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16. Abstract

Due to the frequent presence of median openings in urban arterial settings, the requirements for the deceleration and storage of turning vehicles (e.g. AASHTO Green Book) often exceed the available length between two adjacent openings which leaves traffic engineers having to decide whether left-turn lanes, shorter than the standards, can be used or not. The goal of this research is to investigate the minimum required length for the left-turn lanes at the unsignalized median openings, and study the safety and operational impacts of such left-turn lanes with substandard lengths. To achieve this goal, researchers will: 1) synthesize existing related research; 2) develop models for storage lengths at unsignalized median openings; 3) develop models for estimating the delays caused by substandard deceleration lengths and the resulting excessive deceleration on main travel lanes; and 4) analyze safety impacts of substandard median left-turn lanes.

The results of this study lead to following key findings: 1) at the operational impacts perspective- if a substandard length left-turn lane can accommodate the necessary storage length and the deceleration length assuming a 20mph speed differential, it will not affect the operational performance of median openings significantly and the delays caused by using substandard length left-turn lane are significantly less than the delays associated with the absence of dedicated left-turn lanes; 2) at the safety impacts perspective- substandard length left-turn lanes will affect the safety performance of median openings. However, when it is impractical to provide the Greenbook required length, use of substandard length left-turn lanes may still be an option because of operational benefits comparing the no dedicated left-turn lane option; and 3) based on traffic simulation study- the required storage length is less than that estimated by the AASHTO "two-minute arrival" rule-of-thumb method. The minimum required storage length can be estimated with the regression model developed in this research.

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LEFT-TURN LANES AT UNSIGNALIZED MEDIAN OPENINGS

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SUMMARY

As a representative access-management technique, raised medians are widely used on urban arterials, and a median left-turn lane is a favorable design element for median openings. The lanes provide space for deceleration and then offer refuge for vehicles awaiting an opportunity to turn left, and thereby keep the highway travel lanes clear for through traffic. The placement of median openings determines the maximum available length that can be used for installing median left-turn lanes. Due to the frequent presence of median openings in urban arterial settings, the requirements for the deceleration and storage of turning vehicles (e.g. AASHTO Green Book) often exceed the available length between two adjacent openings which leaves traffic engineers having to decide whether left-turn lanes shorter than the standards can be used or not.

The goal of this research is to investigate the minimum required length for the left-turn lanes at the unsignalized median openings, and study the safety and operational impacts of such left-turn lanes with substandard lengths. To achieve this goal, the researchers have performed the following key tasks:

1) Synthesized existing related research
2) Developed models for storage lengths at unsignalized median openings
3) Developed models for estimating the traffic delays caused by substandard left-turn lanes
4) Analyzed safety impacts of substandard median left-turn lanes

The studies led to a number of findings regarding to the use of short left-turn lanes. Some of the highlighted findings include,

1) No overflows observed at study locations with short left-turn lanes.
2) The use of short left-turn lanes will incur a moderate amount of additional traffic delays, which can be estimated by the proposed analytical model. However, the additional delays are significantly less than the delays associated with the absence of dedicated left-turn lanes.

3) Statistical evidence showed that the difference between actual lane length and the Greenbook required length had significant impacts on crash potential at the study locations. For instance, as opposed to the required length, shortening the lane length by 100 feet led to a 40-percent increase in the likelihood that a crash/crashes could happen. The crash modification factor also showed that shortening the lane length by 45 feet could increase the crash rate to 3.3 times of the original crash rates.

4) The required storage length, simulated under different combinations of turning volume and opposing volume, is much less than that estimated by the AASHTO "two-minute arrival" rule-of-thumb.

The following recommendations are based on the above findings:

1) At the operational impacts perspective- generally, if a substandard length median turn lane can accommodate the necessary storage length and the deceleration length, assuming a 20 mph speed differential, a short left-turn lane would be acceptable.

2) At the safety impact perspective- when it is impractical to provide the Greenbook required length, short left-turn lanes might be acceptable in some particular cases, e.g. at some low crash rate locations, in which engineers' judgments are preferable to make the trade-off decision on whether a short left-turn lane is appropriate.

3) The minimum required storage length can be estimated with the regression model developed in this research.

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CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

Raised medians are used extensively as a representative technique of access management on urban arterial roads where it is desirable to concentrate or restrict mid-block left-turning and crossing maneuvers (*AASHTO, 2011*). A median left-turn lane is a favorable design element for median openings because such lanes provide space for deceleration, offer refuge for vehicles awaiting an opportunity to turn left, and help keep the through-traffic lanes clear for through traffic (*Qi et al., 2012*). As shown in FIGURE 1, a median left-turn lane typically is composed of two functional parts, i.e., vehicle storage and deceleration. Usually, a taper is considered part of the deceleration space.

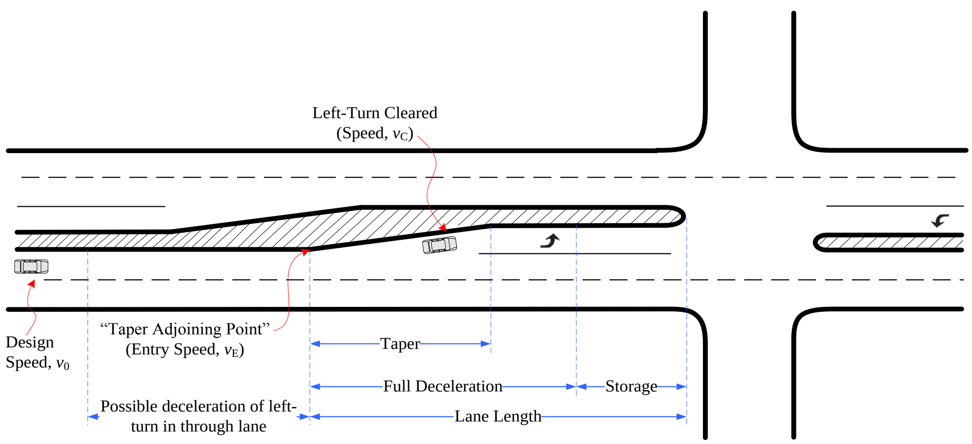


FIGURE 1 Design elements of the length of median left-turn lanes

On median-divided urban roadways, the placement of median openings is a major determinant of the available length along the roadway centerline that can be used for installing median left-turn lanes. While median openings are normally provided at all public roads and major traffic generators, traffic engineers are still under political/public pressure to provide more median openings for abutting businesses, e.g., service stations and restaurants, which rely on pass-by traffic. As a result, the requirements in the AASHTO Greenbook for the deceleration and storage of left-turning vehicles often exceed the available length between two adjacent openings. In these cases, traffic engineers have the option of using left-turn lanes with substandard lengths.

In practice, many left-turn lanes with substandard lengths already exist at many unsignalized median openings on urban arterial roads. In 2011, a survey was conducted among traffic engineers at the Texas Department of Transportation (TxDOT) and at various cities in Texas (*Fitzpatrick et al., 2010*). The survey indicated that seven of the fourteen participating TxDOT districts and agencies, i.e., 50%, already had substandard deceleration/storage lengths in use in their jurisdictions, normally through procedures of design waivers. However, many other traffic engineers still expressed a lack of confidence in using such left-turn lanes for the following reasons:

- In order to ensure that they are able to stop after entering short left-turn lanes, drivers generally decelerate earlier than they do when full-length lanes are available. Therefore, the potential for rear-end crashes increases due to the undesirable speed differential between left-turn vehicles and through vehicles in the through-traffic lanes.
- Short left-turn lanes may result in lane overflow, which can compromise the operation and safety of a corridor significantly.

Recent and current research rarely has addressed the impacts of using left-turn lanes that are shorter than the AASHTO standards, so traffic engineers are reluctant to use such lanes even though it actually may be appropriate and safe to do so.

1.2 RESEARCH GOALS AND OBJECTIVES

The goal of this research is to investigate the minimum required length for the left-turn lanes at the unsignalized median openings, and study the safety and operational impacts of such left-turn lanes with substandard lengths. The study approaches include analytical modeling, micro-simulation based analysis, and historical crash data analysis. To achieve this goal, the research will:

1. Synthesize existing related research

2. Develop models for estimating the delays caused by substandard length left turn lane
3. Analyze safety impacts of substandard left-turn lanes
4. Develop models for storage lengths at unsignalized median openings

1.3 OUTLINE OF THIS REPORT

This report documents all the research activities and findings throughout this project. Chapter 2 reviews and synthesizes national and peer states' practices on left-turn lanes at unsignalized intersections. Chapter 3 describes the study designs for the research. Chapter 4 develops a simulation model to estimate the operational impacts of left-turn lanes with substandard lengths. Chapter 5 compares the crash experience at left-turn lanes with lengths that meet and do not meet design substandards. Chapter 6 develops models to estimate the minimum required storage length at unsignalized median openings. Chapter 7 summarizes the research findings and provides recommendations.

CHAPTER 2: LITERATURE REVIEW

Few studies have been conducted to assess the impacts of left-turn lanes with substandard lengths. This chapter reviews and synthesize the available guidelines for the lengths of left-turn lanes at unsignalized intersections, existing studies related to safety impacts of left-turn lanes at unsignalized intersections, and existing studies for determining the storage length at unsignalized intersections.

2.1 AVAILABLE GUIDELINES

2.1.1 Guidelines in AASHTO Greenbook

Storage length:

According to the AASHTO Greenbook, the storage length at unsignalized intersections should be either the minimum length required (i.e., 50 ft) or the length for turning vehicles likely to arrive in an average two-minute period during the peak hour, whichever is greater. With over 10-percent of vehicles being trucks, provisions should be made for at least one car and one truck (i.e., 75 to 85 ft). In addition, the two-minute interval also may be adjusted, depending on the waiting time for sufficient gaps in the flow of opposing traffic for making permitted left turns.

Deceleration length:

TABLE 1 shows the provisions in the AASHTO Greenbook for desirable full-deceleration lengths, which were calculated based mainly on the following assumptions:

- A left-turning vehicle begins to decelerate when the front bumper passes the taper adjoining point with an entry speed v_{E} equal to the design speed v_0 (FIGURE 1). When left-turn vehicles clear the through-traffic lane, the traveling speed v_{C} (FIGURE 1) is 10 mph lower than the design speed;
- The deceleration rate d is 5.8 ft/s^2 after the turning vehicles move from the through-traffic lane into the turn lane, and then 6.5 ft/s^2 after the turning vehicles clear the traffic lane.

The basic idea in calculating the lengths is to provide an adequate length to ensure that a left-turn vehicle can come to a complete stop before it reaches the rear end of the last stored vehicle. Thus, recommended deceleration lengths were calculated basically as $v_{\mathrm{E}}^2/(2 \cdot d)$.

As stated in the Greenbook, a higher speed differential and a shorter deceleration length may be acceptable for cases in which providing the desirable full-deceleration lengths is impractical due to restricted right-of-way, insufficient length between openings, or extreme storage needs. Using the same method, TxDOT extended the provisions and suggested specific deceleration lengths for assuming speed differentials of 15 and 20 mph.

