Effects of Bus Stops on Pedestrian Safety at Signalized Intersections

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Abstract Of all road users, pedestrians are considered the most vulnerable mainly due to the lack of body protection, mass, and speed. There are many factors that affect the occurrence of a pedestrian involved crash—exposure (e.g., pedestrian and traffic volume), injury severity (e.g., speed and vehicle type), roadway and environment (e.g., proximity to bus stops, presence/proximity of facilities (store, building, school)) and intersections. Among the factors, the presence and proximity of transit bus stops are the distinctive risk factors in the pedestrian involved crashes in urban areas. The objective of this study is to understand the influence of bus stop locations on pedestrian safety near signalized intersections. To accomplish the study objectives, pedestrian safety data collected at a sample of signalized intersections in Texas were used and a safety performance function was developed. It was found that bus stops within 300 ft from the center of the intersection increase pedestrian crashes by 48%. Other variables that also had an influence on pedestrian safety are entering vehicular volume, pedestrian crossing volume, the maximum number of lanes crossed by a pedestrian at an intersection, and left-turn signal phasing.

Keywords Pedestrian crashes · Safety performance functions · Crash modification factors · Bus stops · Signalized intersections · Negative binomial model

1 Introduction

Of all traffic fatalities worldwide, 22% of them are pedestrians [1]. This ratio is much higher in developing countries. In pedestrian crashes, millions of people are injured while walking, and a part of them become permanently disabled. In the United States, 6,283 people were killed in pedestrian/motor vehicle crashes in 2018, an increase of 3.4% from 2017 [2]. On average, a pedestrian was killed every 84 min, equivalent to around 120 people a week [2]. When compared to passenger vehicle occupants, on each trip, pedestrians are 1.5 times more likely to be killed in a car crash [3].

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Importantly, more pedestrian fatalities occurred at non-intersections (74%) than at intersections (17%) in the country [2].

Of all road users, pedestrians are considered the most vulnerable mainly due to the lack of body protection, mass, and speed [4]. There are many factors that affect the occurrence of a pedestrian involved crash—exposure (e.g., pedestrian and traffic volume), injury severity (e.g., speed and vehicle type), roadway and environment (e.g., proximity to bus stops, presence/proximity of facilities (store, building, school)) and intersections [5–10]. Among the factors, the presence and proximity of transit bus stops are the distinctive risk factors in the pedestrian involved crashes in urban areas [6, 11]. The objective of this study is to understand the characteristics associated with the pedestrian crashes near signalized pedestrians. More specifically, this paper evaluates the role of bus stops within the vicinity of signalized intersections on pedestrian crashes.

2 Background

Having an understanding of roadway characteristics, exposure measures and traffic control devices that affect pedestrian crash frequency and severity are correlated with pedestrian crashes could assist in identifying locations with high potential for crashes.

Haleem et al. [7] used a mixed logit model and identified factors that affect pedestrian crash injury severity at signalized and unsignalized intersections using a mixed logit model. Their study used three years of pedestrian crash data from Florida (2008–2010) and included a total of 3038 pedestrian crashes. The study only included state roads and the authors recommended that additional research is needed for local roads. The following variables were associated with pedestrian severity risk for signalized intersections.

- Traffic volume,
- Speed limit,
- Trick percentage,
- Senior pedestrians,
- At-fault pedestrians,
- Rainy conditions. and
- Dark conditions.

Jermprapai and Srinivasan [12] reported on a planning-level model for assessing pedestrian safety. The study results were similar to other studies about the relationship between crashes and transportation, socioeconomic and land use characteristics. They found that a low-income location in a higher-income county is one of the riskiest factors. They also concluded that there is a high-risk at locations that have a larger volume of conflicting vehicular and pedestrian movements.

According to Haleem et al. [7], as annual average daily traffic (AADT) at signalized intersections increases, so does the probability of severe injuries, due to the increased number of vehicle–pedestrian conflicts. Zahabi et al. [9] also found that pedestrian crashes at intersections have a lower probability of injury or fatality; intersection-related pedestrian crashes were 1.21 times less likely to result in a fatality than non-intersection-related pedestrian crashes. One possible explanation for this finding is that motorists operate at lower speeds near intersections. It could also be because both drivers and pedestrians are more likely to expect to interact at intersections, so they pay closer attention.

