TSR TRAFFIC SAFETY RESEARCH
AN INTERDISCIPLINARY JOURNAL

Research article

Safety evaluation of urban roundabouts in India: a safety performance function-based approach

V S Vinayaraj[1*], Vedagiri Perumal[1]

[1] Indian Institute of Technology Bombay, India

[*] Corresponding author: vinayaraj4u@gmail.com

Handling editor: **George Yannis**, National Technical University of Athens, Greece

Reviewers: **Chiara Gruden**, University of Maribor, Slovenia
Andreas Hula, Austrian Institute of Technology, Austria

Received: 30 June 2022; Accepted: 30 September 2022; Published: 21 October 2022

Abstract: There is a lack of comprehensive research in roundabout safety under non-lane-based traffic conditions, mainly due to the absence of relevant crash data and effective tools for safety evaluation. Safety Performance Function (SPF) is a suitable tool for providing valuable information related to factors which can potentially contribute to the likelihood of increasing traffic crashes. Currently, very limited studies are available to explain the usefulness of SPF in the vicinity of roundabouts, especially at non-lane-based traffic conditions. This study aims to develop an SPF model for assessing the safety evaluation at roundabouts as a whole (intersection level) and the approach level. Data corresponding to crashes in nineteen roundabouts with different geometric and traffic characteristics was used for model formulation. Crash data for five years (2015–2019) was obtained from the State Crime Records Bureau. An SPF model was developed using a negative binomial model with a log-link function based on the number of crashes, traffic characteristics, and geometry characteristics of the roundabouts. The proportion of powered two-wheelers, percentage of heavy vehicles, entry-angle, and weaving-length were all significantly related with higher crash occurrences at roundabouts, according to the findings. In contrast, the number of circulatory lanes, inscribed circle diameter, and presence of road lane marking were negatively associated with the increased crash occurrences at the roundabout vicinity. In addition to this, the overall crash rate significantly varies across roundabout sections due to the asymmetric effects of geometric and traffic characteristics. The developed SPF would best explain the relationship between geometric and traffic characteristics and the crash occurrence rate in non-lane traffic conditions. The findings of this study support the need to relook at design parameters for better movement at the roundabouts, thereby improving the existing facilities to enhance road users' safety, especially in developing countries. The proposed SPF tool would help engineers examine the safety of roundabouts in terms of design adequacy, quantifying the risk factors, and future crash predictions.

Keywords: negative binomial, roundabouts, safety performance function, weaving length

1 Introduction

Road safety is a major concern for developed and developing countries because it affects their economy and people’s welfare. Road accidents have increased drastically over the past few years for several reasons. Hence, road traffic safety is gaining increasing importance within our country (India) and around the globe. As per the Ministry of Road Transport and Highways (MoRTH 2019), there were roughly around 449 002 traffic crashes, which resulted in the deaths of 151 113 and injuries of 451 361 people in India. The enormousness of the safety concern is reflected in the fact that there were around 11% of total road accidents worldwide (WHO 2018), out of which 14% of these crash occurrences were reported in roundabouts compared to other intersections in India (MoRTH 2019). This is mainly because of high diversity of vehicle interaction and the disordered nature of traffic. These road accidents may lead to enormous losses to society and the economy, particularly in developing countries like India.

Generally, when compared to other forms of at-grade junctions, roundabouts have a beneficial influence on traffic safety (Polus *et al.* 2005). It may reduce delay and provide safer vehicle movement under moderate traffic conditions compared to signalized or uncontrolled intersections. Similarly, a roundabout significantly reduces conflicts over the conventional intersections and provides better intersection safety based on orderly continuous traffic flow, thus reducing the conflict types and eliminating the crash severity (Robinson *et al.* 2000). Moreover, roundabout entries are not always straight or perpendicular to other approaches. Entering vehicles often trace a curved path which makes proper lane choice difficult for drivers unfamiliar with roundabouts, especially if appropriate lane assignments are not provided. Nevertheless, if the safety measures were not considered properly during the design and operation phase of roundabouts, it adversely affects the overall performance of the roundabout (Montella 2011). However, most of the existing roundabout studies are globally grounded on the estimation of capacity, delay aspects and mechanism of gap acceptance behaviour (Indo-HCM 2017; IRC 2017; Sonu *et al.* 2016; HCM 2010). These are related to the operational performance aspects of roundabouts.