TABLE 1 Standards for full-deceleration lengths in a left-turn lane (in feet)

Design speed (mph) \ Assumed speed differential	AASHTO (2011)	TX	TX	TX	FL	ME	ND	SD	MS
	10 mph	10 mph	15 mph	20 mph	10 mph	N/A	10 mph	10 mph	5 mph
30	160	160	110	75	-	120	190	105	120
35	(215)*	215	160	110	145	-	220	145	-
40	275	275	215	160	-	165	260	185	165
45	(345)	345	275	215	185	-	350	220	-
50	425	425	345	275	240	265	390	320	265
55	(510)	510	425	345	-	-	470	385	310

**Note that, AASHTO (2011) only provides the deceleration lengths for 30 mph, 40 mph and 50 mph. The numbers in parentheses are the estimates based on the AASHTO methods.*

Total left-turn lane length:

Generally, the Greenbook required length can be mathematically written as

$$L_{\text{Required}} = D + \max\left(50,\ \left(v/30\right)\cdot S\right) \tag{1}$$

Where,

D = the deceleration length (feet, see TABLE 1 for the Greenbook requirements);

v = the left-turning volume (vph); 30 = the number of two-minute intervals in each hour;

S = the storage length for a waiting vehicle, and 25 ft/veh can be used when the percentage of trucks is under 5%.

2.1.2 Design Manuals of State Departments of Transportation

Through a careful review, it was found that many state DOTs have established their own guidelines regarding left-turn lanes at unsignalized intersections, as summarized in TABLE 2. These guidelines commonly are different from the AASHTO Greenbook standards. For instance, California, Colorado, Illinois, and Minnesota recommend deceleration lengths longer than the

Greenbook, while a few states, including Florida, Maine, North Dakota, South Dakota, and Mississippi, recommend shorter deceleration lengths (TABLE 1).

For determining the necessary storage lengths, “two-minute arrival” is used by many states as a rule-of-thumb. The method may vary from state to state, e.g., the TxDOT uses twice the two-minute arrival as the storage length, but the ConnDOT suggests that the one-minute arrival can be used for unsignalized locations. For the minimum storage required, most states follow the provisions of 50 ft in the Greenbook. However, Colorado recommends that a minimum length of 25 ft be used, while some other states (e.g., Illinois, South Dakota, Oregon, and Texas) lean toward longer lengths (e.g., 100 or 115 ft) for the minimum storage.

TABLE 2 State DOTs' standards regarding length of median left-turn lanes

	Desirable Full-Deceleration Length	Storage Length (Unsignalized)		Sources
		Rule-of-thumb method	Minimum storage	
AASHTO	See TABLE 1	2-min arrival	50 ft	AASHTO Greenbook
Arizona			50 ft	ADOT Roadway Design Guidelines
California	Longer [1]	2-min arrival	50 ft	Caltrans Highway Design Manual
Colorado	Longer	2-min arrival	25 ft	CDOT Roadway Design Guide
Connecticut		1-min to 2-min arrival	50 ft	CTDOT Highway Design Manual
Delaware	Same [2]	(2-min arrival) ×1.5	50 ft	DelDOT Road Design Manual
Florida	Shorter [3]	(2-min arrival) ×1.5 to 2	50 ft	FDOT Median Handbook
Illinois	Longer		115 ft	Bureau of Local Roads and Streets Manual
Indiana		2-min arrival	50 ft	Indiana Design Manual
Maine	Shorter		50 ft	MDOT Highway Design Guide
Minnesota	Longer	2-min arrival	50 ft	MNDOT Roadway Design Manual
Mississippi	Shorter	2-min arrival	50 ft	MSDOT Roadway Design Manual
New York	Same	(2-min arrival) ×1.5		NYDOT Highway Design Manual
North Dakota	Shorter			NDDOT Design Manual
Oregon			100 ft	ODOT Highway Design Manual
South Dakota	Shorter	2-min arrival	100 ft	SDDOT Road Design Manual
Texas	Same	(2-min arrival) ×2	100 ft	TxDOT Roadway Design Manual
Utah	Same	2-min arrival	50 ft	UDOT Roadway Design Manual of Instruction

Note: [1] “Longer” = the recommended lengths are longer than the AASHTO Greenbook standards. [2] “Same” = the manual follows the provisions in the AASHTO Greenbook. [3] “Shorter” = the recommended lengths are shorter than the Greenbook standards.

Note that some states (e.g., Maine and Mississippi) recommend shorter deceleration lengths and the same storage lengths. This implies that a considerable number of short left-turn lanes may be used in these states. In Houston, Texas, the City of Houston defines the components of the lane length in a different way, i.e., taper and storage, and the City Infrastructure Design Manual (*City of Houston, 2012*) normally leads to left-turn lanes shorter than the AASHTO Greenbook standards. The City of Houston has used the shorter left turn lanes successfully for many years for locations with low traffic demand.

2.2 EXISTING STUDIES ON THE SAFETY IMPACTS OF UNSIGNALIZED LEFT-TURN LANES

Many studies, primarily conducted during the 1960s and 1970s, have documented the safety benefits of providing left-turn lanes as opposed to no left-turn lanes at unsignalized locations. As synthesized in NCHRP Report 420 (*Gluck et al., 1999*), introducing left-turn lanes at unsignalized intersections generally led to consistent reduction in total crashes (by 50% to 77%), which included reduction of rear-end by 62% to 82% and left-turn related crashes by 37% to 90% based on studies performed at in California, Indiana, and Nebraska. An ITE study (Traffic Safety Toolbox, 1987) concluded that there was a crash reduction of approximately 30% to 65% due to the installation of left-turn lanes. Crash modification factors (CMFs) are available in the AASHTO Highway Safety Manual, indicating that, on average, installing left-turn lanes can reduce total crashes by 47% on two-lane streets and 27% on four-lane streets in urban and suburban settings. In addition, the manual provided equations for predicting total crashes with and without left-turn lanes installed at unsignalized locations, which were used in NCHRP Project 03-91 in developing left-turn lane warrants for unsignalized intersections (*Fitzpatrick et al., 2010*). A recent study conducted in Connecticut indicated that installing left-turn lanes reduced the crash severity on average (*Pimiler et al., 2003*). Collectively, safety benefits of providing left-turn lanes at unsignalized locations are widespread acceptance as opposed to no left-turn lanes.

2.3 EXISTING STUDIES ON THE STORAGE LENGTH AT UNSIGNALIZED INTERSECTIONS

A queuing model was developed by Lertworawanich and Elefteriadou (2003) for determining the storage lengths of left-turn lanes at unsignalized intersections with a single through lane and a single lane for opposing traffic. The model was developed based on the assumption that the probability of left-turn lane overflow should be less than a given threshold

(0.01, 0.02, or 0.05). It also assumed that the arrival of traffic follows a Poisson distribution. The storage lengths of left-turn lanes (in number of passenger cars) were estimated and summarized in three tables for different combinations of volumes and probabilities of left-turn lane overflows. The tables were developed based on the assumption of a critical gap of 4.1 seconds and a follow up time of 2.2 seconds. Note that critical gap was defined as the minimum gap that all left turning vehicles were assumed to accept. Follow-up time was defined as the time that elapsed from the time a left-turn vehicle accepted a gap until the next vehicle in the queue started looking for gaps. TABLE 3 is one of the reference tables in Lertworawanich and Elefteriadou (2003).

TABLE 3 Left-turn lane storage length (vehicle units) at unsignalized intersections*

Left-Turn Volume (vph)	Opposing Volume (vph)							
	500	600	700	800	900	1000	1100	1200
100	1	1	1	1	1	1	1	1
200	1	1	1	2	2	2	2	2
300	2	2	2	2	3	3	4	4
400	2	3	3	4	4	5	7	9
500	3	4	4	6	7	11	18	> 50
600	4	5	7	10	18	> 50	> 50	
700	6	9	14	33	> 50	> 50		
800	10	18	> 50	> 50				
900	22	> 50	> 50					
1000	> 50							

*Note, it is assumed that the intersections with single through and single left-turn lane, based on 0.05 probability of overflow and no heavy vehicles)

Source: Lertworawanich and Elefteriadou (2003)

Note that the left-turn queue lengths in this study were estimated based on the assumption that no heavy vehicles were present.

Queuing theory is a sound method for estimating the left-turn queue lengths at unsignalized intersections. However, the left-turn traffic volumes at the unsignalized intersections are usually very low. This is due to the fact that if the left-turn volume is greater than 200 or the cross product of left-turn volume and opposing volume is greater than 50,000, the traffic control at this intersection needs to be upgraded to the signalized or even a protected left-turn traffic control. Therefore, in TABLE 3, only the top-left cell is useful for unsignalized intersections and the recommended left-turn storage length is only one vehicle storage length. However, the occurrence of the occasional truck such as a solid waste vehicle or other heavy vehicle would cause the one vehicle storage length design to fail. Therefore, a minimum storage length, such as two vehicles (50 ft) recommended by AASHTO Green Book (2001) or four vehicles (100 ft) recommended by TxDOT Roadway Design Manual, should be applied to the intersections where there is very low left-turn volume.

2.4 SUMMARY

Existing research has rarely investigated the operational and safety impacts of adding a left-turn lane with substandard length which underscores the need for this study. The results of this study have the potential to help traffic engineers make informed decisions in future applications when it is impractical to provide full-length lanes and the use of short lanes is an option.

CHAPTER 3: DESIGN OF STUDY

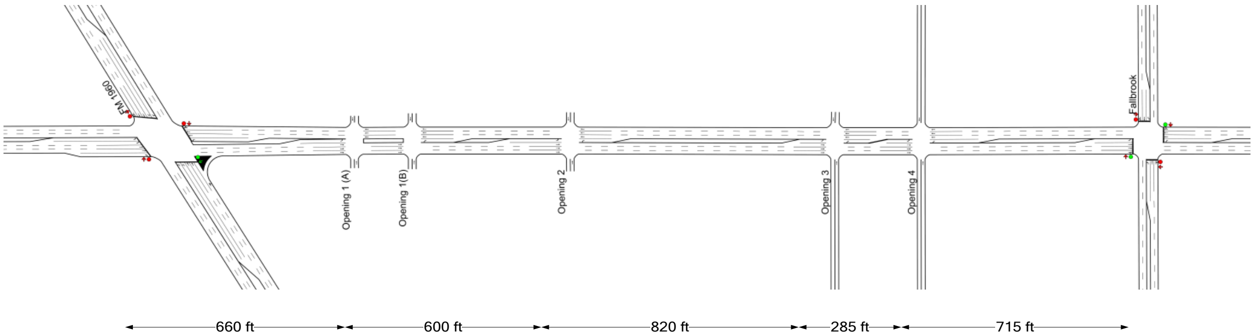
To achieve the research objectives, three different studies are designed to: 1) assess the operational impacts of short left-turn lanes, 2) assess the safety impacts of short left-turn lanes, and 3) develop models to estimate the minimum required storage length. This chapter describes the designs of these three different studies.

