Impact of Road Infrastructure, Traffic Operations and Pedestrian Crossing Behavior on Fatal Pedestrian Crashes at Urban Signalized Intersections

Dipanjan MUKHERJEE [a], Sudeshna MITRA [b]

[a] *Department of Civil Engineering, Indian Institute of Technology Kharagpur, Kharagpur*, India
[b] *Transport Specialist, Global Road Safety Facility, The World Bank, Washington DC, USA*
[a] *E-mail: ddiipp90@gmail.com*
[b] *E-mail: smitra5@worldbank.org*

Abstract: Pedestrian crashes at urban signalized intersections, resulting as a consequence of several risk factors, related to lack of road infrastructure, inefficient traffic operations, and pedestrians' unsafe acts. Explicitly, pedestrians' unsafe acts such as signal violation behavior at urban signalized intersections account for a significant share of pedestrian fatalities in developing countries; however, these variables are generally omitted in crash prediction models due to lack of availability of data. Consequently, the effects of pedestrians' unsafe acts are simply assumed to contribute to model error, with sound emphasis on predictor variables associated with road infrastructure and traffic operations. In this context, the present paper demonstrates a unique approach for modelling fatal pedestrian crashes by combining factors from two major sources, namely, (a) *lack of pedestrian-friendly infrastructure, and inefficient traffic operations*, and (b) *pedestrians' unsafe acts*. The proposed modelling approach is found to produce a model with superior goodness-of-fit compared to conventional approaches.

Keywords: Pedestrian Fatality, Risk Factors, Developing Country, Road Infrastructure, Crossing Behavior

1. INTRODUCTION

Conflicts between pedestrian and motorized traffic at intersections decrease capacity and increase the probability of crashes. However, efficient junction design can considerably increase the traffic flow and reduces the risk of pedestrian crashes. Traffic signal control is a common practice to improve pedestrian safety at intersections. Signalized intersections provide a designated right of way to pedestrians by stopping the conflicting traffic (Koh and Wong, 2014). Traffic signals are generally provided at the pedestrian crossing if the conflicting traffic volume is significantly high and time separation is essentially required for a safe pedestrian crossing. Even though the presence of a traffic signal with a marked pedestrian crosswalk facility is supposed to improve pedestrian safety; a significant number of fatal pedestrian crashes take place at the signalized junctions in Indian cities. The crash statistics obtained from "Kolkata Police" show that in Kolkata City, India approximately 30% of the fatal pedestrian crashes occur at signalized junctions.

Worldwide, a good number of studies have identified several reasons for pedestrian fatalities and injuries at signalized junctions. Amongst them, traffic exposure parameters such as pedestrian and vehicular volume are considered to be major factors (Miranda-Moreno et al., 2011). In addition to the traffic exposures variables, road geometry (Priyadarshini and Mitra, 2018), built environment (Rankavat and Tiwari, 2015), land use (Mukherjee and Mitra, 2019a), on-street parking (Agran et al., 1996), inadequate visibility (Peden et al., 2014), the absence of marked pedestrian crosswalk (Mukherjee and Mitra, 2019b), the width of the major and minor carriageway of an intersection (Mukherjee and Mitra, 2019a; Mukherjee and Mitra, 2019b) and traffic control parameters (Mukherjee and Mitra, 2020a) play a vital role in pedestrian safety. Studies have also shown that beyond the engineering factors pedestrian's unsafe crossing behavior such as pedestrians' signal violation or illegal crossing is a major source of pedestrian fatalities at signalized intersections in developing countries (Mukherjee and Mitra, 2020b, Tiwari et al., 2007) as well as developed countries (Brosseau et al., 2013). Hence, the previous literature on pedestrian safety evidently indicates that there is more than one major source of pedestrian risk at signalized junctions such as *lack of pedestrian-friendly road infrastructure*, *inefficient traffic operations*, and *pedestrians' unsafe crossing behavior*.

In urban India, inadequate road infrastructure (Mitra and Mukherjee, 2017; Priyadarshini and Mitra, 2018) and risky traffic operations (Rankavat and Tiwari, 2015), are the leading causes of pedestrian crashes. Moreover, in a developing country such as India, the enforcement of traffic rules and regulations is frequently low which also encourages pedestrians to act in an unsafe manner (Mukherjee and Mitra, 2017; Tiwari et al., 2007). Thus, in urban India, the observed pedestrian crashes at signalized intersections may be generated by various underlying, simultaneous and interdependent risk factors, and it is essential to investigate the individual and interactive effects of various risk factors in the context of urban India. To do so, it is necessary to formulate a suitable modelling methodology, that accounts for multiple sources of pedestrian risk and their contributions.

To evaluate the safety performance of existing traffic facilities, researchers have paid attention to the development of crash prediction models which is also known as Safety Performance Function (SPF). There are several motivations for developing SPFs, including the identification of causal or contributing factors of crashes, predicting crashes, and the capability to recognize unsafe sites. Researchers have primarily applied single equation crash prediction models to assess pedestrian safety. The basic assumption behind these traditional single equation crash prediction models is that risk factors belong to a single source (Washington et al., 2010). In contrast, the total crash count at a site may be an outcome of multiple distinct sources of risk factors, including lack of pedestrian-friendly road infrastructure, land-use type, inefficient traffic operations, road users' behavior, and their risk-taking attitude, etc. However, these multiple sources are generally overlooked in traditional single equation crash prediction models. Specifically, pedestrian's unsafe acts such as illegal crossing or signal violation behavior account for a major share of crash occurrence in most of the developing countries (Mukherjee and Mitra, 2020b; Mukherjee and Mitra, 2019b; Tiwari et al., 2007); however, these variables are generally omitted due to lack of availability of data. Consequently, the effects of pedestrians' unsafe behavior are simply assumed to contribute to model error, with sound emphasis on predictor variables associated with road infrastructure, geometric design, traffic exposures, and operational parameters. Several studies recommend that in developing countries at urban signalized junctions a significant proportion of pedestrian crashes is mostly the consequence of pedestrian's unsafe crossing behavior and risk-taking attitude (Mukherjee and Mitra, 2020a; Mukherjee and Mitra, 2020b; Mukherjee and Mitra, 2020c; Mukherjee and Mitra, 2020d), which may be a result of planning or design-related deficiencies or lack of enforcement or pedestrian's negligence. Therefore, the observed pedestrian crashes at the urban signalized junctions in a developing country are generated by two major sources of risk factors, namely, (a) *lack of pedestrian-friendly road infrastructure, land use and inefficient traffic operations*, and (b) *pedestrians' unsafe crossing behavior such as illegal crossing or signal violation behavior*. Further, it can be assumed that these two sources of risk provide two distinct crash counts and associated with separate probability distributions, which when summed at an intersection, found the total observed pedestrian crash count of the junction. More precisely, *road infrastructure, land use, traffic exposures, and operational* factors will produce crashes that correspond to an observed distribution across the sites, as do *pedestrians' unsafe crossing behavior*.