In developing countries such as India, traffic is characterized by non-lane based movement (multi-class traffic with poor lane discipline) (Charly & Matthew 2019) where drivers tend to navigate in the roadway along the direction of traffic regardless of lane markings. It leads to more safety problems, especially in the roundabout vicinity. Therefore, detailed and precise crash data is required for an in-depth understanding of how crashes occur at the vantage points of the roundabout vicinity. Safety engineers and planners have utilized the crash prediction model/safety performance function (SPF) as a beneficial tool to analyse and enhance the level of road safety. In recent years, using these methods, intensive studies have been conducted to investigate the impact of various geometric design parameters and traffic volume at intersections on safety (Park *et al.* 2016; Anjana & Anjaneyulu 2015; Abdul Manan *et al.* 2013; HSM 2010; Yan *et al.* 2005). However, the influences of these parameters have not been explicitly quantified in roundabout vicinity, especially in non-lane-based traffic conditions. From this standpoint, there is a lack of comprehensive research on roundabout safety, mainly due to the limited access to crash data from non-lane-based traffic conditions. Hence, detailed information about the factors causing crashes at the roundabouts is essential for planners and road designers to identify existing deficiencies and refine the design criteria. Therefore, the current study aims to develop two SPF model for assessing the safety evaluation at roundabouts entry approach and intersection level along with considering the upshot of geometric, traffic, and crash characteristics.

2 Literature review

The background of the research was examined for the comprehensive review of literature related to various techniques to analyse the crash prediction model and the relationship between the contributing factors related to road traffic accidents. Several research studies have been conducted to identify the factors that may influence the frequency of crash occurrence and the crash severity of traffic accidents. Various researchers have used different regression techniques like log-linear regression (Bauer & Harwood 2000), negative binomial regression (Wong *et al.* 2007), multiple logistic regression (Yan *et al.* 2005), and zero-inflated negative binomial regression (Kumara & Chin 2010). These models were used to predict the crash frequency at a road segment and has been found that the function of the models were following the log-linearity (Kennedy *et al.* 2005; Arndt & Troutbeck 1998; Bared *et al.* 1997). Further, researchers also considered variables related to geometry characteristics such as the diameter of central island, entry width, gradient, and curvature of the entry path. But, the results of the parameters in the literature cited above showed an inconsistent relationship at different research work on the crash occurrence cases (Kennedy *et al.* 2005; Arndt & Troutbeck 1998; Maycock & Hall 1984). The SPF was calculated in the HSM (2010) using regression equation that took into account crash data, annual average daily traffic (AADT), and the length in miles of the road segment for determining the crash frequency for a particular site type. In order to explain the safety aspects, the techniques mentioned above are used to develop the SPF at various facilities, including urban and suburban arterials, rural two-lane highways, rural multi-lane highways, and freeway ramp terminals. Greibe (2003) used a Poisson distribution to develop SPF for urban crossings and found that traffic flow was the most affecting variable. Several studies have developed site-specific safety models based on accident data, AADT, geometric characteristics of the intersection, and so forth (Sawalha & Sayed 2006; Wang & Abdel-Aty 2006).

