Guide, Version 6.0, 2005). However, research (Toledo and Zohar, 2007; Lee, Olsen, and Wierwille, 2003; and Gurupackiam and Jones, 2009) has shown that lane change duration is not an instantaneous process or a constant value; instead, it follows a range of values and a specific distribution based on the location of study. It has been documented that the mean lane change duration is four to six seconds with ranges from three to 8.5 seconds (Toledo and Zohar, 2007; Lee, Olsen, and Wierwille, 2003; and Gurupackiam and Jones, 2009). Hence, it was expected that these values of lane change duration, when incorporated into the existing lane change models, will result in drastic variation in the results or MOEs (Measures of Effectiveness) of the simulation.

The other parameter considered in this study, the longitudinal distance to perform a lane change, refers to the distance required for a vehicle to contemplate and perform one lane change (CORSIM User's Guide, Version 6.0, 2005). In CORSIM, the default value for this parameter is between 225 feet and 375 feet based upon the driver type (CORSIM User's Guide, Version 6.0, 2005). Similarly, SimTraffic addresses this condition with two parameters, namely, mandatory distance (the distance back from the stop bar where a lane change must commence) and positioning distance (the distance back from the mandatory point where a vehicle first attempts to change lanes). These two parameters in SimTraffic also have default values involving speed, cycle length and driver type. In AIMSUN, the longitudinal distance to perform a lane change is governed by defining zones. Zone 1 is the farthest distance from the next turning point. The lane changing decisions are mainly governed by the traffic conditions of the lanes involved. Zone 2 is the intermediate zone. It is mainly the desired turning lane that affects the lane-changing decision. Zone 3 is the shortest distance to the next turning point. Vehicles are forced to reach their desired turning lanes, reducing speed if necessary, and even coming to a complete stop in order to make the lane change.

The previous studies suggest that lane change duration is a range and not a constant value. However, no studies were identified which explored the changes in the simulated results by using a range of values for lane change duration rather than keeping it constant. Studies dealing with the longitudinal distance to make a lane change were not identified during the preparation of this paper. Hence, in this study, a sensitivity analysis of the above mentioned parameters in microscopic traffic simulation is performed. The authors anticipated that the findings from this study will include recommendations for the improvement of the existing lane change models in microscopic traffic simulation in terms of model calibration and accuracy of results i.e., MOEs.

Simulation Modeling

CORSIM 5.1 was selected for this study. It was developed for the Federal Highway Administration (FHWA) and distributed by McTrans. It is a microscopic traffic simulation software package for signal systems, freeway systems, or combined signal and freeway systems (CORSIM User's Guide, Version 6.0, 2005). All the simulation models addressed in the literature (CORSIM, SimTraffic, and AIMSUN) have their own lane changing algorithms for performing lane changes within the traffic stream. However, CORSIM had unique characteristics that led to its selection for this study:

- The lane changing algorithm in CORSIM consists of a comprehensive set of parameters (acceleration/deceleration, headway, lane change duration, look-ahead distance etc.) governing the lane changing process, and CORSIM allows the user to calibrate each of these parameters.
- The user friendly interface in CORSIM enables the user to explicitly modify the default values of all the related parameters including the two parameters considered in this study, namely, the duration of the lane change maneuver and the mean longitudinal distance for making a lane change.
- The output processor of CORSIM supports three different file formats including Microsoft Excel® which was used for this study.
- CORSIM is also one of the most popular and commonly used microscopic traffic simulation model in practice.

Study Road and Data Set

As with the research effort described in Chapter 2, McFarland Boulevard served as the data source for this initiative. The study stretch extends 2.3 miles from Skyland Boulevard to 13th Street. It includes nine intersections, three major and six minor, all of which are controlled by actuated and coordinated signals. Most of the segments between the intersections were long enough (1,000 to 3,000 feet) to facilitate lane changes.

The volume data (turning movements), signal timing, phasing data, and geometrics of the study road were available as a Synchro file from a previous study done at the UTCA. This Synchro file was exported to CORSIM. In order to represent a saturated traffic condition, the PM peak hour volume was used. To represent a free flow condition the PM peak volume was reduced by 50%.

Simulation Runs

The CORSIM file was simulated as per the recommendations of one of the previous studies done at the UTCA (Gurupackiam, Jones, Turner, and Fonseca, 2008) which includes eight simulation runs to get a mean value of the MOEs under consideration and a simulation time of 60 minutes for each run. For the lane change duration parameter, two values were used for the sensitivity analysis, namely three and seven seconds. These values were selected based on the default value in CORSIM, as well as from the available literature (Toledo and Zohar, 2007; Lee, Olsen, and Wierwille, 2003; and Gurupackiam and Jones, 2009). Similarly, for the other parameter, the mean longitudinal distance to make a lane change, the two values selected were 300 and 2,500 feet. The test values were widely separated to make it easier to isolate the effects of the change in the parameters, as compared to the default values embedded in CORSIM.