In this background, the objective of the current paper is to articulate a suitable modelling approach, that accounts for multiple sources of pedestrian risk (i.e., the risk associated with *lack of pedestrian-friendly infrastructure, land use and inefficient traffic operations*, and *pedestrians' unsafe crossing behavior*) and estimate their contributions. While researchers are generally used risk factors pertaining to a single source (Mukherjee and Mitra, 2020c; Mukherjee and Mitra, 2019a; Mukherjee and Mitra, 2019c), the present work demonstrates a unique approach for modelling fatal pedestrian crashes by combing two major sources, namely, (a) lack of pedestrian-friendly road infrastructure, land use and inefficient traffic operations, and (b) pedestrians' unsafe crossing behavior. To model two distinct sources of pedestrian risk, separate univariate Poisson or Negative Binomial (NB) models (crash frequency model) are developed and combined. Afterward, the current study estimates and evaluates the actual share of these two major sources of pedestrian risk in the context of the urban environment in an emerging nation. The modelling approach, when applied in the context of Kolkata City, India, is found to produce a model with superior goodness-of-fit as compared to the model developed using the conventional approach for modelling.

2. MODELLING METHODOLOGY AND ANALYTICAL APPROACH

This section explains the concept of the mixture model (i.e., proposed model) that accommodates multiple distinct sources of pedestrian risk. A brief description of the proposed modelling methodology is given first, followed by two goodness-of-fit criteria utilized to evaluate the prediction performance of the proposed model are described.

2.1 Model Development

To associate crash data with the intersection parameters, the Poisson or NB model is usually applied (Mukherjee and Mitra, 2018).

2.1.1 Single equation NB model

In the single equation crash prediction model Y_i signifies the total crash frequency at intersection i, and Y_i follows a Poisson distribution with the Poisson mean μ_i (Washington et al., 2010),

$$Y \sim Poisson\ (\mu_i)$$

The mean value of the Poisson model is as follows:

$$Log\ (\mu_i) = \beta X_i \quad (1)$$

Where X_i is a vector of covariates representing intersection-specific attributes, β is the regression parameter. To overcome the issues associated with over-dispersion, researchers have suggested the addition of gamma-distributed error term (ε_i) in the parent Poisson model that expresses the NB model as follows (Washington et al., 2010):

$$Y_i \sim NB\ (\mu_i, \phi)$$
$$Log\ (\mu_i) = \beta X_i + \varepsilon_i \quad (2)$$

$$\mu_i = \alpha_0 \, exp \sum \beta_j X_{ij}$$

Where, α_0 is a constant term. ϕ is the dispersion parameter.

2.1.2 Concept of the mixture model

The basic concept of the mixture model was first developed by Washington and Haque (2013). For the mixture model, it was assumed that the total pedestrian crash frequency at a signalized junction Y_i arises from two major sources of pedestrian risk factors. They are (a) lack of pedestrian-friendly road infrastructure, land use, and inefficient traffic operations, and (b) pedestrians' unsafe crossing behavior.

Further, in an emerging nation, pedestrians' crossing behavior is substantially influenced by the road infrastructure, land use, and traffic operational characteristics of the urban road network level (Mukherjee and Mitra, 2020e; Mukherjee and Mitra, 2017; Rankavat and Tiwari, 2016). For example, (i) pedestrian's crossing time depends on the road width (Rankavat and Tiwari, 2016), (ii) pedestrian's waiting time before crossing generally depends on the traffic flow characteristics of the urban road environment (Mukherjee and Mitra, 2019b), (iii) pedestrian-vehicular interaction at a signalized junction primarily depends on the traffic and pedestrian volume, and traffic flow characteristics (Mukherjee and Mitra, 2019b), (iv) Pedestrian's path changing behavior depends on the traffic movement characteristics of the intersection as well as the position and accessibility to the pedestrian crosswalk (Mukherjee and Mitra, 2019b). Thus, it is signifying that pedestrians' crossing behavior may be endogenous with the built environment and traffic characteristics of an intersection. To overcome the problem associated with endogeneity between the "*pedestrian crossing behavior*" and "*road infrastructure, land use type, and operational characteristics*", the current study has proposed the "three-component mixture model". In this model, it was assumed that Y_i (total crash count at an intersection) arises from *three* different sources of pedestrian risk factors, namely, (a) lack of pedestrian-friendly road infrastructure, land use and inefficient traffic operations, and (b) pedestrians' unsafe crossing behavior such as illegal crossing or signal violation, and (c) the *combined effects* of "*road infrastructure, land use, traffic operational parameters*" and "*pedestrians' unsafe crossing behavior*". The conceptual framework of the present model is shown in Figure 1.

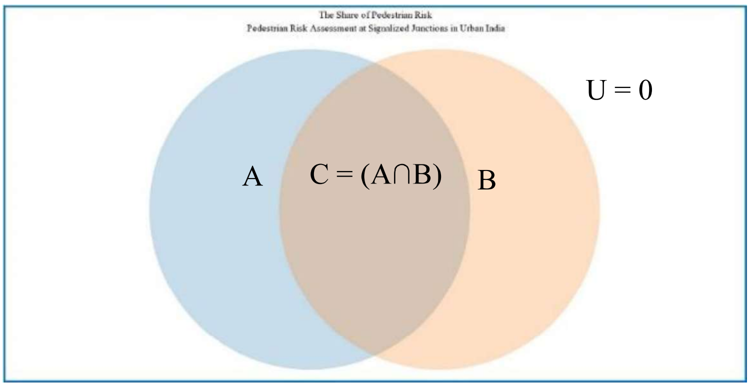


Figure 1. Conceptual framework of the proposed model

A = The risk associated with road infrastructure, land use, and traffic operational characteristics

B = The risk associated with pedestrian crossing behavior
C = The risk associated with the combined effects of A and B
Where,

A only = A - (AB),
B only = B - (AB),
C = (A∩B)
D = U - (A only + B only + C)

Then, Y_i (total pedestrian crash count at an intersection) can be assumed to include three separate density functions (i.e., only A, only B, and C) such that

$$Y_i \sim NB\ (\lambda_i = \sum_{k=1}^{3} \mu_{ik},\ \phi_k) \tag{3}$$

Where, λ_i is the crash mean for i^{th} intersection, μ_{ik} is the crash mean for i^{th} intersection generated from k^{th} source of pedestrian risk factors, and ϕ_k is the over-dispersion parameter of the K^{th} source of pedestrian risk. Let's assume $\theta = (\theta_1, \theta_2, \theta_3)$ is the mixing proportion whose elements sum to unity.

$$\begin{aligned} \mu_{i1} &= \theta_1 \lambda_i \\ \mu_{i2} &= \theta_2 \lambda_i \\ \mu_{i3} &= \theta_3 \lambda_i \\ \sum_{k=1}^{3} \theta_k &= 1 \end{aligned} \tag{4}$$

