Safety Impacts of Short Left-Turn Lanes at Median Openings: Crash Experience of Houston Streets

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ABSTRACT

The AASHTO Greenbook specifically encourages the use of left-turn lanes at median openings on divided roadways to eliminate stopping in through-traffic lanes. However, in urban areas, it is often impractical to provide the Greenbook recommended lengths for median left-turn lanes when the available length between two adjacent openings is inadequate, which is particularly evident in the case of heavy left-turn volumes. Thus, left-turn lanes shorter than the Greenbook lengths (referred to as "short left-turn lane" in this paper) are in wide use on urban divided roadways. The objective of this study was to investigate the safety performance of short left-turn lanes at unsignalized median openings. To this end, six years of crash data were collected from fifty-two median left-turn lanes in Houston, Texas, which included forty short lanes and twelve lanes that adhered to the Greenbook recommendations. A Poisson regression model was developed to relate traffic and geometric attributes to the total count of rear-end, sideswipe, and object-motor vehicle crashes at a left-turn lane. Crash modification factors (CMFs) were calculated for future applications in projecting the crash frequency, given a specific change of the lane length. It was statistically evidenced that the difference between actual lane length and the Greenbook recommended length had significant effects on the crash frequency. However, the increase of crash frequency due to short left-turn lanes might be acceptable in some cases, in which engineers also need to account for traffic, economic, and social impacts in determining whether a short left-turn lane is appropriate.

(Abstract Word Count: 248 words)

INTRODUCTION

The AASHTO Greenbook (*1*) specifically encourages the use of dedicated left-turn lanes at median openings on divided roadways to eliminate stopping in through-traffic lanes. While the Greenbook presents specific recommendations on the desirable length, many left-turn lanes shorter than the length (referred to as “short left-turn lane” in this study) 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 (*2*). The results of the survey indicated that seven of the fourteen participating agencies already had short left-turn lanes in use in their jurisdictions, primarily for the following two reasons:

- Available length along the roadway centerline that can be used for installing median left-turn lanes may be limited by the spacing of median openings. A wide range of median opening spacing has been required by various state Departments of Transportation, which can be as short as 300 feet (*2*). In addition, traffic engineers are often under public pressure to provide more median openings for abutting businesses, which will further reduce the available length. As a result, the recommendations in the Greenbook (*1*) for the length of a left-turn lane often exceed the available length between two adjacent openings. This is particularly evident in the case of heavy left-turn volumes, which leads to a demand for a longer lane length.
- The standards followed by local transportation agencies may recommend shorter lengths for median left-turn lanes. (See Section “Design Manuals of State Departments of Transportation” for examples).

However, many traffic engineers expressed a lack of confidence in using short left-turn lanes for the following reasons:

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

Existing research has rarely addressed the safety performance of short left-turn lanes at unsignalized median openings, so traffic engineers may be reluctant to use such lanes even though it actually may be appropriate and safe to do so. The objective of this study was to investigate the safety impacts of short median left-turn lanes at unsignalized median openings. To this end, historical crash data during 2006-2011 were collected from fifty-two unsignalized median openings located in Houston, Texas. A prediction model was developed to relate the frequency of the related crashes to various explanatory variables, such as traffic and geometric characteristics. The results are presented later in the study, along with a discussion of future applications in a format of crash modification factors (CMFs).

LITERATURE REVIEW

Available Guidelines

As shown in FIGURE 1, a median left-turn lane is typically composed of two functional parts: vehicle storage and deceleration. Usually, a taper is considered as part of the deceleration space.