Investigation Steps

Step I This step focused on the sensitivity of lane change durations. It involved simulating the study road network with two different lane change durations – three and seven seconds. All other parameters were unchanged during the simulation. For this step, the volume data corresponding to the PM peak hour was used. Measures of effectiveness (MOEs) including vehicle miles, total time, delay, and average speed of the entire network were obtained for 10 simulation runs. Network MOEs were considered because it was thought that changes in lane change durations may affect the changes in MOEs for the entire network. Table 3-1 shows the mean, standard deviation, and difference between the means of the MOEs taken into consideration.

Table 3-1. Simulation Results with Two Different Lane Change Durations

MOE	LC Duration – 3 sec Mean	LC Duration – 3 sec STDEV	LC Duration – 7sec Mean	LC Duration – 7sec STDEV	Difference in Mean (%)
Vehicle Miles	38165.88	213.87	38282.27	225.47	0.31
Delay (veh-hrs)	701.66	8.12	705.09	8.61	0.49
Total Time (veh-hrs)	1670.16	12.01	1675.91	12.68	0.34
Avg. Speed (mph)	22.85	0.07	22.84	0.08	-0.03

From Table 3-1, it can be observed that with an increase in the lane change duration from three to seven seconds, there is a marginal increase in the vehicle miles, delay and total time, and a marginal decrease in the average speed. These trends are as expected; however, there is a no statistically significant difference between the two results. A t-test for determining the difference in means proved that the two sets of results are not different at a 90% confidence interval. Hence, to further the investigation the movement-wise MOEs and number of lane changes were considered for comparison for three and seven seconds' lane change durations.

Step II Because this step involves a movement-wise analysis, the MOEs considered were number of lane changes, through movement delay, and the left movement delay. Table 3-2 shows the mean number of lane changes, mean delay of through traffic, and mean delay of left turning traffic traveling south for each segment in the study road. The table also includes the difference (%) between the mean values obtained from the two lane change durations, and the result of hypothesis testing for the null or alternate hypothesis. Hypothesis testing for the difference between the means was conducted with a t-test at a 90% confidence interval; the null and alternate hypotheses are defined as follows:

H_0: There is no difference between the MOEs obtained for different lane change durations or look ahead distances.
H_A: There is a difference between the MOEs obtained for different lane change durations or look ahead distances.

The results in Table 3-2 indicate that, in general, the mean number of lane changes decreased with an increase in lane change duration, and the mean values of through movement delay increased with an increase in lane change duration. The hypothesis testing proved that the mean number of lane changes for four stretches in the study road with a seven-second lane change duration are statistically different, and less than those obtained with a three-second lane change duration.

Table 3-2. MOEs of All the Links in the Study Road

Link/Stretch	Mean Number of Lane Changes			H_0 or H_A	Mean Thru Delay(v-m)			H_0 or H_A	Mean Left Delay (v-m)			H_0 or H_A
	LCD: 3 sec	LCD: 7 sec	Diff (%)		LCD: 3 sec	LCD: 7 sec	Diff (%)		LCD: 3 sec	LCD: 7 sec	Diff (%)	
US-82, north of 13th St	1370	1364	-0.4	H_0	561	562	0.2	H_0	134	131	-1.6	H_0
US-82, between 13th & 15th St	1298	1305	0.5	H_0	701	676	-3.6	H_0	719	711	-1.1	H_0
US-82, between U-Mall & 15th St	1014	1003	-1.1	H_0	533	542	1.8	H_0	174	172	-1.2	H_0
US-82, between Hargrove & Mall	1500	1480	-1.3	H_0	975	1005	3.0	H_0	383	378	-1.3	H_0
US-82, between 31st & Hargrove	1171	1126	-3.9	H_A	274	277	1.3	H_0	7	7	0.0	H_0
US-82, between 31st & 37th St	903	897	-0.6	H_0	507	512	1.1	H_0	103	103	0.0	H_0
US-82, between 37th & Ramp	514	463	-9.9	H_A	92	91	-0.1	H_0	0	0	0.0	H_0
US-82, between Ramp & 37th St	1078	999	-7.3	H_A	196	197	0.7	H_0	0	0	0.0	H_0
US-82, between I-20 Ramps	1338	1302	-2.7	H_0	194	216	11.6	H_A	265	264	-0.2	H_0
US-82, between Mall & I-20 Ramp	1367	1350	-1.2	H_0	157	186	18.8	H_A	399	394	-1.3	H_0
US-82, between Skyland & Mall	1176	1314	11.7	H_A	361	422	17.0	H_A	873	886	1.4	H_0

These observations were as expected. However, there were a few stretches which bucked the general trend (refer to the shaded values on Table 3-2). These stretches either showed an increase in the number of lane changes with increased lane change duration, or a decrease in the mean through delay with increased lane change duration. Also, the trend was mixed for mean values of left movement delay, with increased lane change duration. To understand this, the percentage of southbound turning movements was evaluated (Table 3-3). From this table, it was found that the turning movements (left and right turns) at those stretches which bucked the general trend were considerably higher than those of other stretches. But this alone did not seem to be the only reason for the anomalous results in these few stretches.