The model specification for any risk component (sources of pedestrian risk factors) is similar to the single equation Poisson/NB model. Now, the model specification to estimate the crash count associated with only "road infrastructure, land use and traffic operational characteristics" (i.e., only A) is as follows

$$\begin{aligned} Y_i &\sim NB\ (\mu_{i1}, \phi_1) \\ \mu_{i1} &= \alpha_0 \exp \sum \beta_j X_{ij} \end{aligned} \tag{5}$$

where ϕ_1 is the over-dispersion parameter for the crash occurrences related to "road infrastructure, land use, and traffic operational risk", X_{ij} is the j^{th} "road infrastructure, land use and traffic"-related variable for i^{th} intersection, and other parameters are as previously defined. The model specification for the "pedestrians' unsafe crossing behavior-related risk factors" (i.e., only B) is as follows

$$\begin{aligned} Y_i &\sim NB\ (\mu_{i2}, \phi_2) \\ \mu_{i2} &= \alpha_0 \exp \sum \beta_j W_{ij} \end{aligned} \tag{6}$$

W_{ij} is variable related to the pedestrians' behavior for the i^{th} intersection. ϕ_2 is the over-dispersion parameter for the risk associated with pedestrians' crossing behavior. The specification for the third and last risk component (i.e., the risk associated with the combined effects of "road infrastructure, land use, and traffic operational characteristics" and "pedestrians' crossing behavior", i.e., the risk component 'C') is as follows

$Y_i \sim NB\ (\mu_{i3}, \phi_3)$

$$\mu_{i2} = \alpha_0\, exp \sum \beta_j Z_{ij} \quad (7)$$

Z_{ij} is variable associated with the third source of pedestrian risk factors for the i^{th} intersection, and ϕ_3 is the over-dispersion parameter.

2.2 Modelling Methodology

In reality, it is difficult to know the exact proportion or frequency of crashes that contribute to the observed overall crash frequency at an intersection. In other words, the mixing proportions, θ_k's of the proposed three-component mixture model is unknown, and cannot be estimated without prior information. To overcome such difficulties, the relative weights of the three sources of pedestrian risk were decided based on a trial and error process. The risk associated with only *road infrastructure, land use, and traffic operational characteristics* (the share of only A) is (refer to Figure 1)

$\theta_1 \sim U\ [0.10, 0.80]$

The risk associated with *pedestrians' unsafe crossing behavior* (the share of only B) is

$\theta_2 \sim U\ [0.10, 0.80]$

Therefore, the risk associated with the *combined effects of "road infrastructure, land use, and traffic operational characteristics" and "pedestrian crossing behavior"* (the share of C component) is

$\theta_3 = \{1-(\theta_1+\theta_2)\} \sim U\ [0.10, 0.40]$ (8)

'Equation 8' indicates an analysis where overall crashes are randomly and uniformly drawn from the observed "road infrastructure, land use, traffic operational factors" between 10%-80%, from the "pedestrian crossing behavioral factors" between 10%-80%, and the combined effects of *road infrastructure, land use, traffic operational issues*, and *pedestrians' crossing behavior* influence the remainder portion.

2.3 Goodness-of-Fit Test

In the present study, two common prediction-based model selection criteria applied are: (a) Mean Squared Predictive Error (MSPE), and (b) Predictive Loss Criteria (PLC) (Gelfand and Ghosh, 1998). Assume, ξ_i and ζ_i are mean and variance of maximum likelihood estimation based crash prediction for the intersection 'i'. Then the MSPE is calculated as follows:

$$MSPE = \sum_{k=1}^{3} \left[\sum_{i=1}^{N} (Y_i - \xi_i)^2 / N \right] \quad (9)$$

Where k denotes the sources of pedestrian risk factors, Y_i is the observed crash data and N is the number of intersections. The MSPE depends on the mean of predictions and does not take into account the variance of predictions. In contrast, the PLC comprises the variance of predictions and therefore PLC might be a more accurate measure for model selection (Haque et al., 2010),

$$PLC = \sum_{k=1}^{3} \left[\sum_{i=1}^{N} \zeta_i + \left(\frac{w}{w+1}\right) \sum_{i=1}^{N} (Y_i - \xi_i)^2 \right] \quad (10)$$

Where w is the weight factor. By assuming an infinity value of w, for the present study, equal weight was assigned for variance and mean differences to calculate the PLC value (Haque et al., 2010). Finally, from the statistical point of view, models with comparatively lower MSPE and PLC values are considered better models.

3. RESEARCH METHODOLOGY

The research methodology includes crash data collection, selection of study intersections, survey and data collection, data analysis, and modelling **(Figure 2).**

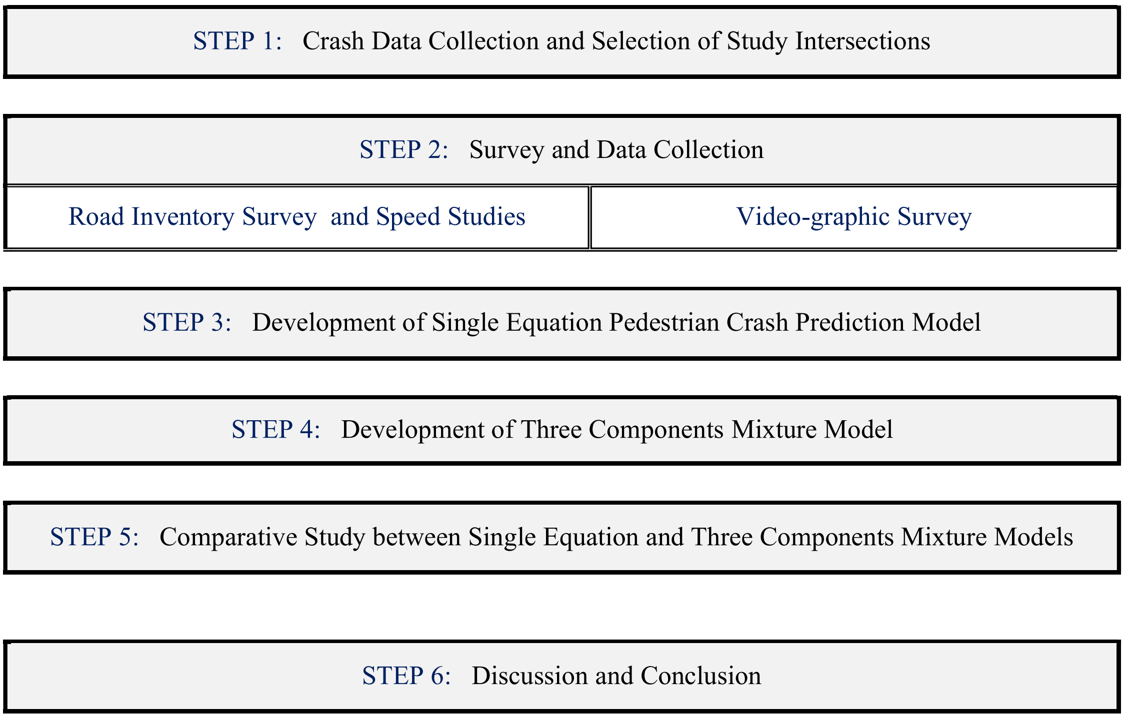


Figure 2. Research design

3.1 Crash Data Collection and Selection of Study Intersections

Kolkata is a premier metropolitan of India, which is located in the Gangetic plain of West Bengal. For eases of traffic management, Kolkata Police has divided the entire city into 25 traffic guards. The Kolkata Police provided the "Monthly Accident Review Report" for the year 2011 to 2016.