3.1 ANALYZE OPERATIONAL IMPACTS

The operational impacts of short left-turn lanes at unsignalized median openings are investigated through an analytical model and were validated by the traffic simulation experiments. For conducting the traffic simulation experiments, a case study was conducted on a 3,000-ft corridor on Jones Rd. in Houston, Texas, where eight median left-turn lanes have been installed, all with substandard lengths. An analytical model was developed to estimate the delay incurred by vehicles as they decelerate in through-traffic lanes in preparation for making left turns. After that, the modeling results were validated by comparing them with the results of traffic simulation experiments. Furthermore, by using the developed model, the traffic delays incurred by using substandard left-turn lanes were compared with the delays at the median openings without dedicated left-turn lanes.

3.1.1 Description of Study Location

The location selected for this study was a 3,000-ft segment located on Jones Rd. in Houston, Texas. Jones Rd. is a six-lane arterial road designed and operated by Harris County, Texas, and it connects U.S. Highway 290 and State Highway 249. Bounded by the signalized intersections at FM 1960 and at Fallbrook Rd., the study segment has four unsignalized full median openings and eight median left-turn lanes along the segment. The four median openings are closely spaced, ranging from 285 to 820 ft, and the lengths of the left-turn lanes range from 130 ft to 260 ft (FIGURE 2(b)). Mainly small businesses abut the study segment, which leads to a high density of driveways; there are a total of 29 driveways or side streets. The posted speed limit is 45 mph (72 km/h), and the peak-hour traffic is heavy, approximately 1,200 to 1,600 vph in the peak direction. The eight median turn lanes are significantly shorter than the provision in the AASHTO Greenbook, which recommends a desirable lane length of 395 ft, including a storage length of 50 ft and a deceleration length of 345 ft (interpolation for 45 mph).



(a) Lane configuration of the study road segment

Lane Length	Direction	Opening 1	Opening 2	Opening 3	Opening 4
Actual length	Southbound	250 ft (76 m)	260 ft (80 m)	200 ft (61 m)	150 ft (46 m)
	Northbound	200 ft (61 m)	260 ft (80 m)	130 ft (40 m)	230 ft (70 m)
Extended length	Southbound	Unchanged	Unchanged	395 ft (120m)	Unchanged
	Northbound	250 ft (73 m)	395 ft (120m)	Unchanged	395 ft (120m)

(b) Lengths of the median left-turn lanes

FIGURE 2 Median left-turn lanes at the study segment on Jones Rd. in Houston

3.1.2 Field Data Collection for Micro-Simulation Model

Field data collection was conducted to provide the data required for this study. Videos of field traffic were recorded with the observation periods spanning the time periods of 6:00 A.M. to 9:00 A.M. and 4:00 P.M. to 7:00 P.M. for three weekdays in November 2011. Videotaping was performed for the signalized intersections and unsignalized openings along the study segment. Then, the videos were replayed to observe lane-specific parameters. The data collected included:

- Traffic volumes at the intersections, median openings, and driveways
- Signal timing at the signalized intersections
- Intersection geometrics, such as lane configurations, lane widths, and driveway widths
- Travel times for through movements in both directions and for left-turn movements from selected median left-turn lanes using the floating-car method

3.2 STATISTICAL REGRESSION MODEL TO INVESTIGATE SAFETY PERFORMANCE

The investigation of safety performance of short left-turn lanes at unsignalized median openings was through a zero-inflated Poisson regression model to relate traffic and geometric attributes to the total crash counts at a left-turn lane. Crash modification factors (CMFs) were then calculated for future applications in projecting the crash frequency, given a specific change of the lane length.

3.2.1 Formulation of ZIP model

The parameters and variables used in the proposed ZIP model are defined as follows:

y_i	=	total number of crashes at left-turn lane i over the study period, including related rear-end, sideswipe, and OMV crashes;
q_i	=	probability for the total number of crashes y_i=0 at left-turn lane i over the study period;
$f(y_i)$	=	distribution function of the probability for $y_i = k$ ($k = 0,1,2,3,...$), effective with a probability of $1-q_i$ at lane i over the study period;
X	=	vector of the explanatory attributes. See the definitions of the attributes in TABLE 4;
β	=	vector of the coefficients to be estimated;
τ	=	coefficient to be estimated.

In a ZIP model, $f(y_i)$ takes the form of a Poisson distribution:

$$f\left(y_i\right) = \frac{\exp\left(-\lambda_i\right)\lambda_i^{y_i}}{y_i\,!} \qquad (2)$$

Where,

$\lambda_i = \mathrm{e}^{\beta \cdot X}$, in which, $\beta \cdot X$ can be tentatively written as:

$$\beta \cdot X = \beta_0 + \beta_1 \cdot s_i + \beta_2 \cdot v_i + \beta_3 \cdot P_i + \beta_4 \cdot T_i + \beta_5 \cdot n_i + \beta_6 \cdot L_i$$

The explanatory variables were defined in TABLE 4. The final selection of the attributes depends on the statistical significance of the attributes in the regression analysis.

The probability of occurrence of a certain number of crashes can be formulated as:

$$\begin{cases} \Pr\left(y_i = 0\right) = q_i + \left(1 - q_i\right) \cdot f(0) \\ \Pr\left(y_i = k\right) = \left(1 - q_i\right) \cdot f(k), \quad \text{where } k = 1,\ 2,\ 3,\ \ldots \end{cases} \tag{3}$$

Where,

$$q_i = \frac{1}{1 + \mathrm{e}^{\tau \cdot \left(\beta_0 + \beta_1 \cdot s_i + \beta_2 \cdot v_i + \beta_3 \cdot P_i + \beta_4 \cdot T_i + \beta_5 \cdot n_i + \beta_6 \cdot L_i\right)}}$$

The ZIP model employs two components that correspond to two zero generating processes for $\Pr\left(y_i = 0\right)$. The first process is governed by a binary distribution that generates structural zeros (i.e., q_i). The second process is governed by a Poisson distribution that generates crash counts, some of which may be zero (i.e., $\left(1 - q_i\right) \cdot f(0)$).

Testing whether a zero-inflated incident state (e.g., ZIP) is more appropriate than the non-zero-inflated incident state (e.g., Poisson regression) is complicated by the fact that the zero-inflated model is not nested within either the Poisson or the negative binomial models. The restriction that produces the simpler model is not a simple parametric restriction. A test statistic proposed by Vuong (1989) is a widely accepted method for distinguishing the non-nested model. The statistic can be expressed as follows for testing the non-nested hypothesis of a zero-inflated model vs. a traditional model:

$$v_{\mathrm{ZIP}} = \frac{\sqrt{n}\left[(1/n)\sum_{j=1}^{n} m_i\right]}{\sqrt{\left(1/n\right)\sum_{j=1}^{n}\left(m_i - \bar{m}\right)^2}} = \frac{\sqrt{n}\left(\bar{m}\right)}{S_m} \lim_{x \to \infty} \tag{4}$$

where

m_i = $\log\left(f_1\left(y_i|X_i\right) / f_2\left(y_i|X_i\right)\right)$;

$f_1\left(y_i|X_i\right)$ = the probability density function of the zero-inflated model;

$f_2\left(y_i|X_i\right)$ = the probability density function of either the Poisson or negative binomial distribution;

$\bar{m}$ = the mean of m_i;

S_m = the standard deviation of m_i;

n = the sample size.

The Vuong statistic v_{ZIP} is distributed as standard normal, so its value can be compared to the critical value of the standard normal distribution, e.g., 1.96. The test is directional, i.e., values greater than 1.96 favor the zero-inflated model while values less than -1.96 favor the Poisson or negative binomial regression models.

3.2.2 Description of Study Location

Fifty-two median left-turn lanes were selected in Houston, Texas covering a wide range of traffic and geometric conditions. The lengths of the median left-turn lanes studied spanned from 140 feet to 450 feet, all located at four-leg unsignalized median openings. FIGURE 3 presents the locations of the studied lanes, as well as the names, posted speed limits, and number of lanes of the streets where the studied lanes are located. For each of the lanes, the AASHTO Greenbook standard (Equation (1)) was used to calculate the required length, given the observed left-turn volume and posted speed limit. Thirty-nine of the lanes studied are shorter than the Greenbook requirements, while thirteen lanes meet the requirements.

Short Left-Turn Lanes				Full-Length Left-Turn Lanes			
Number of Sites	Street	Number of Lanes	Speed Limit, mph	Number of Sites	Street	Number of Lanes	Speed Limit, mph
6	Bellaire Blvd	6-lane	35	1	Hillcroft St	8-lane	35
4	Kirby Dr	4-lane	35	8	Westheimer Rd	8-lane	35
3	Kirby Dr	6-lane	35	1	S Main St	8-lane	40
4	Richmond Ave	6-lane	35	1	Holcombe Blvd	6-lane	30
3	Gulfton Dr	4-lane	30	2	Old Spanish Trail	6-lane	35
3	Renwick Dr	4-lane	35				
4	Blodgett St	4-lane	35				
11	Westheimer Rd	8-lane	35				
1	Beechnut St	6-lane	35				
Total Number of Sites = 39				Total Number of Sites = 13			

FIGURE 3 Study locations in Houston, Texas

3.2.3 Explanatory Attributes Observed

Besides the lengths of the lanes, other attributes were collected from the field. These attributes included geometric and traffic characteristics that may have significant impacts on the safety performance. Another principle in selecting the attributes was that the selected attributes should be either directly observed or easily estimated from field observation, which would ensure the outcomes of this study could be implemented by practitioners. As listed in TABLE 4, the attributes considered and observed in this study included posted speed limit, left-turn volume, percentage of heavy vehicles, type of taper, number of through-traffic lanes on the roadway, and relative length of left-turn lane. In this study, the relative length of a median left-turn lane was defined as the difference between the actual lane length and the Greenbook required length. Positive values represented the actual lane length as longer than the Greenbook requirement, while negative values represented it as shorter than the requirement.

Among the studied locations, the posted speed limits ranged from 30 to 40 mph. The left-turn volumes were observed for PM peak hours on weekdays during April to June 2013, and the peak-hour left-turn volumes spanned from 2 to 162 vph with percentages of heavy vehicles ranging from 0-25%. The types of tapers in the studied lanes included straight-line, partial tangent, symmetrical reverse curve, and asymmetrical reverse curve. (See AASHTO Greenbook (2) for definitions.) The studied lanes were distributed on various types of roadways, including four-lane divided, six-lane divided, and eight-lane divided.

TABLE 4 Attributes observed in the field

Attributes	Denotation	Description	Note
Posted speed limit	s_i	Posted speed limit at left-turn lane i	0 = 30 mph, 1 = 35 mph, and 2 = 40 mph
Left-turn volume	v_i	Observed turning volume at left-turn lane i during PM peak-hour (vph)	Observed values spanned from 2 to 162 vph
Percentage of heavy vehicles	P_i	Observed percentage of heavy vehicles at left-turn lane i	Observed values spanned from 0% -25%
Type of taper	T_i	Type of taper at left-turn lane i	0 = straight-line, 1 = partial tangent, 2 = symmetrical reverse curve, and 3 = asymmetrical reverse curve
Number of traffic lanes on roadway	n_i	The number of through-traffic lanes on the roadway where left-turn lane i is located	0 = four-lane street, 1 = six-lane street, and 2 = eight-lane street
Relative length of a median left-turn lane	L_i	Measured lane length minus required length (in feet) at left-turn lane i	Actual lane length spanned from 140 ft to 450 ft; the relative length ranged from -130 ft to 185 ft

3.2.4 Crash Data Collected for Statistical Regression Model

Actual crash data were retrieved for the studied locations over a six-year period from January 2006 to December 2011. The data were available from the TxDOT Crash Record Information System (CRIS). For each crash record, the data specified the location (in a format of

GIS coordinates and street numbers), severity (e.g., fatalities, injuries, and property damage), crash type (e.g., the relative position, angle of involved vehicles, and contributing factors), and other information (e.g., time, weather, lighting conditions, condition of the surface of the road, and traffic control). Using ArcGIS software, the crashes were mapped onto satellite street maps.