Table 3-3. Percentage of Turning Movements and Volumes for All Links in the Study Road

Link/Stretch	Turning Movements (%)			Volume (vph)
	Left	Thru	Right	
US-82, north of 13th St	9	90	1	1956
US-82, between 13th & 15th St	25	63	12	1830
US-82, between U-Mall & 15th St	8	92	0	1893
US-82, between Hargrove & Mall	12	82	6	2045
US-82, between 31st & Hargrove	1	91	8	1970
US-82, between 31st & 37th St	4	91	5	1905
US-82, between 37th & Ramp	0	100	0	1964
US-82, between Ramp & 37th St	0	83	17	1964
US-82, between I-20 Ramps	14	86	0	1776
US-82, between Mall & I-20 Ramp	13	81	6	2059
US-82, between Skyland & Mall	38	47	15	1503

From the road network, it was also observed that the length of two arterial sections, between I-20 and the Mall and the one between the Mall and Skyland Boulevard, were relatively small but had a high number of lane changes. To give additional insight into traffic behavior of these locations a visual observation was conducted as the simulation was underway. The simulation with each lane change duration was observed separately. The visual observation led to an interesting finding which is described in the following paragraph.

When some of the vehicles turning left or right received instruction from the simulation model (as indicated by a change in the color of vehicles on the display screen) to change lanes for the storage bay, the bay was already queued. These vehicles stopped in the middle of a through lane, causing the following vehicles to change lanes to pass them, and then, to move back to their original lanes. This is a clear case where the simulation model provided of insufficient longitudinal distance to make a lane change.

The default value for the mean longitudinal distance for a lane change in CORSIM is 300 feet and this value can be as low as 225 feet because of the decile distribution used for this parameter. This parameter coupled with an increased lane change duration value of seven seconds could have resulted in the increased number of lane changes for the stretches which bucked the general trend. Visual observation of the simulation also showed that this condition was more prevalent with increased lane change duration. However, visual observation failed to shed light on the delay anomaly in one stretch where increased lane change duration resulted in decreased delay.

The researchers thought that a comparison of results between saturated and free flow conditions could help explain the anomalous results obtained in this step. As mentioned earlier, the volume of the free flow network was 50% of that of a saturated condition. Hence, in the next step, a comparison of simulation results between saturated and free flow conditions was performed with a much smaller network to simplify the analysis.

Step III The reduced network consisted of two intersections, the link between them and one link beyond both of them. Lane change durations of three and seven seconds and look ahead distances of 300 feet and 2500 feet were analyzed. Simulation runs were performed for a saturated network (with PM peak hour volume data) and a network with free flow conditions (half of the PM peak hour volume). The experimental design for performing this sensitivity analysis is shown in Figure 3-1.

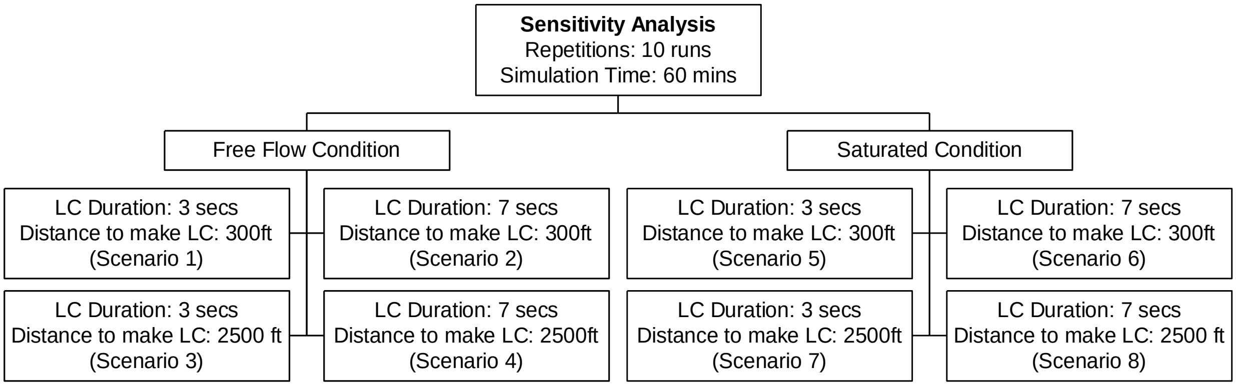


Figure 3-1. Experimental design setup for sensitivity analysis of selected parameters to a saturated and a free flow network.

Eight scenarios were performed as shown in Figure 3-1. For each scenario the number of lane changes and through movement delay on the links of the reduced road network were obtained. Tables 3-4 and 3-5 show the mean number of lane changes for scenarios 1 to 4, and scenarios 5 to 8, respectively.

Table 3-4. Mean Number of Lane Changes from Sensitivity Analysis of Lane Change Duration and Look Ahead Distance in a Free Flow Condition