It may be mentioned that pedestrian crashes are generally classified into three categories, namely (a) fatal crashes (b) major injury crashes, and (c) minor injury crashes. However, in a developing country such as India, the under-reporting of non-fatal crashes is a major issue (Mitra et al., 2019; Mukherjee and Mitra, 2019d; Mitra et al., 2016). Hence, the scope of the present work is restricted to the investigation of fatal pedestrian crashes only.

To recognize the temporal and spatial distribution of pedestrian risk "Analysis of variance" (ANOVA) was performed across the twenty-five traffic guards. The ANOVA test result indicates that the risk of fatal pedestrian crashes is not uniform across the city (F-statistics is 9.47, and $p<0.00$). As the chance of fatal pedestrian crashes is not uniformly distributed across Kolkata city, *nine major road corridors* were selected such that the maximum number of risk-prone signalized intersections for fatal pedestrian crashes could be incorporated in this research. The hazardous road corridors of Kolkata City were identified based on *four principles*, i.e., (a) the fatal pedestrian crash density, (b) the total number of fatal pedestrian crashes in a specific corridor, (c) the overall number of fatal pedestrian crash-prone signalized intersections in a particular corridor, and (d) predominant land use pattern of the corridor (Chakraborty et al., 2019). Afterward, for further investigation, 55 major signalized intersections were chosen from these nine risk-prone road corridors (Figure 3).

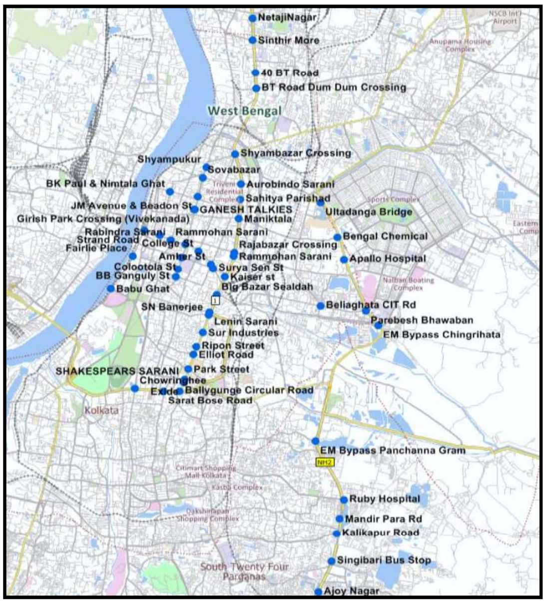


Figure 3. Study intersections

3.2 Survey and Data Collections

Data collection for this study involved three distinct groups, namely (a) road inventory survey, (b) speed studies, (c) video-graphic survey.

The road inventory survey was conducted to collect information regarding road geometry, existing infrastructure, land use details, etc. (Mukherjee and Mitra, 2020a).

The approaching speed of the motorized vehicles was measured using the speed radar gun. The spot-speed study was conducted for two hours: 10:00 am –11:00 am and 3:00 pm – 4:00 pm (Chakraborty et al., 2019).

Further, the video-graphic survey was conducted to collect the average daily traffic and pedestrian volume and pedestrians' crossing behavior. In this study, pedestrian and classified traffic volume with the turning movement was recorded and extracted for 24 hours at each of the study intersections. Besides, pedestrians' behavioral data was extracted for six hours between morning 10 am and 1 pm, and evening 3 pm and 6 pm such that both peak and off-peak traffic could be captured (Mukherjee and Mitra, 2019b). For the video-graphic survey, high-resolution video cameras (at least two cameras) were installed to capture the entire scenario of traffic and pedestrian movement at the study intersections. The video cameras were installed beside the road at a height of about 14 meters from the road level. To examine pedestrian crossing behavior at signalized intersections and their associated factors, crossing behavior was classified into two major groups: illegal crossing and legal crossing (Brosseau et al., 2013).

- **Illegal Crossing** (signal violation): Pedestrians committed a violation when crossing during the red phase. They could either had started too early or crossed during the red phase.
- **Legal Crossing** (non-violation): Pedestrians crossing during the green phase were considered as a legal crossing.

A total of 65,754 pedestrians' crossing behavior was extracted across 55 study junctions. The method of video data extraction was adopted by earlier researchers (Mukherjee and Mitra, 2019b; Mukherjee and Mitra, 2019c; Mukherjee and Mitra, 2019e). A few observations obtained during the site visit and road inventory survey are presented in Figure 4.

Here it should be mentioned that in Kolkata City, there is no specific season when fatal pedestrian crashes are high over a typical year (Pareekh et a., 2019; Mukherjee and Mitra, 2019d). Therefore, in this study, the weather effect, the impact of special events, etc., were not considered and data collection was conducted on a weekday with the normal weather condition. The description of the variables is shown in Table 1.

Table 1. Description of the variables

Variable	**Source of Data**	**Type of Variable**	**Description of the Variable**
Variables Associated with *Road Infrastructure, Land Use, and inefficient Traffic Operations*			
Log(Average Daily Traffic Volume / ADT)	Video graphic Survey	Continuous	Average daily traffic volume of the junction
Log(Average Daily Pedestrian Volume)	Video graphic Survey	Continuous	The average daily pedestrian volume of the junction
Pedestrian vehicular ratio	Video graphic Survey	Continuous	Pedestrian and vehicle volume ratio of an intersection
Vehicle speed (km/hr.)	Spot-speed Survey	Continuous	The average speed of the junction, measured using a radar gun (Chakraborty et al., 2019)
Width of the road (meter)	Road Inventory Survey	Continuous	Major and minor carriageway width
Pavement marking and road signage	Road Inventory Survey	Categorical	Presence =1; Absence = 0
On-street parking (1/0)	Road Inventory Survey	Categorical	Presence =1; Absence = 0
Adequate sight distance (1/0)	Road Inventory Survey	Categorical	Presence =1; Absence = 0
Type of land use (in %)	Road Inventory Survey	Continuous	The share of a certain type of land use such as commercial, residential, office, educational, industrial, park and recreational, hospital, open spaces (Mukherjee and Mitra, 2020a)
Pedestrian zone of attraction (i.e., presence of *hospital / educational institute / heritage building /shopping mall / heritage building / bar,* etc.)	Road Inventory Survey	Categorical	Presence =1; Absence =0 (Mukherjee and Mitra, 2020a)
Variables Associated with *Pedestrians' Unsafe Crossing Behavior*			