The primary function of a median left-turn lane is to separate left-turning vehicles from the through traffic that travels at higher speeds in the same direction, and provide space for left-turning vehicles to come to a complete stop. Once a left-turning vehicle departs from such lane, the left-turn lane finishes serving its purpose and the length of the lane will no longer affect the crash potential for this vehicle. Therefore, as safety indicators for the design of median left-turn lanes, the crashes that occurred between two turning vehicles or between one turning vehicle and a through vehicle traveling in the same direction of the left-turn lane were only considered. The crashes between a left-turning vehicle and an opposing through vehicle were not considered for the purposes of this study.

Due to short left-turn lanes, crashes may happen for the following reasons: (1) an unfavorably large speed differential between a turning vehicle and the follow-up vehicle (i.e., either a through or a turning vehicle), (2) a deceleration length insufficient for a left-turning vehicle to stop, or (3) overflowed turning vehicles stacking in through-traffic lanes. Thus, relating to the lengths of left-turn lanes, three types of crashes were identified and analyzed:

- Rear-end: The collision occurs when a left turning or through vehicle collides with the rear of a left-turning vehicle stopping/moving toward or in the turn lane.
- Sideswipe: The collision occurs when a left-turning vehicle collides with another left-turning vehicle that is stopping/moving in the same direction by “swiping” along the surface with the direction of travel.
- Object-motor vehicle (OMV): The collision occurs when one left-turning vehicle collides with a fixed object (e.g., curb of raised medians and sign poles) when moving toward or in the left-turn lane.

3.3 ESTIMATE MINIMUM STORAGE LENGTH

The minimum storage lengths are estimated based on micro simulation results. An unsignalized median opening is designed in VISSIM, which is then run under different combinations of turning volume and opposing through volumes. The 95% queue lengths at the subject left-turn lanes are collected for each study scenario. Finally, analytical models are developed for estimating queue length, i.e. minimum storage length, at the median opening.

3.3.1 VISSIM Model Development

An unsignalized median opening is developed in VISSIM. Vehicles' inputs include the vehicles making left-turns/u-turns at the subject approach and vehicles on the opposing approach. The left-turn vehicle and u-turn vehicle has to yield to the opposing through traffic. The 95% queue length at the subject approach is collected to estimate the minimum storage length.

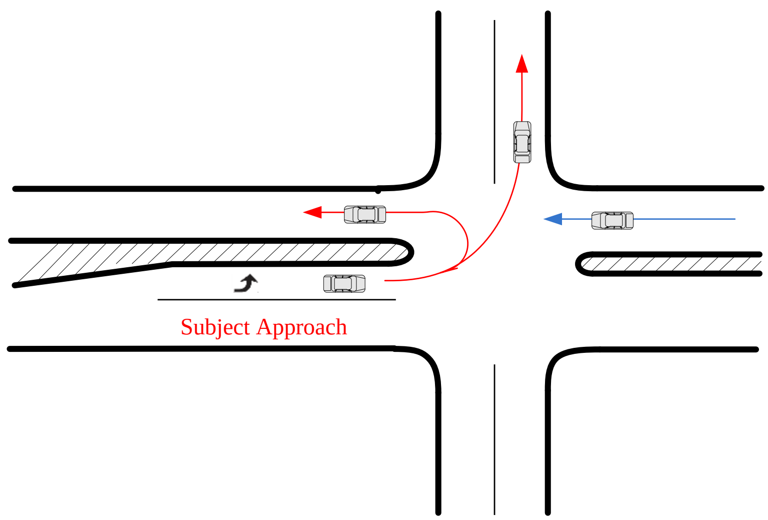


FIGURE 4 An unsignalized median opening

3.3.2 Study Scenarios

Minimum required storage length can be affected by turning volume, opposing volume, and number of lanes for opposing traffic. Turning volume includes left-turn volume and u-turn volume. Since u-turn vehicles and left-turn vehicles have different critical gap acceptance, the percentage of u-turn volume would also affect the minimum required storage length. Therefore, scenarios under different combinations of these factors are designed,

- Number of lanes for opposing traffic, N : {1, 2}
- Total turning volume (left-turn and u-turn volume), v_T : {50, 75, 100, 125} vph
- Percentage of u-turn volume, P_U : {0, 10%, 20%, 30%, 40%, 50%}
- Total opposing volume (all lanes), v_O : {500, 600, 700, 800, 900, 1000} vph
- According to HCM (2010) and Yang et al. (2001), the critical gap for left-turn vehicles and u-turn vehicles are set to be 4.1s and 5.8s respectively.

CHAPTER 4: OPERATIONAL IMPACTS OF SUBSTANDARD MEDIAN LEFT-TURNING LANES

In this chapter, the results of operational impacts of short left-turn lanes at unsignalized median openings are presented and discussed. Field observations are summarized regarding overflows and the speed of turning vehicles. An analytical model was developed to estimate the delay incurred by vehicles as they decelerate in through-traffic lanes in preparation for making left turns.

4.1 FIELD OBSERVATION

The following observations were made during the field-study periods:

- No overflow events were observed for any of the median openings with substandard left-turn lanes. The length of the left-turn queue commonly was less than two vehicles, occasionally three vehicles.
- Where short left-turn lanes were provided, left-turn vehicles decelerated by approximately 10 mph in the through-traffic lane before the taper adjoining point, leading to an actual entry speed v_E 10 mph lower than that assumed by the Greenbook. The left-turn vehicles then developed a speed differential of about 20 mph at the time when they cleared the through-traffic lane. FIGURE 5 shows two representative speed profiles collected by GPS vehicle-tracking devices. Each curve represents the average of 10 field runs at a location. These observations indicated that the Greenbook's desirable full deceleration lengths, which is determined mainly based on v_E, could be shorter and still function properly. Therefore, the estimated necessary deceleration length can be shortened from 345 ft to 215 ft (TABLE 1).

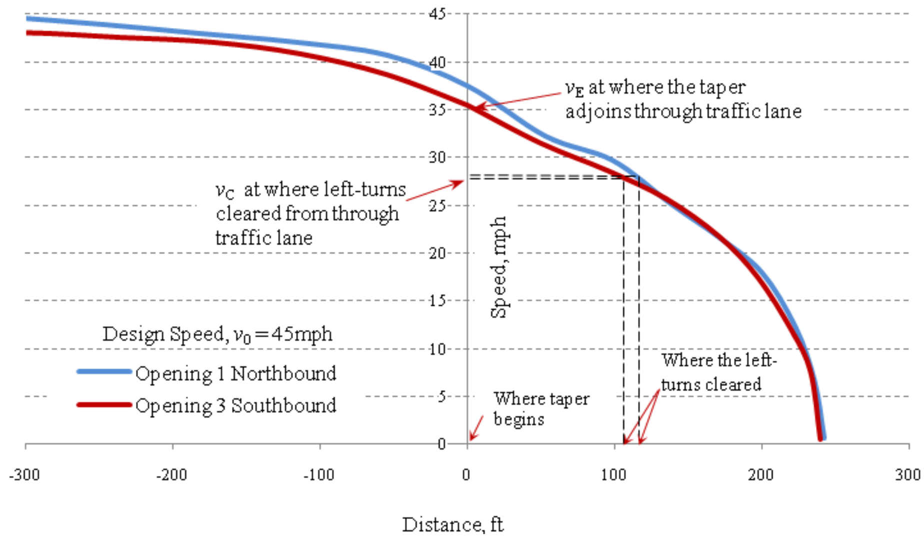


FIGURE 5 Speed profiles observed at selected median left-turn lanes

While the provision of short deceleration lengths may not result in difficulty for left-turn vehicles to stop, concerns can be raised regarding the impacts of left-turn vehicles that decelerate in the through-traffic lanes. Such impacts on the through vehicles that are behind the left-turn vehicles, in terms of operation and safety, will be addressed in the rest of this report.

4.2 DEVELOP MICRO-SIMULATION MODELS

Based on the collected data, micro-simulation models were developed by using VISSIM to provide benchmarks for validating the analytical model developed for the additional delay associated with short left-turn lanes.

First, a base-case model was developed and calibrated, in which actual lengths of median left-turn lanes were inputted. In the calibration process, simulated travel times were compared against field-observed travel times. The VISSIM model was operated similarly to the floating-car measurement of travel time in the field. The simulation of each scenario covered 120 simulation minutes with a warm-up period of 60 minutes, and all of them involved 10 simulation runs with different random-number seeds. Overall, the calibrated model was in good agreement with the field data, as summarized in TABLE 5.

TABLE 5 Effectiveness of the calibrated micro-simulation model

	Travel Time Across Entire Segment		Travel Time at Median Opening 1		Travel Time at Median Opening 4	
Movements	Northbound	Southbound	Southbound Left Turn	Northbound Left Turn	Southbound Left Turn	Northbound Left Turn
Observed	181.0 s	134.0 s	40.4 s	15.9 s	22.0 s	11.7 s
Simulated	165.7 s	148.8 s	40.9 s	12.5 s	23.9 s	12.9 s
Absolute Error	15.3 s	-14.8 s	-0.5 s	3.4 s	-1.9 s	-1.2 s
Relative Error	-8%	11%	1%	-21%	9%	10%

Based on the base-case model that was developed, four different corridor scenarios were created with various combinations of two sets of median left-turn lanes (actual/extended lengths in FIGURE 2(b)) and two traffic volumes (100% and 120% of actual volumes). To exclude the impacts of signal timing, the software, Synchro, in conjunction with SimTraffic, was used to optimize the signal timing in terms of cycle, split, and offset for the signalized intersections in each of the scenarios.

In the corridor scenarios with extended turn-lane lengths, note that it was assumed that the setting of the median openings was unchanged. Then, the scenarios with the original turn lanes and the extended turn lanes had similar traffic conditions (e.g., left-turn traffic patterns), which enabled straightforward comparisons between the scenarios. For this assumption, additional lengths along the centerline are only available for four median left-turn lanes, and only three of them can be extended to the desirable full length of 395 ft. Finally, a total of 24 turn lanes were simulated, representing various traffic volumes and lane lengths (12 lane scenarios with different actual and extended lengths as listed in FIGURE 2(b), multiplied by two levels of traffic volumes).

During the simulations, the following data were simulated and collected, i.e., traffic volumes, proportion of left-turns, entry speed v_E, proportion of left-turns, delay incurred by left-turns decelerating in through-traffic lanes, and simulated vehicle trajectories.