Passenger vehicles are more frequently involved in crashes with pedestrians, although other vehicles like trucks, buses, and emergency vehicles in pedestrian crashes cause more injuries that are severe or fatal. Trucks, vans and buses category are responsible for almost twice the percentage of crashes that resulted in a fatality, compared to passenger vehicles [5]. This finding is supported by Zahabi et al. [9] who found that trucks, vans, and buses involved in crashes resulted in more fatalities compared to passenger vehicles; the risk of pedestrian fatality is 1.2 higher with trucks and vans in a fatal crash. Hu and Cicchno [8] found that the increase in SUV-related fatal single-vehicle–pedestrian crashes was larger than the increases in the other vehicle types (such as cars, vans, pickups, or medium/heavy trucks). Zahabi et al. [9] also found that after controlling for other factors, a vehicle moving in a straight direction is significantly associated with 1.42 times higher risk of a fatality than a pedestrian crash involving a turning vehicle.

Crashes involving at-fault pedestrians were found to be associated with greater pedestrian injury severity than crashes where the driver was at-fault [7]. Alcohol and drug use by a pedestrian is also associated with higher pedestrian injury severity among pedestrian involved crashes [5]. According to Valaar et al. [13], 41% of pedestrians killed in crashes tested positive for alcohol in the U.S. The authors stated that though positive alcohol results among fatally-injured pedestrians have decreased, the numbers of total pedestrians with alcohol use remain as high as 40% based on 2012 Canada data, similar to that of the U.S. results. Additionally, 86.2% of the fatally-injured pedestrians who consumed alcohol had a blood alcohol content (BAC) of over 0.08 g/dL, which is the legal limit to operate a motor vehicle in Canada and the United States. Furthermore, 67.6% had registered BAC of over 0.16 g/dL, which is twice the legal limit, putting such pedestrians at a high level of risk in terms of crash involvement.

A study by Lindsay [14] analyzing fatal crashes in Australia from 2008 to 2010 found that out of 1,490 crash victims admitted to hospitals, alcohol tests were conducted for 1,204. Of that, a positive alcohol result was seen in 274 persons (18%). Additionally, among the people who has a positive result, alcohol impairment was particularly an issue with pedestrians (56%) compared to drivers (24%). When alcohol or drug use is present among pedestrians involved in crashes, a larger percentage of crashes result in injury or fatality. However, alcohol and drug use among pedestrians and other vulnerable road users has not been a much-studied issue when compared to drivers [5].

2.1 Roadway & Environment Characteristics

Zahabi et al. [9] found that the probability of a pedestrian fatality is affected by road type. Pedestrian crashes on arterial roads have a 1.12 times higher risk of fatality, compared to crashes on local roads. In 2002, McMahon et al. [15] analyzed pedestrian crashes that involved walking along the roadway. The researchers found that roadway characteristics such as higher traffic volume, higher speed limit, and lack of sidewalks/wide walkable areas all contributed to significantly higher crash risk for pedestrians.

Crash predictive models developed by Zeeger and Bushell [10] showed that multiple factors are associated with a greater probability of pedestrian crashes. The authors found that pedestrian crashes are more likely to occur:

- on higher traffic volume roads
- on roads with higher volumes of pedestrians
- at intersections where the ratio of minor road traffic and major road traffic is larger
- as the number of lanes to cross increases without the presence of a refuge island
- at intersections with a bus stop within 1000 feet
- within 1000 feet of a public or private school
- as the number of alcohol retail establishments within 1000 feet increases.

Pedestrian fatal crash risk also increased with exposure of pedestrians and increased traffic for signalized crossings. Other factors associated with increased pedestrian fatality risk included "a greater number of lanes, lack of a raised median or median island (for multi-lane roads), and for older pedestrians (65 years and older)" [10]. In multi-lane roads with higher volumes of traffic, there was a higher association between the presence of marked untreated (i.e., without any other traffic control devices) crosswalks and pedestrian crashes, in comparison to just the presence of unmarked crosswalks [10].

According to a study by Clifton et al. [5], over half of the pedestrians involved in crashes and two-thirds killed in crashes are not in crosswalks at the time of the crash. At unsignalized intersections, the presence of crosswalks and road surface conditions are significant predictors of pedestrian injury severity. When present, marked crosswalks are associated with a reduction in pedestrian injury severity, possibly by alerting drivers in advance.