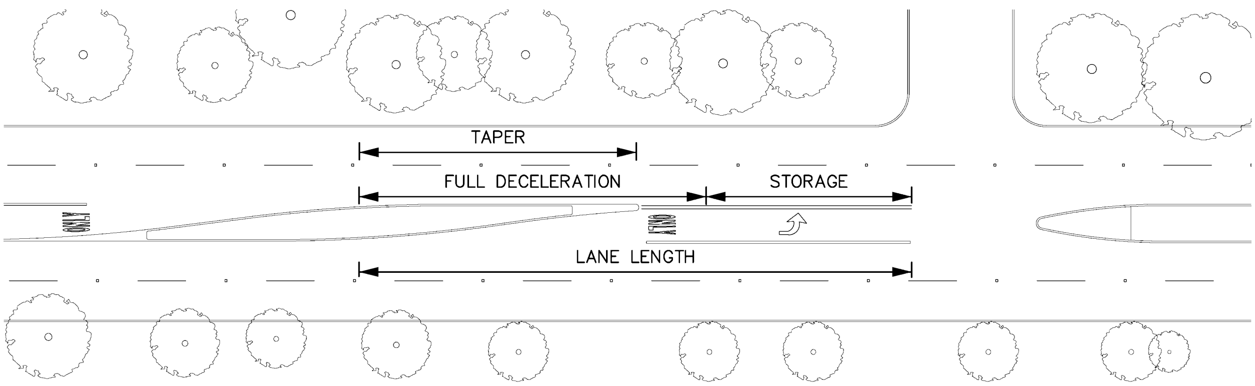

FIGURE 1: Components of length of a median left-turn lane

<u>AASHTO Greenbook</u>

<u>Storage</u>: According to the AASHTO Greenbook, the storage length at unsignalized intersections should be either the minimum length (i.e., 50 feet) 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 trucks, provisions should be made for at least one car and one truck (i.e., 75 to 85 feet). In addition, the two-minute interval may also be adjusted, depending on the waiting time for sufficient gaps in the flow of opposing traffic for making permitted left turns.

<u>Deceleration</u>: TABLE 1 shows the provisions in the 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 point where the taper begins. When the left-turning vehicle clears the through-traffic lane, a speed differential of 10 mph is developed between the left-turning vehicle and the following through traffic;
- The deceleration rate is 5.8 ft/s^2 when the front bumper passes the taper adjoining point, and then 6.5 ft/s^2 after the turning vehicles clear the through-traffic lane.

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: Some standards for deceleration lengths in a left-turn lane (in feet)

Design speed (mph) \ Assumed speed differential	AASHTO	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

Sources: (1,*3*-*8*)

Generally, the Greenbook recommended length can be mathematically written as

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

where D = the deceleration length in feet (see TABLE 1 for the Greenbook recommendations); 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 10%.

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 are often different from the Greenbook. 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 1-minute arrival can be used for unsignalized locations. For the minimum storage, most states follow the provision of 50 feet in the Greenbook. However, Colorado recommends that a minimum length of 25 feet be used, while some other states (e.g., Illinois, South Dakota, Oregon, and Texas) tend toward longer lengths (e.g., 100 or 115 feet) for the minimum storage.

TABLE 2: State DOT 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

Sources: (*1, 3-21*); Note: [1] "Longer" = the recommended lengths are longer than the AASHTO Greenbook lengths. [2] "Same" = the manual follows the provisions in the AASHTO Greenbook. [3] "Shorter" = the recommended lengths are shorter than the Greenbook lengths.

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 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 provisions (*22*) normally lead to left-turn lanes shorter than the Greenbook lengths. This partially explains why short left-turn lanes are widely seen in the Houston area.

Review of 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 (*23*), introducing left-turn lanes at unsignalized intersections generally led to a consistent reduction in total crashes (by 50% to 77%). This included reduction of rear-end crashes by 62% to 82% and left-turn related crashes by 37% to 90% based on studies performed 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 (*24*). Crash modification factors (CMFs) are available in the AASHTO Highway Safety Manual (*25*), 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 (*26*). A recent study conducted in Connecticut indicated that installing left-turn lanes also reduced the crash severity on average (*27*). Collectively, the safety benefits of providing left-turn lanes at unsignalized locations are widely accepted as opposed to having no left-turn lanes.

However, existing research has rarely focused on the safety impacts of the length of left-turn lanes, which underscores the need for better understanding of the safety performance of short left-turn lanes. This study has the potential to help traffic engineers make informed decisions in those future applications when it is impractical to provide full-length lanes and necessary to use short lanes.