4.3 MODELING ADDITIONAL DELAY DUE TO LEFT-TURN VEHICLES DECELERATING IN THROUGH-TRAFFIC LANES

As discussed in section 3.1.2 "Field Data Collection for Micro-Simulation Model", left-turn vehicles commonly decelerate in the through traffic-lane before entering the taper of a substandard left-turn lane, which will block the following through vehicles and cause additional delay at the median opening. While micro-simulation represents a reliable method for estimating such additional delay, the processes of providing inputs and conducting the modeling commonly are quite time-consuming. The purpose of this section was to develop an analytical model that could enable quick estimation of such delay.

4.3.1 Model Formulation

Number of Blocked Vehicles

On urban arterial roads, due to interruption of the upstream traffic signals, vehicles commonly arrive in platoons at an unsignalized median opening. The arrival patterns depend largely on the traffic volume and cycle length of the upstream signal. We denote N as the average number of vehicles in the platoons on the inner traffic lane on a per cycle basis.

Within a platoon of N vehicles, the probability that the kth arriving vehicle will be a left-turn vehicle can be formulated as:

$$\Pr(\text{the } k^{\text{th}} \text{ vehicle is turning left}) = p^{k-1} \cdot (1-p) \tag{5}$$

Where,

p = the proportion of through vehicles in the inner through-traffic lane; k =1,2, ..., N .

When the kth vehicle arriving in the platoon is a left-turning vehicle, there are $(N-k)$ vehicles following the left-turning vehicle. The expected number of vehicles following the left-turning vehicle during each signal cycle can be estimated as:

$$
\begin{aligned}
f &= \sum_{k=1}^{N}\Big(\Pr(\text{the } k^{\text{th}} \text{ vehicle is turning left})\cdot(N-k)\Big)\\
&= \sum_{k=1}^{N}(N-k)\cdot p^{k-1}\cdot(1-p) \approx \sum_{k=1}^{\infty}(N-k)\cdot p^{k-1}\cdot(1-p)\\
&= N-\frac{1-p^{N}}{1-p}
\end{aligned}
\tag{6}
$$

Additional Delay Experienced by Each Blocked Vehicle

The field observations indicated that, when a substandard left-turn lane is provided, the entry speed v_{E} is normally 10 mph lower than v_0. If a constant deceleration rate, d , is assumed, the deceleration distance in the through-traffic lane can be estimated as $(v_0^2 - v_{\mathrm{E}}^2)/(2\cdot d)$. This is the distance from the location at which the left-turning vehicle begins to decelerate in the through-traffic lane to the location at which the taper begins. The actual travel time that corresponds to this distance is $(v_0 - v_{\mathrm{E}})/d$. Under ideal conditions, the travel time for this distance is equal to $(v_0^2 - v_{\mathrm{E}}^2)/(2\cdot d)/v_0$. Then, the delay experienced by the exiting left-turn vehicle is:

$$
D_1 = \frac{(v_0 - v_{\mathrm{E}})}{d} - \frac{(v_0^2 - v_{\mathrm{E}}^2)}{2\cdot d\cdot v_0} = \frac{(v_0 - v_{\mathrm{E}})^2}{2\cdot d\cdot v_0} = \frac{(\Delta v)^2}{2\cdot d\cdot v_0}
\tag{7}
$$

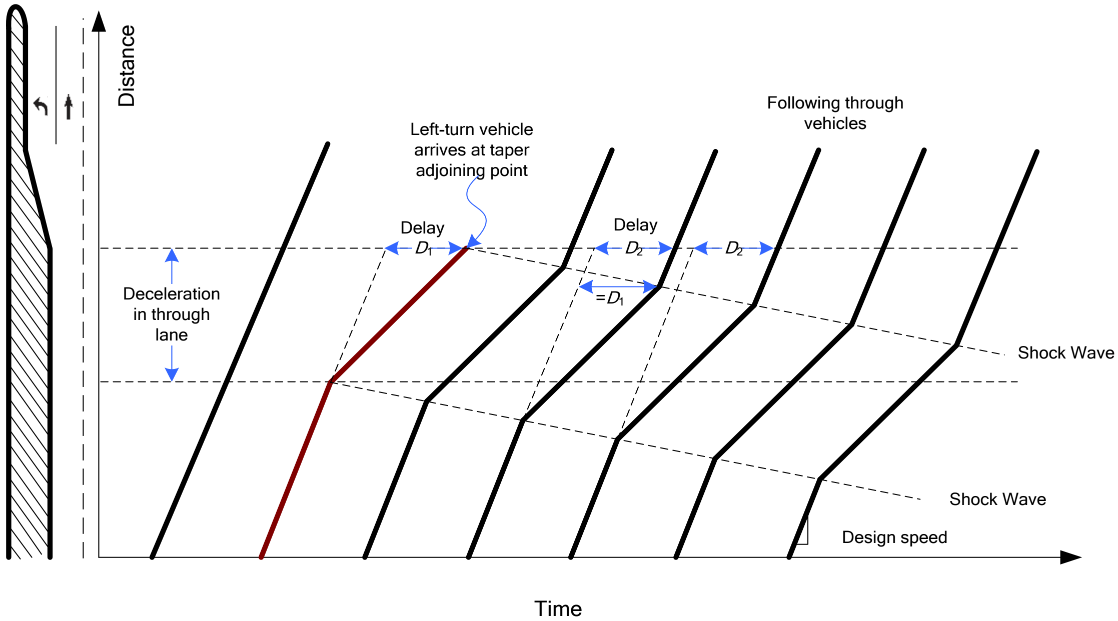


FIGURE 6 Time-distance diagram indicating impacts of a leaving left-turn vehicle on trailing vehicles

A constant speed of shock waves was assumed for the changes of traffic flow states (from v_0 to v_E and from v_E to v_0). Then, as shown in FIGURE 6, the delay experienced by each vehicle following the decelerating left-turn vehicle, D_2, is equal to D_1, according to the congruent-triangles theory.

Therefore, on a per hour basis, the total additional delay experienced by the trailing vehicles on the inner through-traffic lane before the taper adjoining point, AD, can be formulated as:

$$AD = D_2 \cdot f \cdot 3600 / C = D_1 \cdot f \cdot 3600 / C = \frac{3600}{C} \cdot \frac{(\Delta v)^2}{2 \cdot d \cdot v_0} \cdot \left(N - \frac{1-p^N}{1-p} \right) \tag{8}$$

Where,

C = the duration of the upstream traffic signal (s)

d = the deceleration rate in the through-traffic lane (ft/s2); a value of 5.9 ft/s2 (1.8 m/s2) can be used in light of the value provided in the Greenbook

Δv = the differential between the design speed v_0 and the entry speed v_E (ft/s)

N = the average number of vehicles in the platoons on the inner traffic lane on a per cycle basis, which can be approximated by "inner traffic-lane volume divided by the number of cycles of the upstream signals," on a per hour basis

As shown in Equation (8), the estimated delay is a function of Δv (i.e., $v_0 - v_E$). The simulation experiments showed that a shorter left-turn lane is associated with a higher Δv and lower entry speed v_E (FIGURE 7); therefore, a shorter left-turn lane will lead to a greater estimate of the delay based on the proposed model. The reason this occurs is that the left-turn vehicles take more time and travel a longer distance while decelerating in the through-traffic lane as the length of the median left-turn lane decreases; thus, the delay experienced by the trailing vehicles will increase.

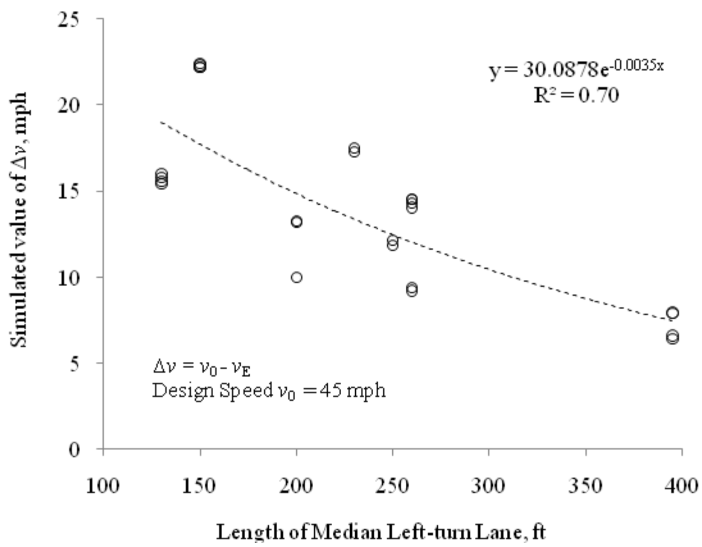


FIGURE 7 Impacts of median turn-lane length on the differential between design and entry speed

4.3.2 Model Validation

To test the effectiveness of the proposed model, the micro-simulation models, which were calibrated to replicate real-world traffic conditions, were used as benchmarks. In the simulations, the delay was measured for the 24 cases of median turn lanes in VISSIM, which represent various traffic volumes and/or lane lengths. The measurements of the delays were conducted for the inner through-traffic lane. In this study, delays were defined as the additional travel times required, compared to ideal conditions (free flow), from the point where the left-turning vehicle begins to decelerate to the point where the taper adjoins the inner through-traffic lane.

Correspondingly, the delay was estimated using the proposed model for the 24 cases. FIGURE 8 shows that the proposed model yielded a mean absolute percentage error (MAPE) of 36.5% relative to the simulated delays. Overall, the model presented reasonable performance in predicting the total additional delay experienced by the trailing through vehicles on the inner traffic lane, which resulted from left-turn vehicles decelerating in the through-traffic lane.

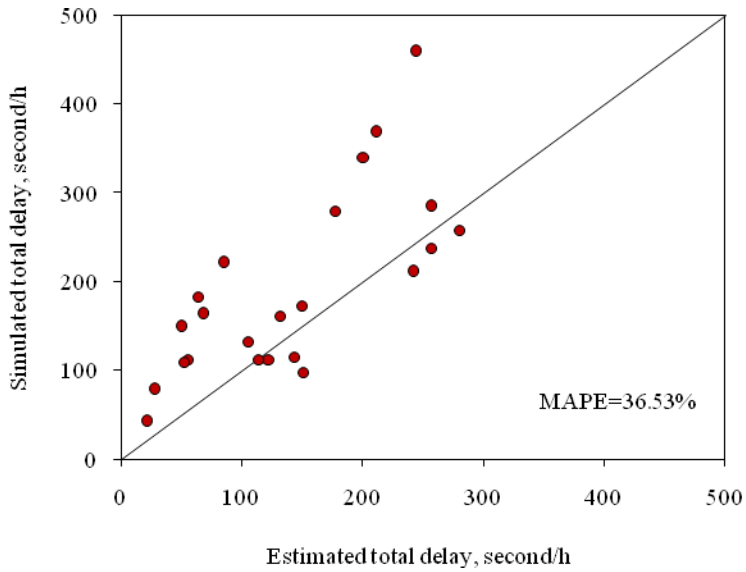


FIGURE 8 Validation of the proposed model using simulation benchmarks

4.4 OPERATIONAL IMPACTS OF USING SUBSTANDARD MEDIAN TURN LANES AT THE STUDY LOCATIONS

During the field observational period, no left-turn overflow occurred at the lanes studied. Delays associated with the short median turn lanes were mostly caused by the left-turn vehicles decelerating in the through-traffic lanes. To understand the benefits of using substandard median turn lanes, the same type of delay for the cases without dedicated left-turn lanes also was estimated. In the calculation for each of delays, we used the observed traffic conditions as input to Equation (8). For the cases without dedicated left-turn lanes, Δv was assumed to be equal to the design speed; while, for cases with dedicated left-turn lanes, Δv was approximated using the curve in FIGURE 7, which fit the simulated data. The results presented in TABLE 6 indicate that the use of substandard turn-lane lengths can reduce the delay significantly compared to the case in which no dedicated left-turn lanes are provided at the median openings. Therefore, from the operational perspective, substandard median turn lanes should be used at locations where it is impractical to provide the desirable, full-deceleration lengths. However, even though the delay caused by using substandard median turn lanes is relatively small, the resulting delays can add up, causing extensive delays, if such lanes are used consistently along a corridor. Therefore, the desirable lengths recommended by the Greenbook should be used whenever it is practical to do so.