Pedestrian signal violation/illegal crossing behavior: Yes (1) No (0)	Video graphic Survey	Categorical	Pedestrian signal violation/illegal crossing is defined as when pedestrians cross the road during the non-green phase; whereas pedestrians crossing during the green phase are considered as legal crossing/non-violation (Mukherjee and Mitra, 2019b)
Variables Associated with the Combined effects of *Road Infrastructure, Traffic Operations, and Pedestrians' Unsafe Crossing Behavior*			
Post Encroachment Time (PET)	Video graphic Survey	Continuous	Time difference between the end of encroachment of crossing pedestrian and the time that the through vehicle arrives at the potential point of collision (Mukherjee and Mitra, 2019c)
Crossing time (seconds)	Video graphic Survey	Continuous	The overall time of a pedestrian to cross a particular intersection
Waiting time before crossing: (seconds)	Video graphic Survey	Continuous	Waiting time of the pedestrian before crossing the road
Path changing condition: Yes (1) No (0)	Video graphic Survey	Categorical	Pedestrian changes the path while crossing the road (Kadali and Vedagiri, 2013)
Pedestrian is following the zebra crossing: Yes (1) No (0)	Video graphic Survey	Categorical	Whether a pedestrian is crossing along the zebra crossing or not
Variables Associated with Pedestrian's Demographic Characteristics			
Gender	Video graphics Survey	Categorical	if, Male = 1; Female = 0
Age of the pedestrian	Video graphics Survey	Categorical	Up to 18; Young: 18 to 49; Elder: 50 and above

To recognize pedestrian risk factors associated with pedestrian crossing behavior at an intersection, several pedestrian-level (i.e., individual-level) data extracted from the video-graphs were combined for each intersection to capture the *intersection-specific* information such as the proportion or the share of the pedestrian signal violation, the average waiting time of the pedestrians at an intersection, the average value of pedestrian-vehicular post-encroachment time at an intersection, etc.

For further explanation, if 'N' number of pedestrians cross the intersection 'i' during the survey period. Out of 'N' pedestrians, 'n' number of pedestrians violate traffic signal, then, the share of pedestrians signal violation at the intersection 'i' is (n/N).

Likewise, at the intersection "i", waiting time for N_1 pedestrian (first pedestrian) is WT_1, waiting time for N_2 pedestrian (second pedestrian) is WT_2, and waiting time for N_n pedestrian (n^{th} pedestrian) is WT_n; then, pedestrians' average waiting time (WT) at the intersection "i" is:

$$WT = \frac{WT_1 + WT_2 + WT_3 + \cdots \ldots + WT_n}{N} \tag{11}$$

Where N is the total number of pedestrians cross the intersection during the survey period.

Similarly, if the post-encroachment time for N_1 pedestrian (first pedestrian) is PET_1, PET for N_2 pedestrian (second pedestrian) is PET_2, and PET for N_n pedestrian (n^{th} pedestrian) is PET_n, Then, average post-encroachment time (PET_i) of the intersection "i" is:

$$PET_i = \frac{PET_1 + PET_2 + PET_3 + \cdots \ldots + PET_n}{N} \tag{12}$$

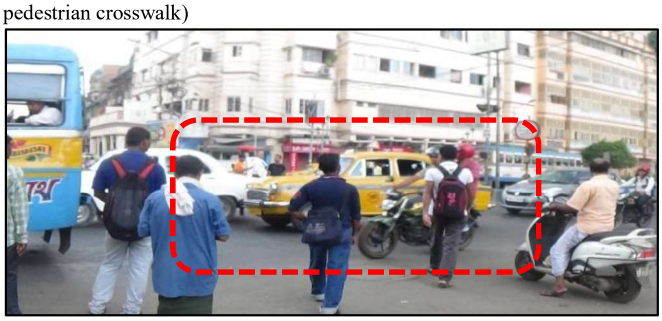
After aggregating such data, the proportions or the shares of these variables were utilized as the independent variables in the intersection-specific fatal pedestrian crash prediction models. Since in this study, the dependent variable is the fatal pedestrian crashes in the last six years' period (2011-2016), and the independent variables are for a one-time period; only a few independent variables were used for the modeling purpose, which has a higher probability of remaining consistent over the study period.

BBD Bagh Crossing (on-street parking, pedestrians' not following zebra crossing)

EM Bypass Ruby Crossing (pedestrians are not using footpath)

MG Road College St (the absence of sidewalk facility, absence of designated pedestrian crosswalk)

MG Road (on-street parking, the absence of adequate sidewalk facilities)



School of Tropical Medicine CR avenue (pedestrians' unsafe crossing behavior)

APC & Maniktala Crossing (vehicles on zebra crossing during pedestrian green phase)

Figure 4. Study intersections

4. RESULTS

The statistical models were estimated using -'R Programming' software. The significant outcomes obtained from the single equation NB model and three-components mixture models are discussed in the following sub-sections.

4.1 Single Equation NB Model

To express the fatal pedestrian crash frequency in terms of parameters related to *"road infrastructure, land use, and traffic operational characteristics*", and "*pedestrians' crossing behavior*", primarily two SPFs were developed (Table 2). Afterward, a combined model with several independent variables was developed. Since the variance of fatal pedestrian crashes was found to be significantly greater than the mean value, the NB regression models were preferred to build the SPFs.

As can be seen from Table 2 (model 1), traffic exposure variables such as the logarithm of average daily traffic volume and speed have a significant impact on fatal pedestrian crashes at signalized intersections in Kolkata. The past study conducted by Rankavat and Tiwari (2015) also found a positive association between fatal pedestrian crashes and traffic volume. Further, a good number of studies have examined the impact of vehicle speed on pedestrian crashes (Cuerden et al. 2007).

The absence of adequate sight distance was found to be a significant cause of fatal pedestrian crashes at signalized intersections. In general, the critical interaction between pedestrians and vehicles at an intersection significantly increases due to the absence of suitable sight distance. During the site visit, it was observed that in Kolkata city, more than 60% of intersections having the issue of inadequate sight distance.

The findings obtained from 'model 2' show that the share of pedestrians' signal violation behavior and fatal pedestrian crash frequency of an intersection are significantly and positively correlated. A number of earlier studies have documented that pedestrian signal violation behavior is a major cause of pedestrian-vehicular crashes at signalized intersections (Ashur et al., 2003).

Table 2. Single equation fatal pedestrian crash prediction model

Attributes	**Single Equation NB Model-1** (Road infrastructure, land use, traffic operational characteristics)	**Single Equation NB Model-2** (Pedestrians' unsafe crossing behavior)	**Single Equation Combined NB Model-3**
	Model Coefficients (t-stat)		
Constant	-10.773 (-4.18)***	-0.273 (-0.67)	-11.277 (-3.15)***
Log (ADT)	2.010 (3.88) ***		2.061 (2.78)***
Pedestrian-Vehicular Volume Ratio	0.679 (2.42)**		0.637 (2.87)***
Speed (kmph)	0.033 (1.90) *		0.028 (1.84)*
Absence of Adequate Sight Distance (1/0)	0.739 (2.55)***		0.659 (2.49)**
Share of Pedestrian Signal Violation (in %)		2.556 (2.59)***	1.176 (1.67)*
	Dispersion Parameter for Count Data Model		
Alpha (α)	0.176 ($\bar{\chi}^2$ = 2.38, p= 0.061)	0.75 ($\bar{\chi}^2$ = 26.88, p= 0.000)	0.160 ($\bar{\chi}^2$ = 1.95, p = 0.082)
	Overall Goodness-of-fit		
Log-Likelihood function	-90.141	-102.190	-88.858
Restricted Log-Likelihood function	-124.396	-124.396	-124.396
ρ^2	0.275	0.178	0.285

*Significant at 90% Confidence Interval; **Significant at 95% Confidence Interval; *** Significant at 99% Confidence Interval

4.2 Three-Components Mixture Model

To develop the three-components mixture regression model, *twenty-two sets* of models were developed with different randomly drawn weight distribution (i.e., $\theta_1, \theta_2, \theta_3$). Subsequently, the best-fitted model was chosen based on standard goodness-of-fit criteria and logical application of variables. Goodness-of-fit statistics for these models are presented in Table 3. Among these twenty-two trial model sets, the **16th trial** shows the best fit than the others with an MSPE of 1.436 and PLC of 187.