Mean Number of Lane Changes – Testing for **Lane Change Duration**						
Link/Stretch	Scenario 1 Free flow 3 s, 300'	Scenario 2 Free flow 7 s, 300'	Diff (%)	Scenario 3 Free flow 3 s, 2500'	Scenario 4 Free flow 7 s, 2500'	Diff (%)
US82, South of Univ Mall, NB	306	298	-2.5	316	305	-3.6
US82, Univ Mall - 15th, NB	418	417	-0.2	371	371	0.0
US82, North of 15th Street, NB	123	113	-8.2	123	117	-4.7
US82, North of 15th Street, SB	512	512	0.0	514	502	-2.4
US82, UMall - 15th, SB	327	331	1.3	325	313	-3.6
US82, South of UMall, SB	198	195	-1.7	196	190	-2.8
Mean number of Lane Changes – Testing for **Look Ahead Distance**						
Link/Stretch	Scenario 1 Free flow	Scenario 3 Free flow	Diff (%)	Scenario 2 Free flow	Scenario 4 Free flow	Diff (%)
US82, South of UMall, NB	306	316	3.3	298	305	2.3
US82, UMall - 15th, NB	418	371	-11.0	417	371	-11.0
US82, North of 15th Street, NB	123	123	0.0	113	117	3.0
US82, North of 15th Street, SB	512	514	0.4	512	502	-2.0
US82, UMall - 15th, SB	327	325	-0.6	331	313	-5.4
US82, South of UMall, SB	198	196	-1.0	195	190	-2.6

In Table 3-4, the sensitivity testing of lane change duration for a free flow condition include the comparison of results from scenarios 1 and 2 and scenarios 3 and 4. As shown in Figure 3-1, in scenarios 1 and 2, the look ahead parameter was kept constant at 300 feet but lane change durations varied (three seconds for scenario 1 representing faster lane changes and seven seconds for scenario 2 representing slower lane changes). Scenarios 3 and 4 are similar to scenarios 1 and 2 except that the look ahead parameter is held constant at 2,500 feet.

From this testing, it can be observed that irrespective of the look ahead distance, an increased lane change duration or slower lane changes resulted in a decrease in the number of lane changes. This is the expected result. A comparison of results from scenarios 1 and 2 shows that in four out of six links the number of lane changes decreased as lane change duration increased. Similarly, considering scenarios 3 and 4, the number of lane changes for five out of six links decreased with an increased lane change duration.

The sensitivity testing of look ahead distances involved holding the lane change duration constant, and varying the look ahead parameter. The results of this test include comparison of scenarios 1 and 3 and scenarios 2 and 4. They indicate that an increased look ahead distance resulted in mixed results, i.e., with an increased look ahead distance, some links showed a decrease in the number of lane changes, and for other links, the number of lane changes increased. Between scenarios 1 and 3, only three out of six links showed a decrease in the number of lane changes with increased look ahead distance. Similarly, between scenarios 2 and 4, four out of six links showed a decrease in the number of lane changes with increased look ahead distance.

Table 3-5. Sensitivity Analysis of Mean Number of Lane Changes for Lane Change Duration and Look Ahead Distance in a Saturated Condition

Mean Number of Lane Changes – Testing for **Lane Change Duration**						
Link/Stretch	Scenario 1 Free flow 3 s, 300’	Scenario 2 Free flow 7 s, 300’	Diff (%)	Scenario 3 Free flow 3 s, 2500’	Scenario 4 Free flow 7 s, 2500’	Diff (%)
US82, South of UMall, NB	688	684	-0.6	676	667	-1.4
US82, UMall - 15th, NB	1163	1162	-0.1	1031	1044	1.3
US82, N of 15th Street, NB	306	282	-7.8	298	287	-3.6
US82, N of 15th Street, SB	1209	1243	2.8	1204	1231	2.3
US82, UMall - 15th, SB	927	924	-0.3	902	893	-0.9
US82, South of UMall, SB	485	456	-6.0	473	452	-4.5
Mean number of Lane Changes – Testing for **Look Ahead Distance**						
Link/Stretch	Scenario 5 Saturated 3 s, 300’	Scenario 7 Saturated 3 s, 2500’	Diff (%)	Scenario 6 Saturated 7 s, 300’	Scenario 8 Saturated 7 s, 2500’	Diff (%)
US82, South of UMall, NB	688	676	-1.7	684	667	-2.5
US82, UMall - 15th, NB	1163	1031	-11.3	1162	1044	-10.2
US82, N of 15th Street, NB	306	298	-2.6	282	287	1.8
US82, N of 15th Street, SB	1209	1204	-0.4	1243	1231	-1.0
US82, UMall - 15th, SB	927	902	-2.7	924	893	-3.4
US82, South of UMall, SB	485	473	-2.5	456	452	-0.9

The results in Table 3-5 obtained from saturated traffic flow are similar to those obtained from Table 3-4 for free flow conditions. The sensitivity testing for lane change duration indicated that an increased lane change duration resulted in a decrease in the number of lane changes. A comparison of results from scenarios 5 and 6 shows that higher lane changing times resulted in decreased numbers of lane changes. The mean number of lane changes decreased for five out of six links when lane change duration increased. The same trend was observed in four out of six links while comparing results from scenarios 7 and 8. Similarly, the sensitivity testing for the look ahead parameter indicated that an increased look ahead parameter resulted in a decrease in the number of lane changes. In other words, when drivers in CORSIM had longer distances to decide to change lanes, they changed lanes fewer times.

By comparing scenarios 5 and 7, it can be observed that all the links showed a decrease in the number of lane changes with increased look ahead distance. Between scenarios 6 and 8, the number of lane changes decreased for five out of six links, when look ahead distance increased. The southward traffic movement on the US-82 link, north of 15th street, bucked the general trend. In this link, the number of lane changes actually increased with increase in the duration of lane changes. As explained earlier in step II, this counter intuitive result in this link could be attributed to two reasons. The first one is insufficient look ahead distance; 300 feet is less than the storage bay length for left turns. The other reason is that the queue on the left turn bay spills back to the through lane, causing drastic variations in driver behavior in the simulation model.