TABLE 6 Additional delays incurred by substandard or no median turn lanes

Median Left-Turn Lane		Substandard Turn Lanes		No Turn Lanes	
		Actual Length (ft)	Total Delay (second/h)	Lane Length (ft)	Total Delay (second/h)
Opening 1	Southbound	250	74	0	9,53
	Northbound	200	168	0	1,523
Opening 2	Southbound	260	84	0	1,165
	Northbound	260	114	0	1,560
Opening 3	Southbound	200	117	0	1,066
	Northbound	130	302	0	1,678
Opening 4	Southbound	150	167	0	1,071
	Northbound	230	134	0	1,506

4.5 CONCLUSIONS

Based on the results of this study, the following conclusions were drawn:

(1) Generally, if a substandard-length median turn lane can accommodate the necessary storage length and the deceleration length assuming a 20-mph speed differential, the operational performances of median openings will not be affected significantly. The use of short left-turn lanes will incur a moderate amount of additional delays, which can be estimated by the proposed analytical model. Usually, the additional delays are significantly less than the delays associated with the absence of dedicated left-turn lanes.

(2) As opposed to the micro-simulation models, the proposed analytical model showed a reasonable performance in estimating the delay due to left-turn vehicles decelerating in through-traffic lanes. In addition, the use of the proposed analytical model is less time-consuming than using the micro-simulation models.

CHAPTER 5: SAFETY IMPACTS OF SUBSTANDARD MEDIAN LEFT-TURNING LANES

This chapter presented the historical crash data analysis results for the safety performance of short left-turn lanes at unsignalized median openings. A zero-inflated Poisson regression model is developed to relate traffic and geometric attributes to the total crash counts at a left-turn lane. Crash modification factors (CMFs) were then calculated for future applications in projecting the crash frequency, given a specific change of the lane length. The modeling methods and data collection were introduced in Section 24.2.

5.1 ZERO INFLATED POISSON REGRESSION

Thirty-two crashes were identified at the studied locations introduced in the 3.2.4 “Crash Data Collected for Statistical Regression Model” section. Among these crashes, rear-end crashes accounted for 38%, sideswipe crashes for 34%, OMV crashes for 25%, and "Not Reported" for 3%. The crashes identified included twenty-five (76%) property-damage-only (PDO) crashes and seven (24%) crashes with injuries. For each of the fifty-two left-turn lanes studied, the crash rate was calculated using Equation (9), and the average rate for the total of the related rear-end, sideswipe, and OMV crashes was 11.3 crashes per million entering vehicles (MEV).

$$R_i = \frac{1,000,000 \cdot A_i}{365 \cdot T \cdot v_i \cdot K} \tag{9}$$

Where,

A_i = total number of rear-end, sideswipe, and OMV crashes reported at location i during the study period.

T = number of years in the study period (T = 6 in this study).

v_i = left-turn volume at left-turn lane i during the peak-hour (vph).

K = K-factor, i.e., the proportion of the 24-hour volume that occurs during the peak hour. A value of 0.093 was used due to the studied lanes located in urban areas.

FIGURE 9 plots the relationship between the calculated crash rate and the relative length of a median left-turn lane. The results showed that those lanes that adhered to the Greenbook requirement (13 of the 52 samples on the right of the vertical axis) experienced no crashes. Among the 39 short left-turn lanes, 15 samples experienced crashes while 24 samples had no crash experience.

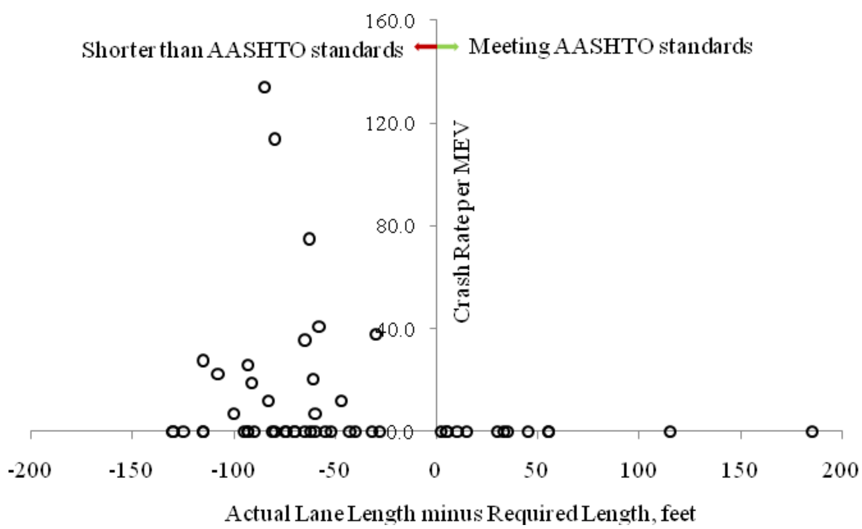


FIGURE 9 Impacts of lane length on crash rates

Among the 52 studied lanes, 37 lanes had no occurrences of crashes in the six-year study period, which indicated that the crash count data may be zero-inflated. A series of preliminary tests were performed by fitting the data into a) Poisson regression model, b) zero-inflated Poisson (ZIP) regression model, c) negative binomial (NB) regression model, and d) zero-inflated negative binomial (ZINB) regression model, respectively. Following a sequential procedure presented in (28), the preliminary tests evidenced that a ZIP model should be selected over the other options in representing the relationship between the attributes and the crash count for a median left-turn lane.

Using the fifty-two data samples, maximum-likelihood estimation (MLE) was used to estimate the coefficients β and τ in the model, and the outcomes are presented in TABLE 7. The final model included relative length of left-turn lane as a statistically significant predictor (p-value = 0.0325). Generally, the extent to which a median left-turn lane meets Greenbook requirements had significant effects on safety performance at unsignalized median openings, i.e., longer lanes that better met the requirements generally led to better safety performance.

TABLE 7 Calibrated coefficients for the model

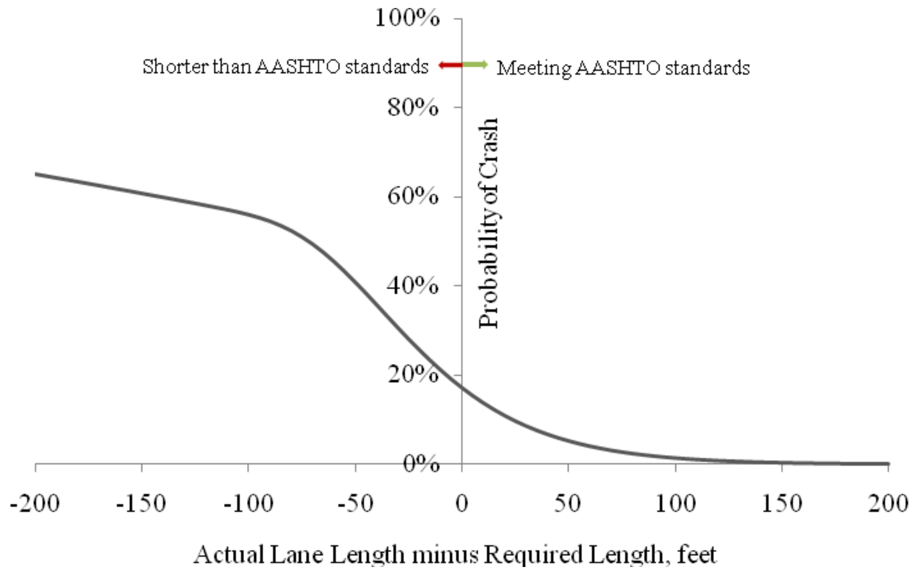
Parameter	Coefficient β_j	Standard Error	Z-Statistics	p-value	95% Confidence Interval	
Intercept	-.78875	.47732	-1.65	.9084	-1.72429	.14679
Relative length of left-turn lane, L_i	-.01636	.00765	-2.14	.0325	-.03136	-.00137

Note: τ = -.15022; Number of samples = 52; Relative length of left-turn lane = actual lane length minus the Greenbook required length.

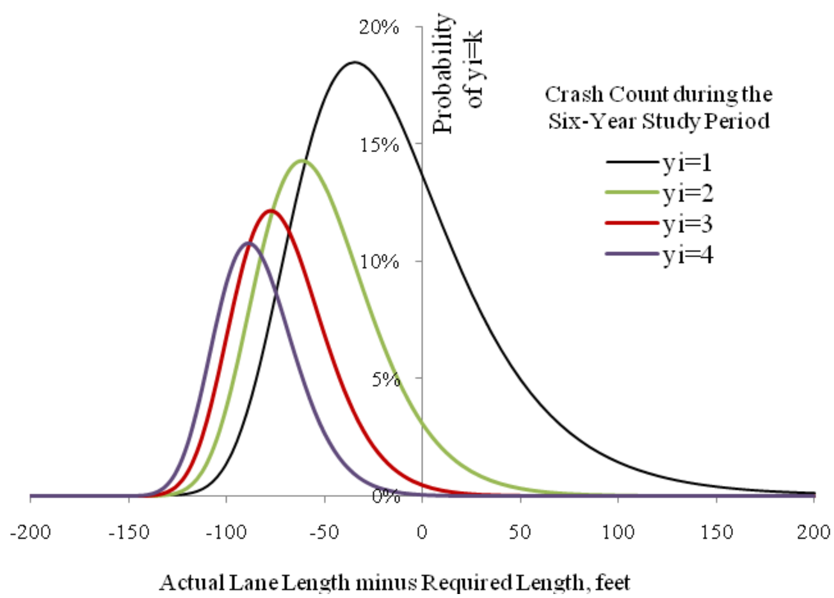
The Vuong statistic was equal to 2.0898, which was greater than +1.96. The result favored the use of the ZIP model over Poisson regression at a confidence level of 95%.