Table 3. Compression of different sets of mixture models

Trial No.	**Road Infrastructure, Land Use and Inefficient Traffic Operations** (only A)	**Pedestrians' Unsafe Crossing Behavior** (only B)	**Combined effects of Road Infrastructure, Traffic Operations and Pedestrians' Unsafe Crossing Behavior** (the combined effects of A and B, that is component C)	**MSPE**	**PLC**
Trial 1	10	80	10	2.809	304.00
Trial 2	18	69	13	2.745	249.00
Trial 3	20	65	15	2.636	241.00
Trial 4	20	60	20	2.169	225.00
Trial 5	20	50	30	2.018	215.00
Trial 6	20	70	10	2.709	249.00
Trial 7	23	57	20	2.181	227.00
Trial 8	25	45	30	1.945	215.00
Trial 9	25	50	25	1.945	211.00
Trial 10	25	70	05	2.228	249.00
Trial 11	30	40	30	1.872	205.00
Trial 12	30	30	40	1.872	221.00
Trial 13	35	35	30	1.891	209.00
Trial 14	35	30	35	1.927	211.00
Trial 15	40	45	15	1.890	207.00
Trial 16	40	40	20	1.436	187.00
Trial 17	45	45	10	2.090	227.00
Trial 18	50	25	25	1.851	198.00
Trial 19	60	20	20	1.818	193.00
Trial 20	65	18	17	1.763	189.00
Trial 21	70	20	10	1.854	199.00
Trial 22	80	10	10	1.952	208.00

Estimation results of the best-fitted model (i.e., 16th trial) are presented in Table 4. In this trial, it was assumed that in Kolkata at the signalized intersection-level, 40% of the fatal pedestrian crashes occur due to lack of pedestrian-friendly road infrastructure and inefficient traffic operations; whereas 40% of the fatal pedestrian crashes occur due to pedestrians' unsafe acts; and remaining 20% crashes occur due to the combined effects of *lack of road infrastructure, inefficient traffic operations* and *pedestrians' unsafe crossing behavior* (shown in Figure 5).

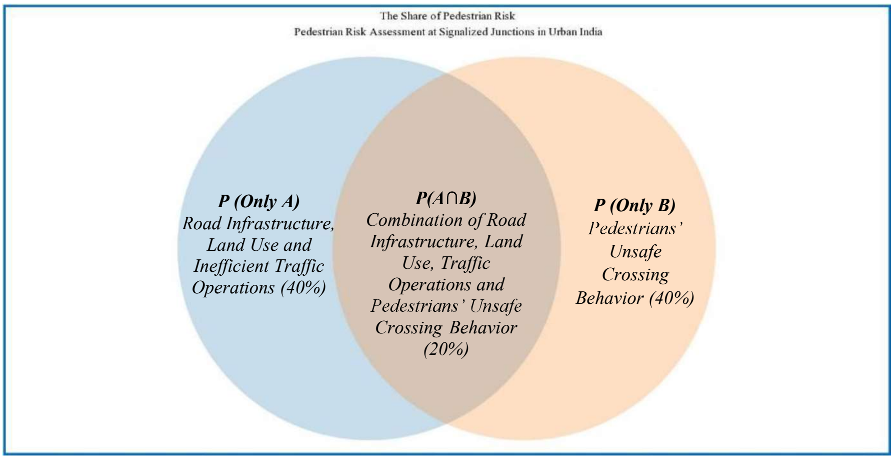


Figure 5. Share of risk components (major sources of risk factors)

To estimate the risk associated with "road infrastructure, land use, and traffic exposures, and operational characteristics" a poison regression model was preferred because the variance of fatal pedestrian crashes was not statistically and significantly different than the mean value of the crashes. The outcome of the Poisson model shows that the logarithm of ADT, pedestrian-vehicular volume ratio, speed, and the absence of adequate sight distance significantly affect the frequency of fatal pedestrian crashes (Table 4). It was also found that the presence of on-street parking has a significant and positive impact on fatal pedestrian crashes. Edquist *et al*. (2012) also examined the relationship between on-street parking and driving behavior based on the outcomes obtained from a driving simulator and concluded that on-street parking is associated with higher crash risk. Further, it was identified that the presence of a "pedestrian attraction zone" without an adequate crossing facility near a junction significantly increases the likelihood of fatal pedestrian crashes. Abdel-Aty *et al*. (2011) identified that in central Florida locations with a high pedestrian trip generation are associated with a higher crash incidence.

To estimate the risk associated with pedestrians' unsafe crossing behavior another Poisson model was developed since the over-dispersion parameter for the NB formulation was not significant. The model outcomes indicate that the share of pedestrian signal violation is strongly correlated with the frequency of fatal pedestrian crashes (Table 4).

Finally, to examine the combined effects of "*road infrastructure, land use, traffic operational characteristics*", and "*pedestrians' crossing behavior*", another Poisson model was developed. The model results suggest that pedestrians' average waiting time before crossing has a significant impact on fatal pedestrian crashes. The model finding also shows that the risk of fatal crashes positively raises with an increase in pedestrian crossing time. In general, at a wider road pedestrian needs a higher crossing time; thus, the chance of pedestrian-vehicular conflicts increases (Priyadarshini and Mitra, 2018). Therefore, pedestrian crossing risk increases as the length of the crosswalk increases as it relates to the comfort and safety of the pedestrian.

The share of pedestrians' having path-changing characteristics was found to have a significant impact on fatal pedestrian crashes at signalized intersection-level in Kolkata City (Table 4). Kadali and Vedagiri (2013) also documented that a pedestrian's sudden path-changing behavior could be a significant cause of critical interaction between pedestrian and vehicle at urban midblock crosswalks in India.