DATA COLLECTION

Study Locations

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 2 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 method (Equation (1)) was used to calculate the recommended length, given the observed left-turn volume and posted speed limit. Forty of the lanes studied are shorter than the Greenbook recommendations, while twelve lanes are longer than the recommendations. The absolute difference between actual lane length and Greenbook recommended length ranged from 130 ft to 125 ft.

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	4	Westheimer Rd	8-lane	35
3	Kirby Dr	6-lane	35	3	Westheimer Rd	8-lane	40
4	Richmond Ave	6-lane	35	1	S Main St	8-lane	40
3	Gulfton Dr	4-lane	30	1	Holcombe Blvd	6-lane	30
3	Renwick Dr	4-lane	35	2	Old Spanish Trail	6-lane	35
4	Blodgett St	4-lane	35				
1	Westheimer Rd	8-lane	40				
11	Westheimer Rd	8-lane	35				
1	Beechnut St	6-lane	35				
Total Number of Sites = 40				**Total Number of Sites = 12**			

FIGURE 2: Study locations in Houston, Texas

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 3, the attributes considered and observed in this study included posted speed limit, left-turn volume, average daily traffic volume, percentage of heavy vehicles, type of taper, number of through-traffic lanes on the roadway, proportion of taper length to the total turn-lane length, and relative length of left-turn lane.

In this study, the relative length of a median left-turn lane was defined as the difference in percentage between the actual lane length and the Greenbook recommended length, as formulated in TABLE 3. The difference in percentage was selected over absolute difference, because the absolute difference may be limited in reflecting the marginal effects of changing the lane length. For instance, shortening a 450-foot-desirable lane by 50 ft should have a different level of impacts as opposed to shortening a 200-foot-desirable lane by 50 ft. Positive values of relative length represented the actual lane length as longer than the Greenbook recommended lengths, while negative values represented it as shorter than the recommended lengths. The observed values spanned from -47% to 38% at the study sites.

TABLE 3: Attributes observed in the field

Attributes	Denotation	Description	Note
Posted speed limit	s_i	Posted speed limit at left-turn lane i	0 = speed limit of 35 mph or lower (i.e., 30 mph or 35 mph), and 1 = speed limit over 35 mph (i.e., 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
Directional ADT volume per lane	V_i	Directional average daily traffic volume per lane in the direction the left-turns travel at studied left-turn lane i	Retrieved from ADT counts available from the City of Houston and the TxDOT. Values ranged from 1,639 to 10,805 vpdpl
Percentage of heavy vehicles	P_i	Observed percentage of heavy vehicles at left-turn lane i	Observed values spanned from 0% to 25%
Type of taper	T_i	Type of taper at left-turn lane i	0 = straight-line taper, 1 = curved taper (partial tangent, symmetrical reverse curve, or 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 or eight-lane street
Proportion of taper length to the total turn-lane length	a_i	Length of taper versus the total length of the left turn lane at left-turn lane i	Observed values spanned from 17% to 78%
Relative length	L_i	At left-turn lane i, relative length is $\frac{(\text{Actual length} - \text{Greenbook length})}{\text{Greenbook length}} \times 100\%$	The values spanned from -47% (i.e., 47% shorter than the Greenbook length) to 38% (i.e., 38% longer than the Greenbook length)

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%.

Average daily traffic counts were retrieved from records available at the City of Houston and the TxDOT. It should be noted that, once a left-turning vehicle departs from a median left-turn lane, the lane finishes serving its purpose, and thus, the opposing traffic volume should be excluded from analyzing those crashes attributed to a short left-turn lane (i.e., three types of crashes identified in the following section). Therefore, traffic volumes (expressed in vehicles per day per lane or vpdpl) were only prepared for the direction, in which the left-turns travel at the studied left-turn lanes. The observed values ranged from 1,639 to 10,805 vpdpl.