The results did not provide statistical evidence that speed limit (s_i), number of traffic lanes on the roadway (n_i) or left-turning volume (v_i) had significant effects on the total number of the related crashes. Thus, these predictors were excluded from the final model. The hypothesis that the percentage of heavy vehicles may be associated with crash frequency was not statistically supported. The relatively rare presence of heavy-vehicle samples may have prevented us from obtaining statistically significant results. The type of taper also did not have significant effects on the crash potential.

A sensitivity analysis was performed on safety impacts of the relative length of left-turn lane (i.e., the difference between the actual lane length and Greenbook required length). FIGURE 10(a) indicated that a left-turn lane with the exact length required by the Greenbook (i.e., zero at the horizontal axis) was associated with a chance of 17% for crashes to occur. Given a left-turn lane 100 feet shorter than the required length (i.e., -100 feet at the horizontal axis), the chance was increased to 56%, which was approximately a 40% greater chance to have any crashes occurring. FIGURE 10(b) plots the crash potential in the cases that a non-zero number of crashes occur (e.g., y_i = 1, 2, 3, and 4).



(a) Relative length of left-turn lane vs. probability of zero crash



(b) Relative length of left-turn lane vs. probability of a certain number of crashes

FIGURE 10 Safety implications of meeting AASHTO requirement for lane length

5.2 DEVELOPING CRASH MODIFICATION FACTOR

A crash modification factor (CMF) is a multiplicative factor used to compute the expected number of crashes after implementing a given change at a specific site. The concept of CMF is central to the predictive methods presented in the AASHTO Highway Safety Manual (25). A CMF greater than 1.0 indicates an expected increase in crashes, while a value less than 1.0 indicates an expected reduction in crashes after implementation of a given countermeasure. For example, a CMF of 0.8 indicates an expected safety benefit, specifically a 20 percent expected reduction in crashes.

In this study, a CMF was developed for the total number of related crashes (i.e., rear-end, sideswipe, and OMV crashes) at median left-turn lanes. As an indicator of crash potential, the mathematical expectation (i.e., mean value) given a specific lane length was used to formulate the CMF as Equation (10). In the calculation, the base case represented a lane that is 100 feet shorter than the Greenbook required length.

$$\mathrm{CMF}(L_i = x) = \frac{E(y_i \mid L_i = x)}{E(y_i \mid L_i = -100)} = \frac{\sum_k k \cdot \Pr(y_i = k \mid L_i = x)}{\sum_k k \cdot \Pr(y_i = k \mid L_i = -100)} \tag{10}$$

where

$\mathrm{CMF}(L_i = x)$ = CMF for a median left-turn lane that is x feet in length, accounting for the total number of rear-end, sideswipe, and OMV crashes relating to this lane;

$E(y_i \mid L_i = x)$ = The mathematical expectation of total number of related crashes y_i given a median left-turn lane that is x feet in length; thus, $E(y_i \mid L_i = -100)$ represents the mathematical expectation of crash count for the base case, i.e., a left-turn lane that is 100 feet shorter than the Greenbook required length;

$\Pr(y_i = k \mid L_i = x)$ = Probability for a median left-turn lane to have a total of k crashes given a lane length of x feet; $\Pr(y_i = k \mid L_i = -100)$ represents the probability for a left-turn lane of x feet in length to have k crashes. Note that the probability can be calculated using the ZIP regression model proposed or looked up from FIGURE 10.

For instance, given a left-turn lane 75 feet shorter than the Greenbook required length, the CMF was calculated as

$$\text{CMF}(L_i = -75) = \frac{E(y_i \mid L_i = -75)}{E(y_i \mid L_i = -100)} = \frac{\sum_k (0.490\times 0 + 0.086\times 1 + 0.125\times 2 + 0.121\times 3 + 0.087\times 4 + ...)}{\sum_k (0.439\times 0 + 0.014\times 1 + 0.038\times 2 + 0.068\times 3 + 0.09\times 4 + ...)} = 0.52$$

(11)

The CMF value of 0.52 projected that a left-turn lane 75 feet shorter than the required length would have approximately 52 percent of the total crashes expected for a lane 100 feet shorter than the required length. In this approach, the CMFs were calculated for various lengths of lanes and plotted in FIGURE 11.

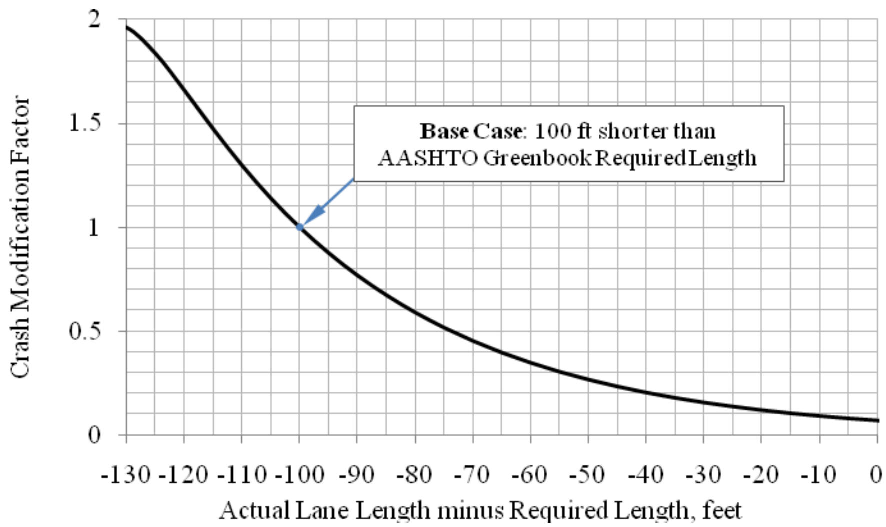


FIGURE 11 CMFs for short left-turn lanes

To explain how the CMFs can be used and interpreted, the following is an example. A left-turn lane of 265 feet in length is located at an unsignalized median opening, and the posted speed limit is 35 mph along the street. The left-turning volume per design hour is 50 vph, leading to two vehicles arriving in each two-minute intervals on average. In light to the Greenbook requirements, the length of the lane should be 265 feet, including a deceleration length of 215 feet and a storage length of 50 feet. Thus, the lane meets the Greenbook requirements and the relative lane length is zero. Reportedly, the lane had a crash frequency of 0.20 crashes/year including related rear-end, sideswipe, and OMV crashes. Construction of a new median opening is planned at close upstream of this lane, which will encroach the right-of-way of the existing left-turn lane. The existing lane needs to be shortened by 45 feet to accommodate a new left-turn lane (i.e., relative length=-45 feet), which will be placed back-to-back to the existing left-turn lane and aligned to the new opening. Under the given conditions, the total crash frequency can be projected as:

$$0.20 \text{ crash/year} \times \frac{\text{CMF}(L_i = -45)}{\text{CMF}(L_i = 0)} = 0.20 \times \frac{0.234}{0.071} = 0.66 \text{ crash/year} \tag{12}$$

While the relative length of the lane has statistically significant effects on the total number of related crashes, the increase of crash frequency due to short left-turn lanes might be acceptable in some cases (e.g., in the above case, from 0.20 to 0.66 crash/year). Engineers' judgments should be involved to determine whether a short left-turn lane is appropriate.

It is important to note that a CMF represents the long-term expected change in crash frequency and the CMF proposed in this study was based on the crash experience at a limited number of study sites. As such, the actual change in crashes may vary by location and by year.

5.3 CONCLUSIONS

Based on the results of this study, the following conclusions were drawn:

- The historical crash data in this study showed that the lanes that adhered to the AASHTO Greenbook requirements generally presented appropriate safety performance.
- Statistical evidence showed that the difference between actual lane length and the Greenbook required length had significant impacts on crash potential at the study locations. For instance, as opposed to the required length, shortening the lane length by 100 feet led to a 40-percent increase in the likelihood that crash/crashes could happen.

- When it is impractical to provide the Greenbook required length, use of substandard-length left-turn lanes may still be an option because of its operational benefits comparing with the no dedicated left-turn lane option. In this case, engineers' judgments are preferable to make the trade-off decision on whether a short left-turn lane is appropriate.

CHAPTER 6: MINIMUM STORAGE LENGTH AT UNSIGNALIZED MEDIAN OPENINGS

This chapter presents the results for determining minimum storage lengths at unsignalized median openings. The 95% queue length, i.e. minimum storage length, under different combinations of turning volume and opposing volume are summarized and compared. Analytical models are developed to estimate the minimum storage length.

6.1 SIMULATION RESULTS

The detailed simulation model development and scenario design were introduced in Chapter 3, Section 3.3. For each designed study scenario, 10 simulation runs were conducted. The 95% queue length, L , were then collected and averaged for the 10 simulation runs. Finally, the average 95% queue length for each study scenarios were converted to storage length, in terms of number of vehicles, assuming the storage length for a waiting vehicle is 25 ft/vehicles. TABLE 8 and 9 summarizes and compares the storage length for each study scenario. As seen in TABLE 8 and 9, the storage length increases with the increases of opposing volume, total left turning volume, and the percentage of u-turns. In addition, it also shows that, when opposing traffic has one lane, i.e. $N = 1$, the number of vehicles in the queue ranges from 0 to 4; while when opposing traffic has two lanes, i.e. $N = 2$, the number of vehicles in the queue ranges from 0 to 3. Note that, the estimated numbers of vehicles in the queue are all less than the estimates from AASHTO "two-minute arrival" rule-of-thumb method. For example, for the case total left turn volume is 125 vph, by using the "two-minute arrival" method, the number of vehicles in the queue should be *125/30=**4.16***, which is greater than all the estimates provided in TABLE 8 and TABLE 9. In addition, the "two-minute arrival" rule-of-thumb method only considers the left turn volume. For the results presented in TABLE 8 and TABLE 9, it can be seen that opposing traffic volume and number lanes in opposing direction and the percentage of u-turns are all important influencing factors on the queue length at unsignalized intersection.