Table 4. Outcomes of three components mixture models

Risk Component	Variable	Coefficient	t-Statistics	P-Value
Road Infrastructure, Land Use, Traffic Operational Characteristics (Only A)	Constant	-11.291	- 4.01	0.000***
	Log (ADT)	1.866	3.30	0.001***
	Pedestrian and Vehicle Volume Ratio	0.470	2.04	0.041**
	Speed (kmph)	0.028	2.12	0.034**
	Presence of On-street Parking	0.492	1.94	0.052**
	Absence of Adequate Sight Distance	0.520	1.82	0.069*
	Presence of Pedestrian Attraction Zone	0.693	2.98	0.003***
	Log Likelihood	-51.248		
	Restricted Log-Likelihood	-67.598		
	The goodness of fit: Model-Level (ρ^2)	0.242		
	Wald χ^2 (p-Value)	86.25 (p<0.001)***		
Pedestrians' Unsafe Crossing Behavior (Only B)	Constant	-0.817	-1.99	0.046**
	The Share of Pedestrians' Signal Violation (in %)	1.676	1.82	0.069*
	Log Likelihood	-66.151		
	Restricted Log-Likelihood	-68.056		
	The goodness of fit: Model-Level (ρ^2)	0.028		
	Wald χ^2 (p-Value)	3.31 (p <0.05)**		
Combination of Road Infrastructure, Traffic Operational Characteristics, and Pedestrian Unsafe Crossing Behavior (C = AB)	Constant	2.108	3.03	0.002***
	Waiting Time before Crossing	0.078	3.26	0.001***
	Post Encroachment Time (seconds)	-2.509	-5.14	0.000***
	Crossing Time (seconds)	0.089	2.82	0.005***
	The Share of Path Changing Characteristics by the Pedestrians' (in %)	2.420	2.41	0.016***
	Log Likelihood	-31.370		
	Restricted Log-Likelihood	-43.935		
	The goodness of fit: Model-Level (ρ^2)	0.286		
	Wald χ^2 (p-Value)	43.97 (p<0.000)***		
The goodness of Fit of Joint Model Estimation (global goodness-of-fit)	Sample Size	55		
	Mean Square Predictive Error (MSPE)	1.436		
	Predictive Loss Criteria (PLC)	187.00		

*Significant at 90% Confidence Interval; **Significant at 95% Confidence Interval; *** Significant at 99% Confidence Interval

4.3 Comparative Study between Traditional and Proposed Models

This section compares the performance of several alternative models. On global goodness of fit measures, MSPE for the single equation combined NB model is 2.618, while the MSPE for the three-components mixture model is about 1.436. The PLC for the single equation combined NB model is 327.85; whereas the PLC value for the three-components mixture model is 187.00. The study outcomes evidently indicate that the mixture model is statistically and significantly superior to the traditional single equation models. Figure 6a and Figure 6b illustrate a comparative study of PLC and MSPE across three sets of single equation traditional models and the proposed three-components mixture model.

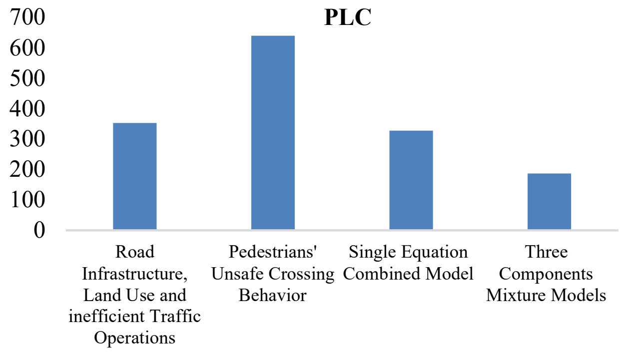


Figure 6a. Comparative study of Predictive Loss Criteria

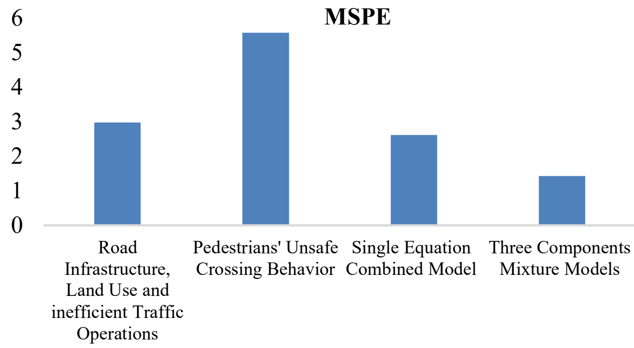


Figure 6b. Comparative study of Mean Squared Predictive Error

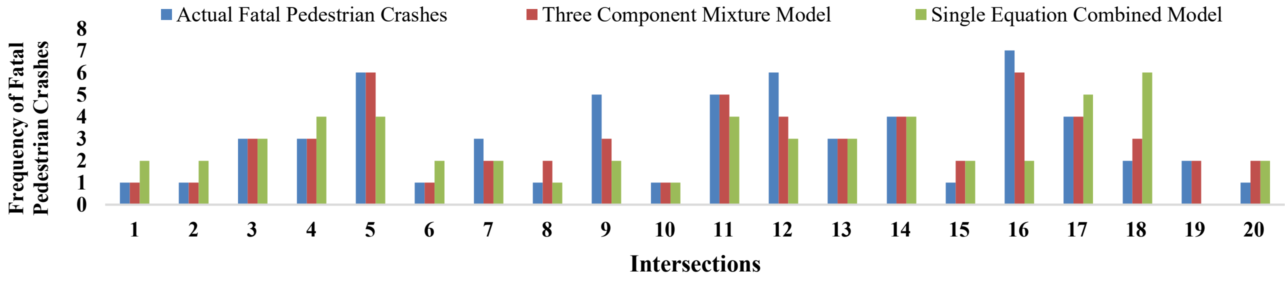


Figure 6c. Comparison between Single Equation Combined Model and Three Components Mixture Model

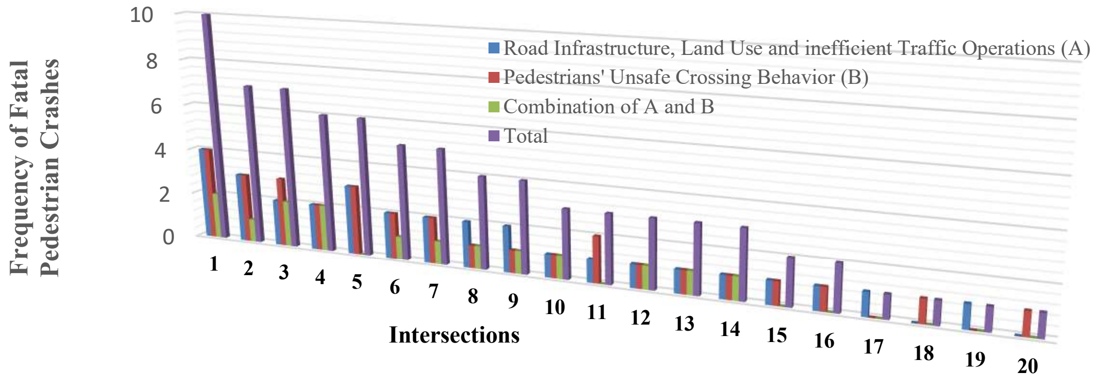


Figure 6d. Share of fatal pedestrian crashes (Three-Components Mixture Model)