The percentage of heavy vehicles ranged from 0 to 25% at the studied left-turn lanes. 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.) As one of the candidate attributes, proportion of taper length to the total turn-lane length was calculated and the observed values ranged from 17% to 78%. The studied lanes were distributed on various types of roadways, including four-lane divided, six-lane divided, and eight-lane divided.

For the categorical variables, various viable 0-1 coding methods were experimented in the data analysis. In this way, the impacts of selecting coding methods was minimized in identifying the significant attributes.

Crash Data Collected

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, we only considered 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. 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.

In all, thirty-two crashes were identified at the studied locations. 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 (2), 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).

$$R_i = \frac{1,000,000 \cdot A_i}{365 \cdot T \cdot v_i \cdot K} \tag{2}$$

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 design hour (vph).

K = *K*-factor, i.e., the proportion of the 24-hour volume that occurs during the design hour. A value of 0.093 was used as suggested by HCM for streets located in urban areas (*28*). In addition, the value used was consistent with the data for urban streets presented in the Texas Transportation Institute's "2011 Congested Corridors Report - Powered by INRIX Traffic Data" (*29*).

FIGURE 3 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 recommendations (12 of the 52 samples on the right of the vertical axis) experienced no crashes. Among the 40 short left-turn lanes, 15 samples experienced crashes while 25 samples had no crash experience.

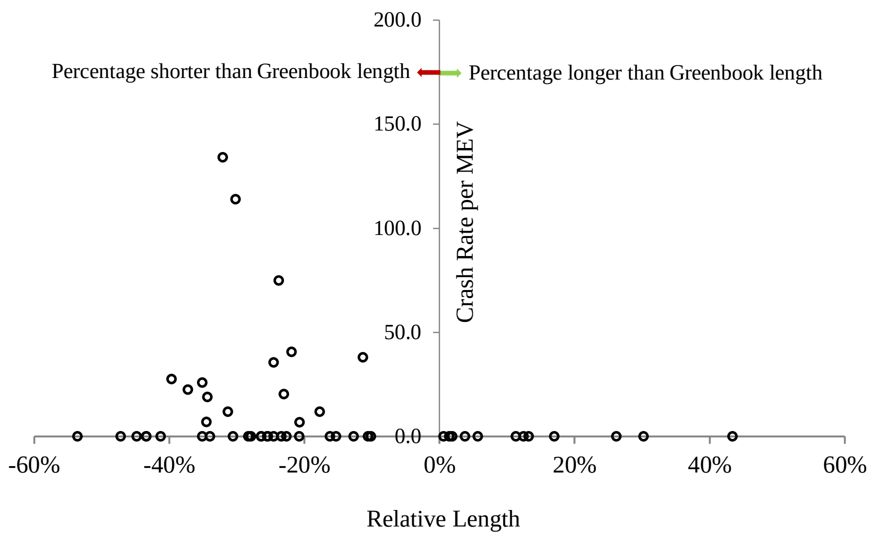

FIGURE 3: Impacts of lane length on crash rates

DATA ANALYSIS AND RESULTS

Poisson Regression

Using the data acquired from the 52 studied lanes, 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 (*30*), the preliminary tests evidenced that a Poisson regression 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. In addition, overdispersion tests indicated that we could not reject the null hypothesis of equidispersion at a confidence level of 95%, which further justified the use of Poisson regression modeling approach.

<u>*Notation*</u>

The parameters and variables used in the proposed regression 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;

$f(y_i)$ = distribution function of the probability for $y_i = k$ ($k = 0,1,2,3,\ldots$) at left-turn lane i over the study period;

X = vector of the explanatory attributes. See the definitions of the attributes in TABLE 3;

β = vector of the coefficients to be estimated;

Formulation

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

$$f\left(y_i\right)=\frac{\exp\left(-\lambda_i\right)\lambda_i^{y_i}}{y_i\,!} \tag{3}$$

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

$$\beta\cdot X=\beta_0+\beta_1\cdot s_i+\beta_2\cdot v_i+\beta_3\cdot V_i+\beta_4\cdot P_i+\beta_5\cdot T_i+\beta_6\cdot n_i+\beta_7\cdot a_i+\beta_8\cdot L_i$$