The observations from tables 3-4 and 3-5 generally matched what was intuitively expected.

- Slower lane changes need relatively larger gaps when compared to gaps needed for faster lane changes. Hence, an increased lane change duration (slower lane changes) resulted in a reduced number of lane changes.
- The look ahead distance governs lane changing to reach a specific goal lane. Perhaps, an increased look ahead distance directs drivers to change lanes at a more upstream location thus reducing the opportunity for any desired lane changes further downstream till the turn movement. Hence, an increased look ahead distance results in a reduced number of lane changes.

Table 3-6 shows the mean through delay for scenarios 1 to 4. The sensitivity testing for lane change duration indicated that in a free flow traffic condition, faster or slower lane changes did not increase or decrease the through movement delays significantly. A comparison of results between scenarios 1 and 2 and scenarios 3 and 4 of Table 3-6 shows that the through delay at all the six links did not increase or decrease significantly (the change in mean through delay was less than 1%). Similarly, the look ahead distance did not have any significant impact on the through delay for a free flow traffic condition. The testing for look ahead distance in Table 3-6 shows that five out of six links had changes in mean through delay of less that 1%. It can be noted that the changes observed in the number of lane changes in Table 3-4 had a minimal effect on the through movement delays.

Similarly, from Table 3-7, the sensitivity testing of lane change duration for a saturated traffic condition shows that irrespective of the look ahead distance, slower lane changes resulted in increased through delay. This is intuitive (slower lane changes increase travel time and hence increase delay). In Table 3-7, a comparison between the results of scenario 5 and 6 shows that the mean through delay increased for four out of six links. The same comparison between scenarios 7 and 8 showed that the mean through delay increased for five out of six links. The sensitivity testing for look ahead distance yielded mixed results

Table 3-6. Sensitivity Analysis of Mean Through Delay for Lane Change Duration and Look Ahead Distance in a Free Flow Condition

Mean Number of Lane Changes – Testing for **Lane Change Duration**

Link/Stretch	Scenario 1 Free flow 3 s, 300’	Scenario 2 Free flow 7 s, 300’	Diff (%)	Scenario 3 Free flow 3 s, 2500’	Scenario 4 Free flow 7 s, 2500’	Diff (%)
US82, South of UMall, NB	68.5	68.6	0.1	69.6	69.4	-0.3
US82, UMall - 15th, NB	171.8	171.7	-0.1	171.8	171.1	-0.4
US82, North of 15th Street,	38.2	38.3	0.3	38.2	38.4	0.5
US82, North of 15th Street,	176.9	176.8	-0.1	178	176.5	-0.8
US82, UMall - 15th, SB	86.1	86	-0.1	85.8	85.5	-0.3
US82, South of UMall, SB	41.3	41.5	0.5	41.2	41.5	0.7

Mean number of Lane Changes – Testing for **Look Ahead Distance**

Link/Stretch	Scenario 1 Free flow 3 s, 300’	Scenario 3 Free flow 3 s, 2500’	Diff (%)	Scenario 2 Free flow 7 s, 300’	Scenario 4 Free flow 7 s, 2500’	Diff (%)
US82, South of UMall, NB	68.5	69.6	1.6	68.6	69.4	1.2
US82, UMall - 15th, NB	171.8	171.8	0.0	171.7	171.1	-0.3
US82, N of 15th Street, NB	38.2	38.2	0.0	38.3	38.4	0.3
US82, N of 15th Street, SB	176.9	178	0.6	176.8	176.5	-0.2
US82, UMall - 15th, SB	86.1	85.8	-0.3	86	85.5	-0.6
US82, South of UMall, SB	41.3	41.2	-0.2	41.5	41.5	0.0

Table 3-7. Sensitivity Analysis of Mean Through Delay for Lane Change Duration and Look Ahead Distance in a Saturated Condition

Mean Number of Lane Changes – Testing for **Lane Change Duration**

Link/Stretch	Scenario 5 Saturated 3 s, 300’	Scenario 6 Saturated 7 s, 300’	Diff (%)	Scenario 7 Saturated 3 s, 2500’	Scenario 8 Saturated 7 s, 2500’	Diff (%)
US82, South of UMall, NB	294.4	295.0	0.2	299.6	301.8	0.7
US82, UMall - 15th, NB	719.5	707.6	-1.7	704.5	702.7	-0.3
US82, North of 15th Street,	92.4	93.1	0.8	92.7	92.9	0.2
US82, North of 15th Street,	795.4	814.8	2.4	798.7	818.5	2.5
US82, UMall - 15th, SB	497.3	503.5	1.2	495.7	497.7	0.4
US82, South of UMall, SB	126.1	125.4	-0.6	125	125.7	0.6