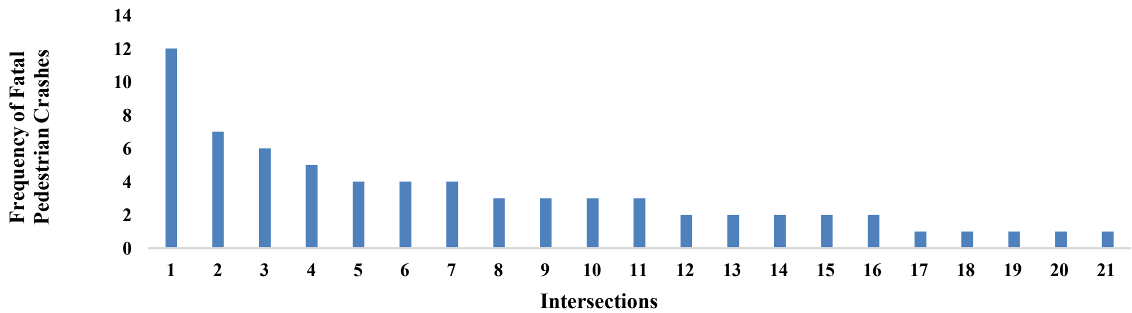


Figure 6e. Outcomes of Single Equation Crash Prediction Model

Figure 6. Comparative study between several alternative models

Figure 6c compares the prediction performance of the traditional single equation combined model (model 3, Table 2), proposed three-components mixture models, and actual crash data across 20 intersections (randomly chosen from the data set of 55 intersections). The figure undoubtedly indicates that the accuracy level of the three-component mixture model is significantly better than the traditional models.

Finally, Figure 6d shows a bar diagram for the crash components (sources of pedestrian risk factors) described previously, abbreviated as “road infrastructure, land use and traffic operational characteristics”, “pedestrians’ unsafe crossing behavior”, and “combination of road infrastructure, land use, traffic operations, and pedestrians’ unsafe crossing behavior”. The figure shows a set of 20 intersections (randomly chosen from the data set of 55 intersections) with crash frequencies on the vertical axis. The critical point here is that theoretically these three components of crashes contribute to the total crashes at an intersection. Interestingly it was found that at several intersections, for example, intersection 3, 11, and 18, the risk associated with pedestrians’ unsafe crossing behavior is significantly high. On the other hand, at several junctions (e.g. intersection 8, 17, 19) the risk associated with “road infrastructure, land use, and traffic operational characteristics” is considerably high. However, traditional single equation NB models (i.e., model 3 in Table 2) are unable to capture such insights (Figure 6e). Thus, the comparative study between several alternative models highlights the limitations of traditional count data models over the recommended three-components mixture model.

5. DISCUSSION AND CONCLUSION

The present study argues from a hypothetical perspective that in a developing country observed fatal pedestrian crashes at signalized junctions are not caused by a single source of risk factors and instead arise as an outcome of three separate sources of risk factors including the influence of (a) lack of pedestrian-friendly infrastructure, inefficient traffic operations; (b) pedestrians’ unsafe crossing behavior, and (c) the combined effects of *road infrastructure, land use, traffic operational parameters*, and *pedestrians’ unsafe crossing behavior*. Based on this concept, the present study formulates a statistical model that takes into account these three sources of pedestrian risk factors (i.e., a, b, c). In the current study, fatal pedestrian crash data for 2011 to 2016 of Kolkata, India, was utilized to demonstrate our modelling methodology, and a latent mixture model was systematically developed. Several key contributions to the current study are summarized below:

- A unique approach is developed for modelling fatal pedestrian crashes by combining factors from three major sources of pedestrian risk. The modelling approach, when applied in the context of Kolkata City, was found to produce a model with superior goodness-of-fit as compared to the model developed using the conventional approaches of crash prediction modelling. The mean square predictive error (MSPE) and the predictive loss criteria (PLC) were found to decrease by at least 43%, indicating that the proposed model performs better than the traditional crash prediction models.
- The present study estimates and evaluates the share of two major sources of pedestrian risk based on a systematic risk assessment technique. For the first time, the segregating among the pedestrians’ behavioral, infrastructural, and traffic operational risk through statistical modelling was achieved.
- The study outcomes indicate that in Kolkata City, India at signalized intersections, nearly 40% of the fatal pedestrian crashes take place due to pedestrians’ unsafe crossing behavior (i.e., signal violation or illegal crossing); almost 40% of the fatal pedestrian crashes occur due to lack of pedestrian-friendly infrastructure and inefficient traffic operations; and the

remaining portion occurs due to the combined effects of *lack of road infrastructure, land use, inefficient traffic operations*, and *pedestrians' unsafe crossing behavior*.

- The traditional hot spot identification methods for pedestrian safety improvement in a developing country, which primarily depend on total crash counts (Mitra et al., 2016), could be focused on where best to invest funds to address the risk components, whether infrastructure-related, traffic operational-related, behavior-related, or the outcomes of the combined effects of lack of infrastructure, inefficient traffic operations, and pedestrians' unsafe crossing behavior.
- Methods that depend on safety performance functions—including the current concept of single equation modelling technique to identify hot spots—would yield completely dissimilar outcomes, whereby several intersections may be dominated by pedestrians' risky behavior; whereas some others are dominated by inefficient planning and design or lack of pedestrian infrastructures or traffic operational problems (Figure 6d).

While the current model's outcomes presented in this study are extremely hopeful, they are not finally conclusive and suffer from several challenges that need to be targeted in future researches.

- Firstly, the share of risk components was initially assumed in this study. However, in reality, the share may be very different. Therefore, it would be important to know the correct distribution weights (i.e., the share of risk components/sources of different risk factors) before any practical application. The excess dissimilarity between the actual scenario and the assumed distribution of risk components might yield significantly different outcomes.
- Secondly, the study methodology was examined on one dataset and performed satisfactorily. Further, the application of the present methodology to other developing countries would be useful to develop a more widespread conclusion about pedestrian risk.
- Thirdly, risk factors and the share of risk components estimated in the present study precisely applicable for developing nations. However, the nature of risk factors and the contribution of different sources of risk factors in developed countries might be very dissimilar. Thus, it is important to identify and estimate the contribution of different sources of risk factors in the context of the developed country as well.
- Fourthly, the geographical stability of the models is also an important issue that must be validated. Additionally, validation of the statistical models must be performed in the future.
- Fifthly, in this study, weather effects and seasonal effects were omitted. However, several research studies have confirmed the influence of weather effects on pedestrian crashes (Li and Fernie, 2010). Thus, it is also important to examine the impact of weather effects on fatal and injury crashes in the context of a developing country.
- Sixthly, in the existing study, several surveys and data collection (i.e., video-graphic and speed study) were conducted one time (between the years 2014 and 2016). As the dependent variable is the fatal pedestrian crashes in the last six years' period (2011-2016), and the independent variables are for a one-time period; only a few selected independent variables were utilized for the modeling purpose, which has a greater chance of remaining consistent over the study period. This is one of the major limitations of the current study.
- Finally, as stated earlier, the police crash history records suffer from non-reporting and under-recording of the non-fatal crashes. The share of risk components associated with non-fatal pedestrian crashes may be very different than fatal crashes. Therefore, it would be beneficial for future researches to target non-fatal crashes to capture better inferences.

Despite these limitations, findings from the present study can provide a clear direction about the share of three major sources of pedestrian risk factors at the urban signalized intersection level in the context of a developing country. Further, it was statistically justified that the total fatal pedestrian crash count at an urban signalized intersection is a combination of crashes caused by primarily three distinct causal mechanisms. This insight is the most vital contribution of the present paper.

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