The projected number of crashes at left-turn lane i over the study period can be estimated by:

$$E(y_i\,|X)=e^{\beta\cdot X}=e^{\left(\beta_0+\beta_1\cdot s_i+\beta_2\cdot v_i+\beta_3\cdot V_i+\beta_4\cdot P_i+\beta_5\cdot T_i+\beta_6\cdot n_i+\beta_7\cdot a_i+\beta_8\cdot L_i\right)} \tag{4}$$

The explanatory variables were defined in TABLE 3. The final selection of the attributes depends on the statistical significance of the attributes in the regression analysis.

Testing whether the non-zero-inflated incident state (e.g., Poisson regression) is more appropriate than a zero-inflated incident state (e.g., ZIP) 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 in 1989 (*31*) 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:

$$v_{\mathrm{ZIP}}=\frac{\sqrt{n}\left[(1/n)\sum_{j=1}^{n}m_i\right]}{\sqrt{(1/n)\sum_{j=1}^{n}\left(m_i-\bar{m}\right)^2}}=\frac{\sqrt{n}\left(\bar{m}\right)}{S_m}\lim_{x\to\infty} \tag{5}$$

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 rejects the zero-inflated model (*31*).

Results and Sensitivity Analysis

Using the fifty-two data samples, maximum-likelihood estimation (MLE) was used to estimate the coefficients β in the model, and the outcomes are presented in TABLE 4.

TABLE 4: Calibrated coefficients for the model

Parameter	Coefficient β_j	Standard Error	Z-Statistics	*p*-value	95% Confidence Interval	
Intercept	-2.9155	0.7437	-3.92	.0001	-4.373	-1.458
Directional ADT volume per lane (V_i)	0.2208	0.0784	2.82	.0048	0.067	0.374
Relative lane length (L_i)	-4.1993	1.3227	-3.17	.0015	-6.792	-1.607

Note: Number of samples = 52; Directional average traffic volume was measured in 1,000 vpdpl; Relative length = $\frac{\text{(Actual length-Greenbook length)}}{\text{Greenbook length}} \times 100\%$

Therefore, the final model can be expressed as:

$$E(y_i|X) = e^{(-2.9155+0.2208\times V_i - 4.1993\times L_i)} \tag{6}$$

The final model included relative length of left-turn lane as a statistically significant predictor (*p*-value = 0.0015). Generally, the extent to which a median left-turn lane follows Greenbook recommendations had significant effects on safety performance at unsignalized median openings, i.e., longer lanes that better follows the recommendation generally led to better safety performance. In addition, the final model included the directional average daily traffic volume of the street (vpdpl) in the direction that the studied left-turns traveled. Given the same lane length, higher volumes were associated with more interactions between through traffic and left-turning vehicles that decelerated in preparation for entering median left-turn lanes, which led to a higher crash potential.

The Vuong statistic was equal to 1.7038, which was not greater than +1.96. The result did not favor the use of a ZIP model over the Poisson regression at a confidence level of 95%, which further justified the model proposed.

The results did not provide statistical evidence that posted speed limit (s_i), number of traffic lanes on the roadway (n_i), proportion of taper length (a_i) or left-turning volume (v_i) had significant effects on the total number of the related crashes. The left-turning volumes observed were generally low and had a narrow spectrum, leading to a weak association between crashes and the turning volumes. Many locations with left-turning volumes sufficiently high were already signalized, making such locations out of our study scope (i.e., unsignalized median openings). 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. Thus, these predictors were excluded from the final model.

A sensitivity analysis was performed on safety impacts of the relative length of left-turn lane (i.e., the difference (in percentage) between the actual lane length and Greenbook recommended length). FIGURE 4 indicated that a left-turn lane with the same length as the Greenbook recommendation (i.e., zero at the horizontal axis) was associated with relatively low crash frequency and a low likelihood for crashes to occur. Given a specific lane length, a low directional average daily traffic (e.g., under 3,000 vehicles per day per lane) generally presented low crash frequency; a short left-turn lane was associated with significantly higher crash potentials given a high directional average daily traffic (e.g., 10,000 vehicles per day per lane).