Mean number of Lane Changes – **Testing for Look Ahead Distance**

Link/Stretch	Scenario 5 Saturated 3 s, 300’	Scenario 7 Saturated 3 s, 2500’	Diff (%)	Scenario 6 Saturated 7 s, 300’	Scenario 8 Saturated 7 s, 2500’	Diff (%)
US82, South of UMall, NB	294.4	299.6	1.8	295.0	301.8	2.3
US82, UMall - 15th, NB	719.5	704.5	-2.1	707.6	702.7	-0.7
US82, N of 15th Street, NB	92.4	92.7	0.3	93.1	92.9	-0.2
US82, N of 15th Street, SB	795.4	798.7	0.4	814.8	818.5	0.5
US82, UMall - 15th, SB	497.3	495.7	-0.3	503.5	497.7	-1.2
US82, South of UMall, SB	126.1	125	-0.9	125.4	125.7	0.2

From the sensitivity analysis of lane change duration and look ahead distance in both free flow and saturated traffic condition, the following broad observations were drawn:

- Lane changing parameters are less sensitive to free flow traffic conditions than congested conditions. A change in the lane change duration or the look ahead distance does not significantly affect the results of microscopic traffic simulation. Saturated traffic conditions are complex to understand. Sensitivity analyses of lane changing parameters in saturated conditions yielded mixed results, thus clear patterns could not be drawn. Speed of lane changing is easier to interpret than look ahead distance. Irrespective of the look ahead distance, increased lane change durations resulted in decreases in the number of lane changes and increases in delay.
- For a saturated network, the two parameters considered in this study alone cannot explain the results. It is possible that the anomalies and mixed results observed in the sensitivity analysis might be explained with more rigorous analysis with different parameters governing the lane changing process.

Apart from these sensitivity analyses, an attempt was made to study the combined effect of speed of lane changes and look ahead distance; for instance, the simulation results obtained using three seconds lane change duration and 300 feet look ahead distance were compared with that obtained using seven seconds lane change duration and 2500 feet look ahead distance. However, the comparison did now show any clear pattern. The investigators concluded that it would take a more rigorous analysis to identify the effects of changes to multiple parameters.

Extension of the Understanding of Lane Changing Parameters in CORSIM to SimTraffic and AIMSUN

CORSIM was used for this study, but since the lane changing algorithms in other simulation tools including SimTraffic and AIMSUN are similar in principle, an attempt was made to extend the findings of this study to SimTraffic and AIMSUN.

- In SimTraffic, ‘positioning distance’ is similar to the mean longitudinal distance to make a lane change in CORSIM. This positioning distance is determined using the formula Max(300’, v * 30s) where ‘v’ is the speed of the vehicle. For instance, assuming the range of speed for vehicles to be within 30 to 50 mph for an urban street, the range of the parameter is obtained as 1,320 to 2,200 feet. This range appears to be much larger than the length of most of the storage bays for turning movements on urban arterials. Hence, it can be expected that the lane changing issues relating to insufficient length of storage bays during queuing conditions will not arise. The other parameter, the duration of lane change, could not be found in the SimTraffic user manual.
- Similarly, in AIMSUN, ‘Zone 2’ is the parameter which is equivalent to the positioning distance in SimTraffic and mean longitudinal distance to make a lane change in CORSIM. Zone 2 is calculated using the following formula:

$$D_m = D_t \cdot S_{\mathrm{lim}\,it}(s) \cdot \left[\frac{S_{\mathrm{lim}\,it}(s)}{v_{\max}(i,s)} \right] \qquad \text{……………………………………………………………………… (3.1)}$$

Where

D_m: Distance in meters
D_t: Distance in seconds (default value 23 seconds)
S_{limit}: Speed limit of the section 's'
v_{max} (i, s): Maximum desired speed of vehicle 'i' on a section or turning 's'

In this function, faster vehicles (with respect to the speed limit) require shorter zones than slower vehicles. Assuming an urban street with a speed limit of 50 mph and the speed of a vehicle ranging between 40 and 60 mph, the value of the parameter 'Zone 2' will be between 2,110 and 1,410 feet, respectively. This range of the parameter appears to be much larger than most of the storage bay lengths for turning movements on urban arterials. In this case, it appears that the lane changing issues relating to insufficient length of storage bays during queuing conditions will not arise. The other parameter, namely the duration of lane change or any other equivalent parameter, could not be found in the AIMSUN user manual.

Conclusions

This study explored the sensitivity of two lane changing parameters, the lane change duration, and the mean longitudinal distance for making lane changes, in saturated and free flow traffic conditions. The following conclusions were drawn from the study of one location:

- The MOEs are sensitive to lane change duration. An increase in lane change duration resulted in a decrease in the number of lane changes on the links of the study road. Since the second research step and earlier studies have shown that lane change duration follows a specific distribution, it seems reasonable that the current simulation lane changing models be calibrated with the specific distribution of lane change duration of the location that is being studied.
- The MOEs are also sensitive to the mean longitudinal distance needed to make lane changes. Since this parameter affects vehicles changing lanes in preparation for a turn (left or right) at the approaching intersection, the mean value of this parameter should be larger than the length of storage bays for turning movements so that vehicles can change lanes well ahead of approaching the turning bay, thus reflecting field conditions, particularly during saturated traffic flow. For instance, the default value of the mean longitudinal distance to make a lane change in CORSIM is only 300 feet, and this value can be as small as 225 feet because of the decile distribution used for this parameter. Some of the storage bays for turning movements may be longer than 225 feet; so some vehicles may not even receive instructions to change lanes even while nearing the turn bay.
- For saturated links in general, and particularly those with a high percentage of turning movements, it was difficult to study the trend in MOEs with changes to lane change parameters. This could be because of high interaction between vehicles in such traffic conditions, but the researchers were not able to establish such a finding.