TABLE 8 Storage Length When Opposing Direction Has 1 Lane (in number of vehicles**)**

Storage length for Opposing Direction Has 1 Lane (in number of vehicles)

Total turning volume=50 vph (Left turn +U Turn)

Opposing volume (vph)	UT percentage					
	0%	10%	20%	30%	40%	50%
500	0	1	1	1	1	1
600	1	1	1	1	1	1
700	1	1	1	1	1	1
800	1	1	1	1	1	1
900	1	1	1	1	1	1
1000	1	1	1	1	1	2

Total turning volume =75 vph (Left turn +U Turn)

Opposing volume (vph)	UT percentage					
	0%	10%	20%	30%	40%	50%
500	1	1	1	1	1	1
600	1	1	1	1	1	1
700	1	1	1	1	1	1
800	1	1	1	1	2	2
900	1	1	2	2	2	2
1000	2	2	2	2	2	2

Total turning volume =100 vph (Left turn +U Turn)

Opposing volume (vph)	UT percentage					
	0%	10%	20%	30%	40%	50%
500	1	1	1	1	1	1
600	1	1	1	1	1	1
700	1	1	1	2	2	2
800	1	2	2	2	2	2
900	2	2	2	2	2	2
1000	2	2	2	2	2	3

Total turning volume=125 vph (Left turn +U Turn)

Opposing volume (vph)	UT percentage					
	0%	10%	20%	30%	40%	50%
500	1	1	1	1	1	1
600	1	1	1	1	1	1
700	1	2	2	2	2	2
800	2	2	2	2	2	2
900	2	2	2	3	3	3
1000	2	3	3	3	3	4

TABLE 9 Storage Length When Opposing Direction Has 2 Lanes (in number of vehicles**)**

Storage length for Opposing Direction Has 2 Lane
(In number of vehicles)

Total turning volume=50 vph

(Left turn +U Turn)

Opposing volume (vph)	UT percentage					
	0%	10%	20%	30%	40%	50%
500	0	1	1	1	1	1
600	1	1	1	1	1	1
700	1	1	1	1	1	1
800	1	1	1	1	1	1
900	1	1	1	1	1	1
1000	1	1	1	1	1	1

Total turning volume =75 vph

(Left turn +U Turn)

Opposing volume (vph)	UT percentage					
	0%	10%	20%	30%	40%	50%
500	1	1	1	1	1	1
600	1	1	1	1	1	1
700	1	1	1	1	1	1
800	1	1	1	1	1	1
900	1	1	1	1	1	2
1000	1	1	2	2	2	2

Total turning volume =100 vph

(Left turn +U Turn)

Opposing volume (vph)	UT percentage					
	0%	10%	20%	30%	40%	50%
500	1	1	1	1	1	1
600	1	1	1	1	1	1
700	1	1	1	1	1	1
800	1	1	1	2	2	2
900	1	1	2	2	2	2
1000	2	2	2	2	2	2

Total turning volume =125 vph

(Left turn +U Turn)

Opposing volume (vph)	UT percentage					
	0%	10%	20%	30%	40%	50%
500	1	1	1	1	1	1
600	1	1	1	1	1	1
700	1	1	1	1	2	2
800	2	2	2	2	2	2
900	2	2	2	2	2	2
1000	2	2	3	3	3	3

6.2 REGRESSION MODELS

To estimate the minimum storage length at unsignalized median openings, regression models are developed based on the above simulation results.

When number of lanes for opposing traffic is 1, the regression model is as follow,

$$Q_{Storage} = {v_T}^{0.5663} * e^{(0.0014*v_O + 0.0044*P_U - 3.3832)} \tag{13}$$

R square: 0.67

When number of lanes for opposing traffic is 2, the regression model is as follow,

$$Q_{Storage} = {v_T}^{0.4588} * e^{(0.0011*v_O + 0.0035*P_U - 2.7350)} \tag{14}$$

R square: 0.57

Where,

$Q_{Storage}$ = the queue length, in term of number of vehicles in the queue

v_T = the total turning volume, vph

P_U = the percentage of u-turn volume

v_O = the total opposing volume (all lanes), vph

In Chapter 4, it is found that if a substandard-length median turn lane can accommodate the necessary storage length and the deceleration length assuming a 20-mph speed differential, the operational performances of median openings will not be affected significantly. Combining this finding with the developed model for storage length, the minimum required left-turn length can be estimated by the following equation:

$$L_{\text{Re}quired} = D_{20mph} + Round(Q_{storage}) * 25\,ft \quad (15)$$

Where,

D_{20mph} = the deceleration length assuming a 20mph speed differential (feet, see TABLE 1 for TX 20mph requirements);

$Q_{Storage}$ = the queue length, in term of number of vehicles in the queue, estimated by Equation 13 or 14.

By using Equation 15 the required minimum left-turn length can be significantly reduced when comparing it with the AASHTO Green book requirement provided in Equation 1.

For example, on a corridor with a designed speed of 40 mph, if an unsignalized median opening has 90 vph total turning volume with 20% u-turn volume and the opposing direction has 2 lanes with 700 vph opposing volume on each lane, than according to AASHTO Green book requirement, the required minimum left-turn lane length should be

$$L_{\text{Re}quired}^{AASHTO} = D + \max(50, (v/30) \times \text{S})$$

$$= 275\,ft + \max(50, (90/30) \times 25)$$

$$= 350\,ft$$

By using Equation 15, the required minimum left-turn lane length will be

$$L_{\text{Re}quired} = D_{20mph} + Round(v_T^{\;0.4588} * e^{(0.0011*v_O + 0.0035*P_U - 2.7350)}) * 25\,ft$$

$$= 160\,ft + Round(90^{0.4588} * e^{(0.0011*700 + 0.0035*0.2 - 2.7350)}) * 25\,ft$$
$$= 185\,ft$$

Comparing these two results, the required left turn lane length is reduced by 48% using the new method developed in this study.

6.3 CONCLUSIONS

Based on the simulation results, it is found that, the storage length increases with the increases of opposing volume, total turning volume, and the percentage of u-turns. In addition, it is also found that, the simulated number of vehicles in the queue is much less than that estimated by the AASHTO “two-minute arrival” rule-of-thumb. Two regression models are developed in Equations 13 and 14 for estimating the minimum storage length at unsignalized median openings. In addition, a new method for estimating the minimum length of left-turn lane at unsignalized median openings was also provided in Equation 15, which results in much less left-turn lane length when comparing it to the AASHTO Green Book method.

CHAPTER 7: CONCLUSION AND RECOMMENDATION

This study investigated the safety and operational impact of left-turn lanes with substandard lengths, and developed models for estimating the minimum required storage length for left-turn lanes at unsignalized median openings.

The studies led to a number of findings. Some of the highlighted findings include:

1) No overflows were observed at study locations with short left-turn lanes.

2) The use of short left-turn lanes will incur a moderate amount of additional delays, which can be estimated by the proposed analytical model. However, the additional delays are significantly less than the delays associated with the absence of dedicated left-turn lanes.

3) Statistical evidence showed that the difference between actual lane length and the Greenbook required length had significant impacts on crash potential at the study locations. For instance, as opposed to the required length, shortening the lane length by 100 feet led to a 40-percent increase in the likelihood that crash/crashes could happen.

4) The required storage length simulated under different combination of turning volume and opposing volume is much less than that estimated by the AASHTO "two-minute arrival" rule-of-thumb.

Based on these findings, provided are the following recommendations:

1) At the operational impacts perspective, generally, if a substandard-length median turn lane can accommodate the necessary storage length and the deceleration length assuming a 20-mph speed differential, short left-turn lane would be acceptable.

2) At the safety impact perspective, when it is impractical to provide the Greenbook required length, use of substandard-length left-turn lanes may still be an option because of its operational benefits comparing with the no dedicated left-turn lane

option. In this case, engineers' judgments are preferable to make the trade-off decision on whether a short left-turn lane is appropriate.

3) The minimum required left turn lane storage length can be estimated with the regression model developed in this research.

While the outcomes of this study provide important understanding of the design issues associated with substandard-length median turn lanes, the results may be limited in scope and applicability due to the small sample size involved in the case study. In the future, more study locations need to be selected to further validate these results.

REFERENCES

A Policy on Geometric Design of Highways and Streets (The Greenbook). American Association of State Highway and Transportation Officials (AASHTO). Washington, D.C., 2011.

Arizona Department of Transportation. Roadway Design Guidelines, May 2012.

California Department of Transportation. Highway Design Manual, May 2012.

City of Houston, Department of Public Works and Engineering, Infrastructure Design Manual, 2012.

Colorado Department of Transportation. Roadway Design Guide, 2005.

Connecticut Department of Transportation. Highway Design Manual, 2003.

Delaware Department of Transportation. Road Design Manual, July 2004.

Fitzpatrick, K., M.A. Brewer, J.S. Gluck, W.L. Eisele, Y. Zhang, H.S. Levinson, W. Zharen, M.R. Lorenz, V. Iragavarapu, E.S. Park. Development of Left-Turn Lane Warrants for Unsignalized Intersections, NCHRP Web-Only Document 193 - Final Report for NCHRP Project 03-91, 2010.

Florida Department of Transportation. Median Handbook, January 1997.

Gettman, D., and Head, L. (2003). "Surrogate Safety Measures from Traffic Simulation Models." Transportation Research Record, 1840, 104–115. Transportation Research Board, Washington, D.C.

Gettman, D., Pu, L., Sayed, T., and Shelby, S. (2008). "Surrogate Safety Assessment Model and Validation." FHWA-HRT-08-051. FHWA, Washington, D.C.

Gluck, J., H.S. Levinson, and V. Stover. NCHRP Report 420: Impacts of Access Management Techniques. Transportation Research Board, National Research Council, 1999.

Hayward, J.C. (1972). "Near-Miss Determination through Use of a Scale of Danger." Report HRR 384. Highway Research Board, pp. 24–35.

Highway Safety Manual, First Edition. American Association of State Highway and Transportation Officials. Washington, D.C., 2010.

Hyden, C. (1987). “The Development of a Method for Traffic Safety Evaluation: the Swedish Conflicts Technique.” Department of Traffic Planning and Engineering, Lund University: Sweden.

Illinois Department of Transportation. Bureau of Local Roads and Streets Manual, January 2006.

Indiana Department of Transportation. Indiana Design Manual, January 2010.

Iowa Department of Transportation, Design Manual, 2010.

Lertworawanich, P., and L. Elefteriadou. Determination of Storage Lengths of Left-Turn Lanes at Unsignalized Intersections Using M/G2/1 Queuing. TRB, Proceeding, Washington, D.C., 2003.

Maine Department of Transportation. Highway Design Guide, December 2004.

Michigan Department of Transportation, Road Design Manual, 2004.

Minnesota Department of Transportation. Roadway Design Manual, June 2000.

Mississippi Department of Transportation. Roadway Design Manual, September 2001.

New York Department of Transportation. Highway Design Manual, April 2011.

North Dakota Department of Transportation. Design Manual, February 2011.

Oregon Department of Transportation. Highway Design Manual, 2003.

Qi, Y. Incident Delay Analysis and Estimation. Ph.D. Dissertation, Polytechnic University of New York, 2002.

Qi, Y., X. Chen, L.Yu, H. Liu, G. Liu, D. Li, K.R. Persad, and K. Pruner. Development of Guidelines for Operationally Effective Raised Medians and the Use of Alternative Movements on Urban Roadways. Texas Department of Transportation, 2012. Available at: tti.tamu.edu/documents/0-6644-1.pdf

Rimiller, J., J. Ivan, N. Garrick. Estimating Benefits from Specific Highway Safety Improvements: Phase III: Safety Benefits From Left Turn Treatment, Connecticut Cooperative Highway Research Program, Project 97-1(3), Final Report, Report JHR 03-290, 2003.\

South Dakota Department of Transportation. Road Design Manual.

Texas Department of Transportation. Roadway Design Manual, March 2009.

Traffic Safety Toolbox. A Primer on Traffic Safety. ITE, Washington, D.C., 1987.

Utah Department of Transportation. Roadway Design Manual of Instruction, August 2011.

Vuong, Q., Likelihood Ratio Tests for Model Selection and Non-nested Hypothesis, Econometrica, Volume 57, Issue 2, March 1989, 307-333

Yang, X., H. Zhou, N. Castillo, and J. Lu. The Gap Acceptance Study of U-turn at Median Openings. 2001 Annual Meeting of Institute of Transportation Engineers, in Chicago, Illinois, USA, August, 2001.