Haleem et al. [7] in Florida identified environmental predictors of pedestrian injury severity using a mixed logit model. Significant environmental predictors identified in signalized intersections included weather and lighting conditions, and the hour of the crash. Significant environmental predictors related to pedestrian involved crashes identified at unsignalized intersections included dark lighting conditions and dry road surface conditions. The probability of severe injury is associated with night-time and dawn, both periods when there is poor visibility and high vehicle speeds [7]. This was true for both signalized and unsignalized intersections. However, pedestrian severity was found to be higher at unsignalized intersections. Also, rainy weather is associated with higher injury severity, possibly due to visibility restrictions and/or inability to stop or slow before the collision [7]. Similarly, Zahabi et al. [9] found that pedestrian crashes occurring in the dark after sunset resulted in a higher probability of injury or fatality. The likelihood of fatality in pedestrian crashes after dark increased by 1.45 times according to their study.

Similar to the findings of Haleem et al. [7] and Zahabi et al. [9], Uttley and Fotios [16] found that pedestrians faced increased risk in the roadway, especially in the dark. Interestingly, the researchers found that this risk increased when using a crosswalk in the dark compared to the crossing at non-crosswalk locations. The researchers attribute this to the confidence that pedestrians feel when using the crosswalks, where they are likely to overestimate their visibility to drivers on the road.

A noteworthy result found by Zahabi et al. [9] is that pedestrian crashes close to schools or parks had a significant association with crash severity. For example, pedestrian crashes around a school resulted in 1.13 times less likelihood of a severe injury or fatality, possibly due to the placement of calming traffic measures like lower speed limit around schools. However, if a pedestrian crash occurred around a park, the probability of fatality increased by 1.25 times, suggesting a need for calming traffic measures around parks just like in schools [9].

2.2 Transit/Bus Stop Characteristics

Among the factors affecting pedestrian involved crashes, the pedestrian crossing's proximity to transit bus stops is more likely to increase a pedestrian crash risk. Torbic et al. [17] developed the pedestrian safety prediction methodology of vehicle–pedestrian collisions at signalized intersections. The methodology includes crash modification factors associated with the number of bus stops, the presence and proximity of schools, the number of alcohol sales establishments, and neighborhood income level within 1000 ft. from the intersection. For the number of bus stops within 1000 ft. from the intersection, the pedestrian–vehicle collisions increased by up to 4 times at an intersection with one or more bus stops relative to an intersection without bus stops.

Specifically related to transit bus stops, the risk of pedestrian crashes increased with the number of bus stops around an intersection [18, 19]. A study by Walgren [19] presented that 89% of high crash locations were within 150 ft of a bus stop and 90% of these locations were within 70 ft of a crosswalk. The higher risk of pedestrian involved crashes near bus stops can be related to increased distraction and poor yielding behavior [6]. Craig et al. [6] analyzed whether the presence of a bus stop influences a driver yielding behavior to pedestrians at marked unsignalized crosswalks compared with other locations and whether a High-Visibility Enforcement (HVE) affects a driver yielding behavior. At the sixteen crosswalks in Saint Paul, MN, a driver yielding behavior to a pedestrian improved with HVE. In addition to HAV, Craig et al. [6] conducted public outreach and educational activities to increase awareness of pedestrian laws and safety tips for local residents and drivers, and concluded that community outreach has been shown to measurably improve yielding behaviors to pedestrians at the studied crosswalks.

Although the proximity of transit bus stops leads to an increased risk of pedestrian involved crashes, the risk is not equal to all bus stops. Ulak et al. [11] developed a bus Stop Safety Index (SSI) to quantify and access pedestrian safety around bus stops for the purpose of screening the urban roadway network and identifying the high-risk bus stops similar with that of the Safety Performance Functions (SPFs) in the Highway Safety Manual. Ulak et al. [11] analyzed the pedestrian involved crashes in Palm Beach County, FL, and then each bus stop was assigned an SSI score based on injury severities and the spatial distance between the bus stop and the pedestrian involved crash. Then SSI scores are tabulated by using socio-demographic factors (i.e., median income, population), traffic indicators (i.e., traffic volume and speed), the proximity of facilities (i.e., supermarket, hospital, school), and bus stop metrics (i.e., daily boarding and frequency). Using the factors, the high-risk bus stops can be prioritized.