- Lane changing parameters are relatively less sensitive during free flow traffic conditions. A change in the lane change duration or the look ahead distance does not significantly affect the results of microscopic traffic simulation.
- Speed of lane changing is easier to interpret than look ahead distance. Irrespective of the look ahead distance, an increased lane change duration resulted in a decrease in the number of lane changes or an increase in delay.
- Observations from sensitivity analysis of lane change parameters showed what was thought intuitively i.e., slower lane changes or higher look ahead distances resulted in lesser number of lane changes.
- For a saturated network, the two parameters considered in this study alone cannot explain the results. The anomalies and mixed results observed in the sensitivity analysis may be explained with more rigorous analysis with different parameters governing the lane changing process.
- In SimTraffic and AIMSUN, the range of default look ahead distance appears to be much larger than the length of most of the storage bays for turning movements on urban arterials. Hence, it can be expected that the lane changing issues relating to insufficient length of storage bays during queuing conditions will not arise. However, the other parameter, the duration of lane change, could not be found in the user manual of either of these simulation models.

Future Research

Though this study showed that the number of lane changing and delay are sensitive to changes in lane change parameters, due to time constraints, the model was not validated with field results. Hence, further work should be done to calibrate the model with lane changing duration and longitudinal distance parameter for making lane changes, reflecting field conditions. They should also be validated for the same model with field results. Other lane changing parameters such as minimum deceleration for lane changing, mean time for a driver to react to a sudden deceleration of the lead vehicle, headway below which all drivers will attempt to change lanes, etc., should be explored particularly in saturated traffic conditions.

4.0 Findings and Recommendations

Summary

The objective of this UTCA project is to investigate the changes between undersaturated and saturated traffic conditions at arterial signals in terms of performance measures (delay) and operational parameters (gap acceptance and lane changing). This research utilized field data and microscopic traffic simulation to investigate free flow and saturated traffic conditions of traffic signals on arterial highways. Despite the robustness and wide spread use of traffic microsimulation models for this type of analysis, some gaps and limitations still exist that can affect the accuracy of the results produced by the models. Also, changes in driver behavior parameters such as lane changing and gap acceptance under different traffic conditions are not completely understood. Hence, the purpose of this research was to enhance the understanding of traffic characteristics and driver behavior parameters such as lane changing and gap acceptance under different traffic conditions to improve the accuracy of microscopic traffic simulation, particularly, while simulating saturated traffic conditions.

Overall Findings

Based on the analysis conducted using field data and microscopic traffic simulation to investigate free flow and saturated traffic conditions on arterial highways, the following broad findings were obtained:

- Traffic flows at signals that are approaching saturation are still complex to analyze, and the interactions between traffic parameters are not well understood.
- When traffic flow on an arterial approaches saturation, drivers take higher risks. For instance, drivers accept smaller gaps.
- The statistical distributions obtained for gap acceptance and lane changes confirmed what is suspected intuitively, i.e., when the traffic flow is heavy the probabilities of drivers accepting smaller gaps and changing lanes rapidly are higher than that during a moderate traffic flow.
- Existing microscopic traffic simulation tools simplify some of the traffic parameters in simulation models. These parameters may be recoded or recalibrated for better accuracy of simulation results.

Findings from the Research Effort Entitled "Observed Variations in Gap Acceptance and Lane Changing in Relation to Traffic Flow Rates in Urban Streets"

This part of the research was a field investigation of the variations in gap acceptance and lane changing in relation to different traffic flow rates. It compared the field results with corresponding values in some of the common microscopic traffic simulation models. The key findings of this research effort are given below:

- The sizes of accepted gaps (seconds) are statistically different for free flow and saturated traffic conditions. Specifically, the mean values of accepted gaps ranged from 4.33 to 4.04 seconds for average flow rates of 20 and 80 vehicles per minute, and standard deviations were around 1.6 seconds. A hypothesis test proved that the extreme values (4.33 and 4.04) are statistically different.
- With increased flow rate, there was an increase in the number of drivers accepting smaller gaps. In other words, the median value of accepted gaps for the lowest flow rate (20 vehicles per minute) was 4.33 seconds, and that for the highest flow rate (80 vehicles per minute) was 3.74 seconds, respectively.
- The shape and skewness of the best fitted distributions for accepted gaps also showed a higher probability of drivers accepting smaller gaps when the traffic flow is heavy.
- The observations of lane change durations were similar to observations of accepted gaps. The lane change durations corresponding to free flow and saturated traffic conditions were statistically different. Specifically, the mean value of the lane change durations ranged from 4.34 to 4.19 seconds for average flow rates of 20 and 80 vehicles/minute, and the standard deviations were around 0.9 seconds. A hypothesis test proved that the extreme values (4.34 and 4.19) are indeed different.
- The variation of lane change durations is less than the variation of accepted gaps, which indicates that gap acceptance is more sensitive than lane change duration.
- The median values of lane change duration irrespective of the flow rate were around 4.25 seconds, which shows that 50% of the drivers took 4.25 seconds or less to change lanes.
- The shape and skewness of the best fitted distributions of lane change durations showed that the probability of drivers changing lanes more rapidly is marginally higher when traffic flow is heavy.
- The rate of lane changes decreased with increased traffic flow, probably because the number of available gaps decreased with increased traffic flow. Also, since there are fewer available gaps during higher traffic flow or saturated flow conditions, drivers accept smaller gaps.
- To summarize the findings of this part of the research, it can be observed that when traffic flow on a typical arterial approaches saturation, a considerable number of drivers accept smaller gaps and change lanes more rapidly. In other words, drivers take higher risks to change lanes during congested traffic flow.
- All the above findings in this research have direct implications upon the gap acceptance and lane changing parameters used in microscopic traffic simulation, particularly during model calibration. The default values of lane changing and gap acceptance parameters used in some of the common traffic simulation tools are different from those obtained in this study. For instance, CORSIM has a default lane change duration value of 3 seconds while the results obtained in this study show that the mean value of lane change duration