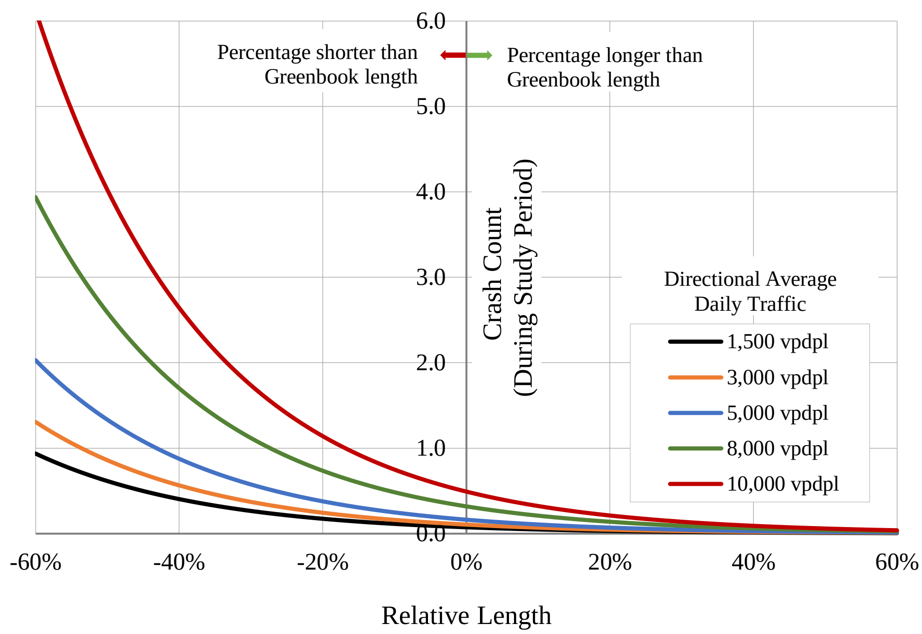

FIGURE 4: Safety implications of lane length relative to Greenbook recommended length

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, projected by Equation (6)) given a specific lane length was used to formulate the CMF as Equation (7). In the calculation, the base case represented a lane that is equal to the Greenbook recommended length. Given a directional average daily traffic volume of V_i, the CMF of a median left-turn lane with $L_i = x$ can be expressed as:

$$\mathrm{CMF}(L_i = x) = \frac{E(y_i | L_i = x)}{E(y_i | L_i = 0)} = \frac{e^{(-2.9155+0.2208\times V_i-4.1993\times L_i)}}{e^{(-2.9155+0.2208\times V_i-4.1993\times 0)}} = e^{(0.2208\cdot L_i)} \quad (7)$$

where

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

$E(y_i | L_i = x)$ = mathematical expectation of total number of related crashes y_i at a median left-turn lane that has a relative length of x; for example, $E(y_i | L_i = -20\%)$ represents the mathematical expectation of the crash count at a left-turn lane that is 20 percent shorter than the Greenbook length.

For instance, given a left-turn lane 20 percent shorter than the Greenbook recommended length and a directional ADT of 3,000 vpdpl, the CMF can be calculated as:

$$\mathrm{CMF}(L_i = -20\%) = \frac{E(y_i | L_i = -20\%)}{E(y_i | L_i = 0)} = \frac{e^{(-2.9155+0.2208\times 3.000-4.1993\times(-20\%))}}{e^{(-2.9155+0.2208\times 3.000-4.1993\times 0)}} = 2.32$$

The CMF value of 2.32 projected that the left-turn lane would have approximately 2.32 times of the total crashes expected for a lane with the Greenbook recommended length. In this approach, the CMFs were calculated for various lengths of lanes and plotted in FIGURE 5.