In addition to the location of bus stops, the design of bus stops can be influential on the risk of pedestrian involved crashes. Fitzpatrick and Nowlin [20] analyzed the effect of bus stop design (i.e., curbside versus bus bay/open bus bay, and queue jumper versus no queue jumper, as shown in Fig. 1) on travel time, speed and traffic volume. Results indicated that the bus bay and queue jumper design provided better benefits for traffic flow at the intersection.

Fitzpatrick and Nowlin [20] concluded that the collisions are more likely to occur when a transit stop is located immediately prior to an intersection (near-side transit stop) rather than immediately after passing through an intersection (far-side transit stop) as shown in Fig. 2. At intersections, near-side transit stops can increase the number of conflict points between the transit vehicles and right-turning vehicles. However, the far-side stop design may result in the intersections being blocked during peak hours by stopping buses or may obscure sight distance for crossing vehicles/pedestrians [21]. In addition, the presence of transit signal priority (TSP) technology at an intersection increased the probability of transit-involved collisions.

Miranda-Moreno et al. [22] investigated the relationship between pedestrian activity and the built environment and found that pedestrian activity is highly related to the number of bus stops and the presence of rail transit. In consequence, the frequency of pedestrian collision at signalized intersections significantly increased with the number of bus stops as well as traffic and pedestrian volume, intersection configuration (4-legged or 3-legged), and land use (commercial area).

Although previous research had studied the role of bus stops on the pedestrian crash risk, the effect on the number of crashes is not accurately quantified. In addition, not many previous studies included the signal characteristics in the regression models. This study tries to fill the knowledge gap by including the signal characteristics and bus stop presence among other variables in the model and presents the crash modification factor (CMF) for each variable.

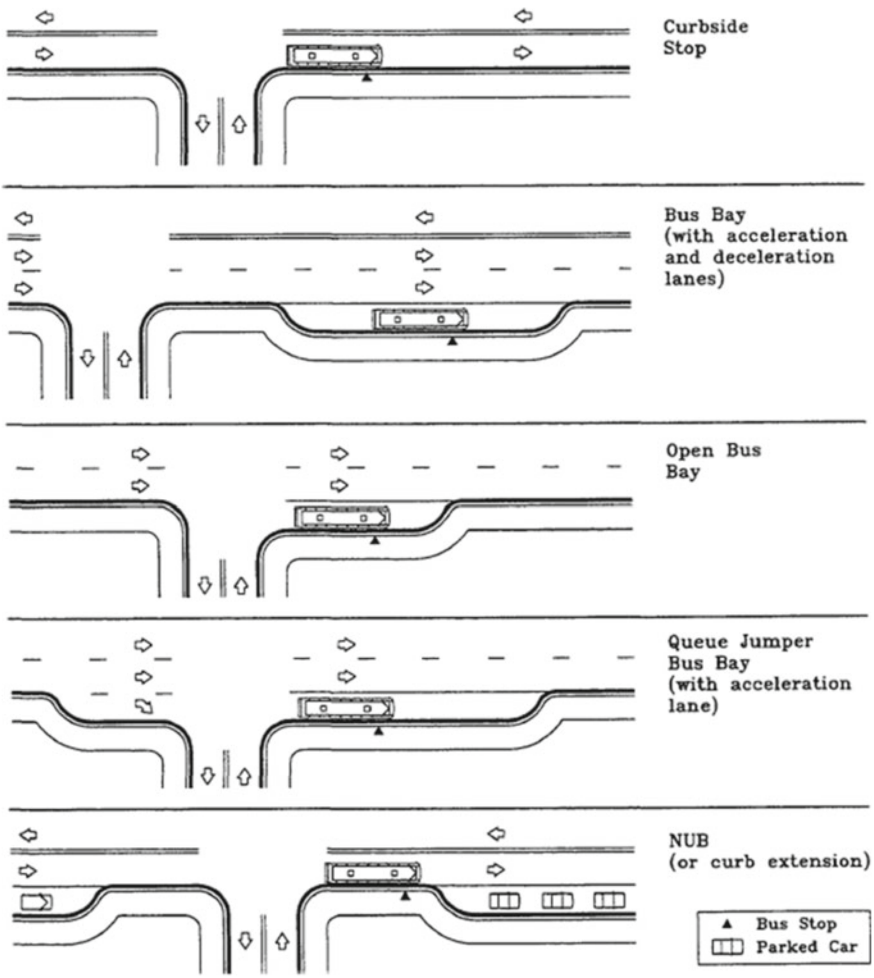

Fig. 1 Bus stop design [21]