varied from 4.19 to 4.34 seconds depending on the traffic flow rate. Moreover, the gap acceptance (while changing lanes) distributions obtained in this study may be used in lane change models in microscopic traffic simulation models.

Findings from the Research Effort Entitled “Sensitivity Analysis of Lane Change Parameters to Saturated and Free Flow Traffic Conditions in Microscopic Traffic Simulation Models”

This research effort investigated the sensitivity of lane change parameters, including lane change duration and look ahead distance, to free flow and saturated traffic flow in microscopic traffic simulation models. The major findings of this part of the research, drawn from a simulation of a single arterial, are given below:

- The MOEs are sensitive to lane change duration. An increase in lane change duration resulted in a decrease in the number of lane changes on the links of the study road. Since the second research step and earlier studies have shown that lane change duration follows a specific distribution, it seems reasonable that the current simulation lane changing models be calibrated with the specific distribution of lane change duration of the location that is being studied.
- The MOEs are also sensitive to mean longitudinal distance needed to make lane changes. Since this parameter affects vehicles changing lanes in preparation for a turn (left or right) at the approaching intersection, the mean value of this parameter should be larger than the length of storage bays for turning movements, so that vehicles can change lanes well ahead of approaching the turning bay, thus reflecting field conditions, particularly during saturated traffic flow. For instance, the default value of mean longitudinal distance to make a lane change in CORSIM is only 300 feet and this value can be as small as 225 feet because of the decile distribution used for this parameter. Some of the storage bays for turning movements may be longer than 225 feet; so some vehicles may not even receive instructions to change lanes even while nearing the turn bay.
- For saturated links in general, and particularly those with a high percentage of turning movements, it was very difficult to study the trend in MOEs caused by changes to lane change parameters. This could be because of high interaction between vehicles in such traffic conditions, but the researchers were not able to establish such a finding.
- Lane changing parameters are relatively less sensitive during free flow traffic conditions. Modifying the lane change duration or the look ahead distance does not significantly affect the results of microscopic traffic simulation.
- Speed of lane changing is easier to interpret than look ahead distance. Irrespective of the look ahead distance, an increase in lane change duration resulted in a decrease in the number of lane changes or an increase in delay.
- Observations from a sensitivity analysis of lane change parameters showed what was thought intuitively, i.e., slower lane changes or higher look ahead distances resulted in less lane changes.
- For a saturated network, the two parameters considered in this study alone cannot explain the results. The anomalies and mixed results observed in the sensitivity analysis might be

explained with more rigorous analysis with different parameters governing the lane changing process.

- In SimTraffic and AIMSUN, the range of default look ahead distances appears to be much larger than the length of most of the storage bays for turning movements on urban arterials. Hence, it can be expected that the lane changing issues relating to insufficient length of storage bays during queuing conditions will not arise. However, the other parameter, the duration of lane change, could not be found in the user manual of either of these simulation models.

Recommendations for Future Research

This research project has advanced knowledge of traffic flow characteristics at busy traffic signals, and has contributed to enhanced accuracy of microscopic traffic simulation under saturated conditions. The research also has led to additional ideas for future research to increase knowledge in this area. These ideas are listed below:

- The sample size of collected data for accepted gaps and lane changes should be increased to reduce data-related variation.
- Instead of flow rates, driver behavior parameters including accepted gaps and lane change durations should be compared with more representative parameters such as delay, speed or LOS of the arterial approach under consideration.
- Though this study showed that MOEs are sensitive to modifications to lane change parameters, due to time constraints, the model was not validated with field results. Hence, further work should be done to calibrate the model with the lane change parameters (lane changing duration and the longitudinal distance for making lane changes) reflecting field conditions. The model should also be validated with field results obtained from different locations.
- Other lane changing parameters such as minimum deceleration for lane changing, driver reaction times, and headway below which drivers attempt to change lanes, etc., should be explored, particularly in saturated traffic conditions.
- Enhanced statistical methods should be used for analyzing results of microscopic simulation models.
- Since this study was conducted at one single site, the same study could be repeated on other sites and other roadways to verify or extend the findings of this dissertation research.

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