According to the NCHRP report (Rodegerdts *et al.* 2010) on the roundabout approach level safety log-linear models are used to forecast crashes as a function of annual average daily traffic (AADT) and roundabout geometric design attributes. Entry radius, entry width, central island diameter, angle to the next leg, and entry path radius are the geometric parameters that influence entering-circulating crashes. In addition to this, Maycock & Hall (1984), Arndt & Troutbeck (1998), Harper & Dunn (2005), and Turner *et al.* (2009) developed SPFs for roundabouts at the approach level based on total crashes. Rodegerdts *et al.* (2007) used 39 roundabouts to develop SPFs at the roundabout intersection and leg levels. The intersection level significant factors are AADT, number of approaches and number of circulating lanes, whereas the leg level significant variables are entry radius, entry width, central island diameter, approach half-width, and circulating width respectively. Dixon & Zheng (2013) considered 21 single-lane roundabouts and developed SPF for intersection level based on total AADT. Anjana & Anjaneyulu (2015) investigated the approach level of roundabout safety based on the geometric elements and traffic conditions. The geometric elements of the central island, circulation-roadway, and approach roads were found to be linked to the incidence of crashes on roundabout approaches. McIntosh *et al.* (2011) developed intersection-level crash prediction models for 36 roundabouts and indicated that the total entering AADT and the number of circulating lanes are significant factors. Using 14 roundabout data sets, Kim & Choi (2013) identified the variables associated with roundabout crashes and used NB distribution models to examine the influence of contributing factors on road safety. The results revealed six significant parameters contributing to safety namely, number of approaches, circulating lane width, entry width, flare length, flare width, and circulating lane.

Recently, Kamla *et al.* (2016) examined the effects of traffic and geometric variables on crash frequency. According to their findings, the frequency of crashes tended to rise with increase in the traffic volume and inscribed circle diameter. Novák *et al.* (2018) found that entry design parameters significantly influence safety in terms of crash frequency and speeds at the roundabout, especially at the approach level. Similarly, Al-Marafi *et al.* (2020) considered traffic and geometric features and their influences on the safety performance of roundabouts. It was found that increasing the number of entry lanes, entry width, entry radius, traffic volume, circulatory roadway width, weaving width, and speed limit positively affects roundabout safety. To date, design standard guidelines such as IRC (2017) and Indo-HCM (2017) focused on operational performance roundabouts. Moreover, it could not address the crash data-based safety evaluation measures for safety assessment of roundabouts. Few safety studies have been done at the roundabout approach and intersection level based on SPF (Ferguson *et al.* 2019). The existing studies indicate that roundabouts crash studies have been mainly carried out in homogenous lane-based traffic conditions. Mostly, these studies analysed the relationship between accident causes and crash prediction frequency based on traffic and geometric characteristics. In a nutshell, we can thus conclude that safety performance measures related to those studies are limited at roundabouts, especially at non-lane-based traffic conditions.

Very few studies have analysed crash-based SPF outcomes at uncontrolled intersections and roundabouts. Therefore, there exists a discernible research gap in explaining the safety aspects of roundabouts using the SPF model considering the field crash data from non-lane-based traffic conditions. A comprehensive crash dataset is required to investigate the potential factors associated with the crashes occurring at roundabouts. Most previous studies focused on the crash prediction/SPF model is evaluated in lane-based traffic conditions. These models have been developed for road entities like urban and suburban arterials, rural two-lane highways, rural multi-lane highways, signalized intersections, and freeway ramp terminals. However, studies related to roundabouts are limited. Hence, the evaluation of this lane-based safety model in non-lane-based traffic conditions is not very accurate. Considering that fact, a detailed understanding of further investigation is still pertinent, especially in developing countries like India. It is also evident that studies related to SPF modelling for safety assessment of roundabouts, particularly under non-lane-based traffic scenarios, are minimal. Hence, while explaining the contributing factors of crashes at roundabouts in India, it is worth studying the appropriateness of the SPF model. In this context, this study aims to develop two SPF model for assessing the safety evaluation of roundabouts, one at the approach level and other at the intersection level along with the consideration of the geometric design features, traffic characteristics, and historical crash occurrence data.

3 Methodology

3.1 Study sites and crash data description

In the present study, roundabouts were selected at 19 different locations (comprised 71 approaches/legs) from two states namely Kerala and Maharashtra in India. The selected roundabouts are located in five urban cities which are Trivandrum, Thrissur, Adoor, Calicut and Nasik respectively. The selection of various cities in India is based on different physical characteristics, geometry, living standards, economic background and working environment of the different land use that influences driver behaviour. All study sites were unsignalized roundabouts with varying traffic volume and geometric characteristics ensuring sufficient variability for modelling purpose.