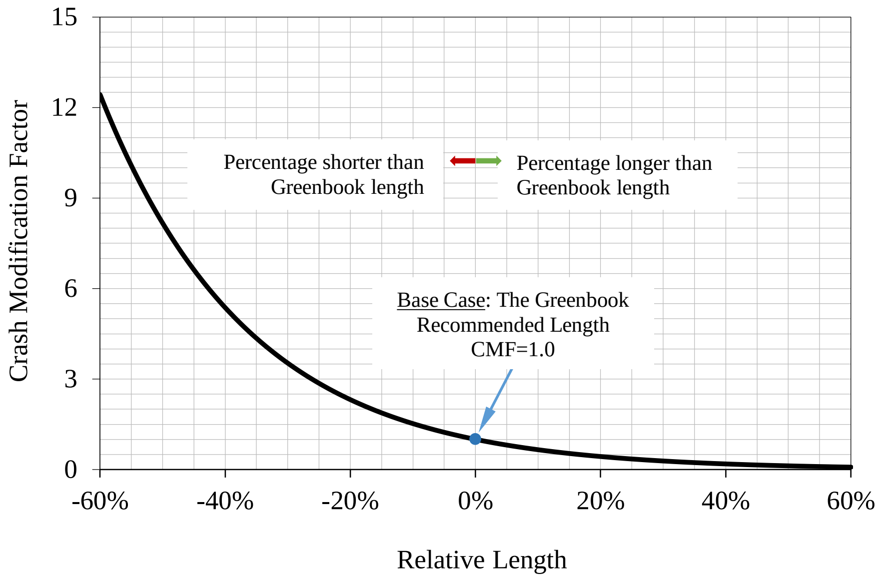

FIGURE 5: CMFs for short left-turn lanes

After lengthening/shortening a given left-turn lane, the crash frequency expected can be estimated as:

$$f_{\text{After}} = f_{\text{Before}} \times \frac{\text{CMF}(L_i = x_{\text{After}})}{\text{CMF}(L_i = x_{\text{Before}})} \tag{8}$$

where

f_{After} = expected crash frequency after the lane is changed to a relative length of x_{After}

f_{Before} = historical crash frequency given the existing relative length of x_{Before}

Applications of the CMF Developed

To explain how the CMFs can be used and interpreted, the following is an example. A left-turn lane of 300 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 peak hour is 50 vph, leading to two vehicles arriving in each two-minute interval on average. In light to the Greenbook recommendations, the desirable 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 is 35 feet longer than the Greenbook length and the relative length is equal to 35/265 = +13%. Reportedly, the lane had a historical 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 80 feet to accommodate a new left-turn lane, which will be placed back-to-back to the existing left-turn lane and aligned to the new opening. Shortened by 80 feet, the relative length will become $-45/265 = -17\%$. Under the given conditions, the total crash frequency after shortening the lane can be projected as:

$$0.20 \text{ crash/year} \times \frac{\text{CMF}(L_i = -17\%)}{\text{CMF}(L_i = +13\%)} = 0.20 \times \frac{2.042}{0.579} = 0.71 \text{ crash/year}$$

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 0.71 crash/year). In addition to the crash potentials, engineers need to comprehensively consider all aspects of the traffic (e.g. mobility and accessibility) and other concerns (e.g. economic and social impacts) in determining 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.

CONCLUSIONS

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

- Median left-turn lanes that adhered to the AASHTO Greenbook recommendations generally presented appropriate safety performance.
- Statistical evidence showed that the difference between actual lane length and the Greenbook recommended length had significant impacts on crash potential at the study locations. In addition, directional average daily traffic volumes had significant effects on the crash potential.
- When it is impractical to provide the Greenbook recommended length, short left-turn lanes might be acceptable in some particular cases (especially urban streets), in which engineers' judgments are needed for a trade-off decision accounting for crash potential, mobility, accessibility, and economic and social impacts in determining whether a short left-turn lane is appropriate.

Although the outcomes of this study provided important understanding of the safety performance of short left-turn lanes at unsignalized opening, the results may be limited in scope and applicability due to the limited sample size involved.

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