3 Data Description

To provide a better understanding of the relationship between various intersection characteristics and pedestrian safety performance, it was first necessary to assemble a comprehensive database. As a part of this study, data were assembled for a sample of signalized intersections spanning over multiple years in Texas from multiple different sources. In total, 621 signalized intersections in four metropolitan cities (Houston, San Antonio, Austin and Dallas-Fort Worth) were randomly selected. Traffic volumes were obtained using the 2018 Texas Department of Transportation (TxDOT's) Road Inventory Network (i.e., RHINO) data.

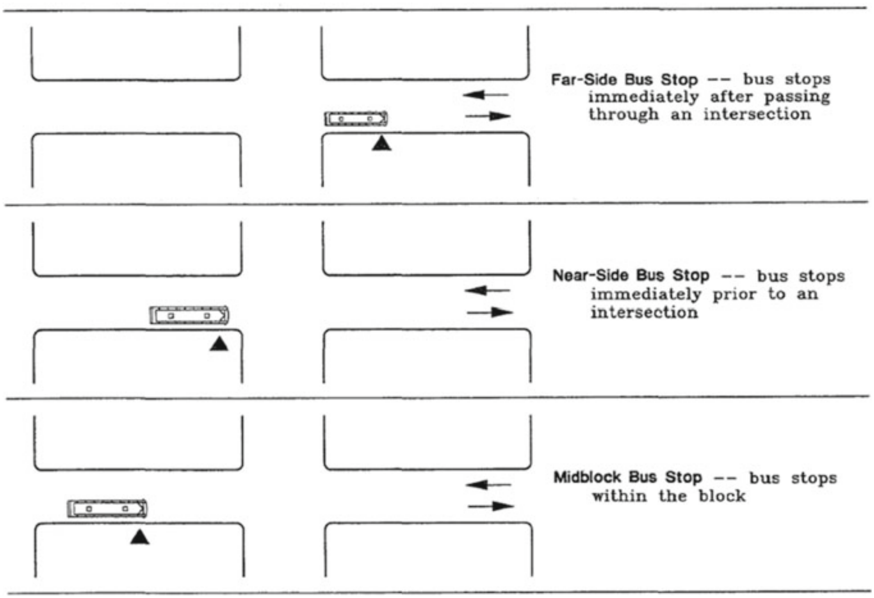

Fig. 2 Example of far-side, near-side, and midblock stops [21]

Intersection characteristics such as presence in the central business district (CBD), adjacent land uses (i.e., commercial, single and multifamily, industrial, and vacant), light rail stop presence, bus stop presence, sidewalks, and special generators within 300 ft of the intersection were extracted from aerial photography. Generally, the variables were quantified within the 300 ft buffer of the intersection. However, it was found that many of the school's coordinates did not locate them within the 300 ft buffer and given the number of potential pedestrians around schools, a variable that reflects the proximity of schools (K-12 and higher education) was created. The number of schools within ¼, ½, and 1 mile of each intersection, and along with the available street network, were counted. The number of lanes crossed by a pedestrian at an intersection is counted for all legs. The maximum number of lanes is then used in the model to quantify the distance a pedestrian needs to walk during a particular signal phase.

The most important variable that influences pedestrian safety is pedestrian volume. We conducted 2 h pedestrian counts at intersections in addition to the 24 h counts at two signalized intersections in each city. The 2 h counts were often started in the middle of a clock-hour (e.g., 1:30–3:30 pm), such that the expansion factors, time durations, and counts within each clock-hour needed to be considered separately. This approach was chosen based on a balancing of the competing objectives of (1) obtaining pedestrian volume estimates at a reasonable number of sites in each city and (2) obtaining estimates that are robust and defensible. The 24 h pedestrian count site was used to obtain a distribution of pedestrian volumes throughout the day, such

Table 1 Summary statistics for signalized intersections

Variable	Minimum	Maximum	Mean	Std. deviation
Major street AADT (vehicles per day)	460	72,868	23,336	14,269
Minor street AADT (vehicles per day)	70	67,599	7193	7615
Pedestrian crossing volume (pedestrian per day)	10	22,044	1169	2349
Maximum number of lanes crossed	2	10	4.67	1.32
Indicator for presence bus stops within 300 ft	0	1	0.88	0.33
Indicator for protected signal operation	0	1	0.59	0.49
Maximum posted speed limit (miles/h)	25	50	35.2	4.8
Pedestrian crashes	0	8	1.14	1.25
Number of intersections	621			

that expansion factors could be derived for each hour of the day. These adjustment factors are used to obtain daily volumes at every intersection.

All fatal to possible injury (KABC) pedestrian-related crashes were obtained for the years 2017–2019 from TxDOT's Crash Record Information System (CRIS). Only crashes that were identified as TxDOT reportable are included in the analysis. TxDOT reportable is defined as a crash occurring on a public roadway and resulting in death or injury or $1,000 in damage. About 3% of the crashes were missing location coordinates. Various techniques were used to geo-code them based on available information such as street name, intersecting street, block number, etc. so that the dataset was as complete as possible. Descriptive statistics for important variables are provided in Table 1.

4 Modeling Results

The proposed model coefficients were estimated using the NLMIXED procedure in the SAS software (SAS, 2015). The negative binomial (NB) distribution log-likelihood function was used to determine the model coefficients. Different variable combinations and various model forms were examined to identify the best possible relationship between crash frequency and independent variables. The model presented below was informed by findings from several preliminary regression analyzes. This model form includes variables that are intuitive, in-line with previous findings and best fit the data. The predicted average pedestrian crash frequency of a signalized intersection is calculated as shown below.

$$N_i = N_{base} \times CMF_{ltph} \times CMF_{lanesX} \times CMF_{bus}. \tag{1}$$

$$N_{base} = n \times e^{b_0 + b_1 \ln(TotEntVol) + b_2 \ln(PedVol)}. \tag{2}$$

with,

$$CMF_{ltph} = e^{b_{pt} \times I_{pt}}.$$

$$CMF_{lanesX} = e^{b_{lanesX}(n_{lanesX} - 4)}.$$

$$CMF_{bus} = e^{b_{bus} \times I_{bus}}.$$

where,

N_i = predicted annual average crash frequency at intersection i,

I_{pt} = protected signal phasing indicator variable (=1.0 if protected, 0.0 otherwise),

$TotEntVol$ = Total entering vehicular volume from all approaches (=$AADT_{\text{Major}}$ + $AADT_{\text{Minor}}$ if 4-leg; =$AADT_{\text{Major}}$ + $AADT_{\text{Minor}}$/2 if 3-leg),

$PedVol$ = Total pedestrian crossing volume for all legs combined,

n_{lanesX} = Maximum number of traffic lanes crossed by a pedestrian (in any crossing maneuver) at the intersection,

I_{bus} = presence of bus stop within 300 ft of the intersection,

b_i = calibration coefficient for variable i.

The variable coefficients for signalized intersections are presented in Table 2. Some variables that are not statistically significant at the 5% level are included if they are intuitive and within logical boundaries. Although many other signal characteristics such as signal cycle length, pedestrian push button type, and walk length were considered, they were not statistically significant in the model.

Table 2 Calibrated coefficients for pedestrian crashes at signalized intersections

Coefficient	Variable	Int. type	Value	Std. Dev	t-statistic	p-value
b_0	Intercept	4-Leg	−4.8428	1.0113	−4.79	<0.0001
		3-Leg	−5.0672	1.0126	−5	<0.0001
b_1	Total entering vehicle vol.	All	0.2272	0.09336	2.43	0.0152
b_2	Pedestrian vol.	All	0.1955	0.03172	6.16	<0.0001
b_{pt}	Protected signal phasing	All	−0.1881	0.1016	−1.85	0.0646
b_{lanes}	Max. number of lanes crossed	All	0.06504	0.04067	1.6	0.1103
b_{bus}	Bus stop presence	All	0.3897	0.1598	2.44	0.015
k	Inverse dispersion parameter	All	0.4018	0.1063	3.78	0.0002
Number of intersections						621

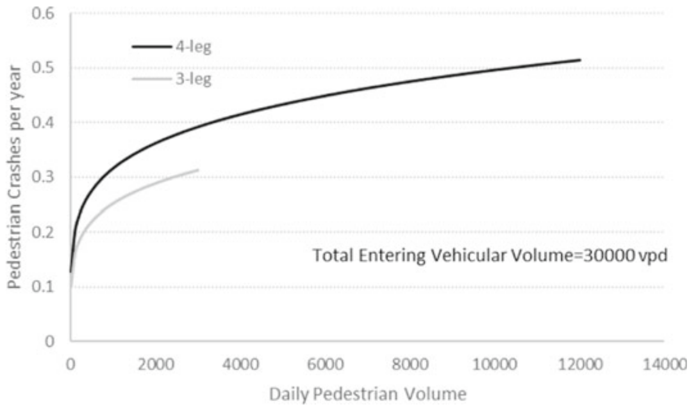

Fig. 3 Predicted crashes at different types of signalized intersections

The relationship between pedestrian crash frequency and pedestrian demand for base conditions, as obtained from the calibrated models, is illustrated in Fig. 3 for signalized intersections.

4.1 Crash Modification Factors

The following paragraphs present the CMFs for the variables significant in the model.

Intersection Left-Turn Signal Phasing. The base condition for this CMF is permissive or permissive/protected left-turn signal phasing. The CMF is determined as:

$$CMF_{ltph} = e^{-0.1881 \times I_{pt}}. \quad (3)$$

The CMF values are presented in Table 3. During the permissive phase, drivers mostly concentrate on the opposite direction vehicles to find a gap and often miss seeing the pedestrian crossing the street. This results in an increased chance for pedestrian crash occurrence. The results show that protected signal phasing reduces crashes by 17%.

Number of Lanes. This variable represents the maximum number of traffic lanes crossed by a pedestrian (in any crossing maneuver) at the intersection. The base

Table 3 CMF for left-turn signal phasing

Left-turn signal phasing	CMF
Permissive	1.00
Protected/Permissive	1.00
Protected	0.83

Table 4 CMF for number of lanes

Maximum number of lanes crossed	CMF
2	0.88
4	1.00
6	1.14
8	1.30
10	1.48

Table 5 CMF for bus stop presence

Bus stop present	CMF
No	1.00
Yes	1.48

condition for this CMF is four lanes. This CMF is applicable for all signalized intersections. Table 4 presents the relationship between the number of lanes and pedestrian crash frequency.

Bus Stop Presence. The base condition for this CMF is the absence of bus stops within 300 ft from the center of the intersection. This CMF is applicable for all signalized intersections. Table 5 presents the relationship between the presence of bus stops and pedestrian crash frequency.

5 Conclusions

Pedestrians are more likely than passenger vehicle occupants to sustain fatal or severe injuries in a vehicle–pedestrian collision. Identifying the high-risk locations (or hot-spots) is an important step to reduce the pedestrian crashes. In the traditional hot-spot identification process, crashes that occurred on a highway network or a geographical area are routinely considered. Since pedestrian crashes are rare and random, the traditional approaches could potentially identify very few to no sites where pedestrian crashes might occur. Crash prediction models (also called SPFs) play a critical role in predicting the number of pedestrian crashes that occur at a site. This study developed the SPFs for signalized using the Texas intersection data. The variables that are found to be significant in influencing the pedestrian crashes at intersections are the following.

- Sum of major and minor street AADT,
- Intersection left-turn signal phasing,
- Pedestrian crossing volume,
- Presence of a bus stop within 300 feet from the center of the intersection, and
- Maximum number of lanes crossed by the pedestrian.

The study results showed that the presence of a bus stop within the vicinity of an intersection increases pedestrian crashes by 48%. In addition, if the bus stop is present at an intersection with 10 lanes on a particular street, then the pedestrian crashes increase by 119% when compared to a four-lane street with no bus stops. Similarly, the results suggest that the agencies should try to avoid constructing bus stops if the signal left-turn operation is permissive. The results of this study will assist the planners in their safety activities and identifying hazardous signalized and stop-controlled intersections. It is recommended to conduct further research to explore the transferability of the SPFs in this study to other geographical and if an adjustment factor is needed.

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