The geometric aspects of a typical roundabout are seen in Figure 1. The primary criterion used to define the size of a roundabout is the diameter of the inscribed circle (IRC 2017). It is measured between the outer edges of the circulatory roadway. Total station survey was conducted at different study locations to get the geometric elements. The collected data was imported into AutoCAD drawing software, and then required variable values were extracted from this software.

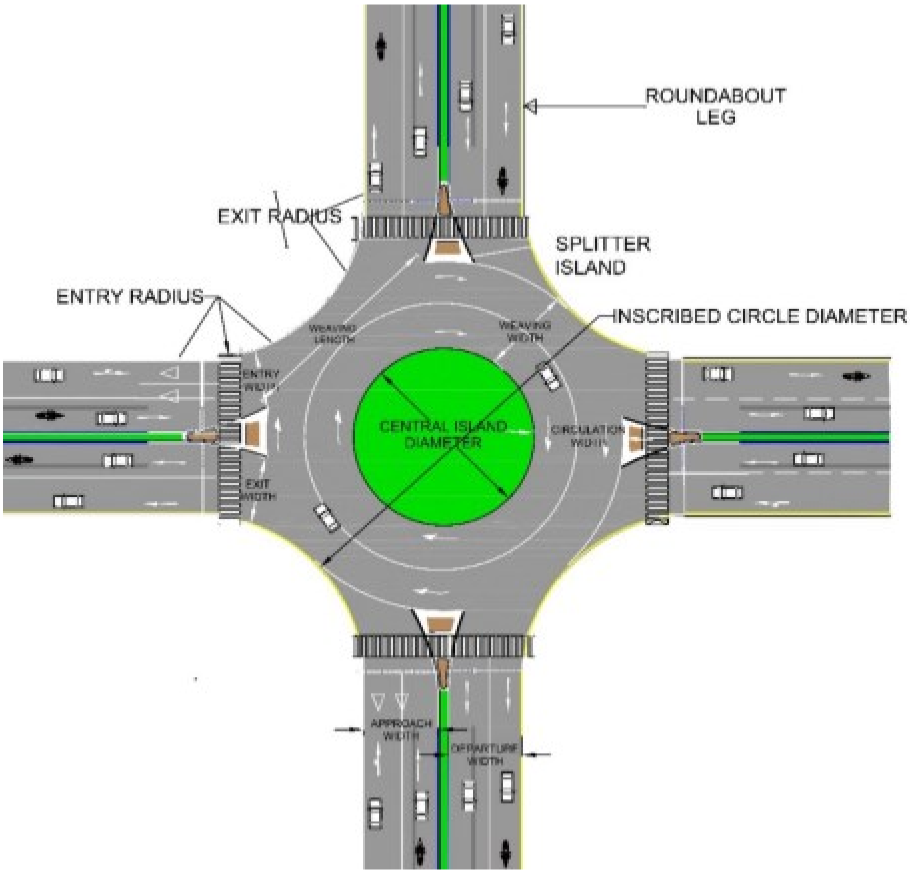

Figure 1 Geometric features of a typical roundabout

Figure 2 presents the photographs of the two selected roundabouts study locations labelled as A and B respectively. Further, a video graphic survey (drone as well as a normal camera) was also conducted at each roundabout at different time slots such as morning peak hour (9:00 a.m. to 10:00 a.m.), and evening peak hour (4.30 p.m. to 5:30 p.m.) to get the non-lane-based traffic-flow related information. Furthermore, the National Transportation Planning and Research Centre (NATPAC), Kerala, India, has provided information regarding the average daily traffic (ADT) and intersection drawings for this study. The recorded video data was retrieved from Avidemux video editor software (Avidemux n/d), and the parameters like classified vehicle count, entry flow, exit flow, and circulatory flow were obtained and analysed. The variation of average traffic composition in the entire study stretches has been analysed. Results found that mode share of the powered two-wheeler (PTW) was dominant as compared to other mode shares.

Figure 2 Examples of selected roundabout study locations

Table 1 Descriptive statistics of the studied roundabouts

Variable	Minimum	Maximum	Mean	Standard deviation
Continuous variables (unit)				
Central island diameter (meter)	8.10	50.61	20.23	10.90
Central island height (meter)	0.22	1.00	0.55	0.21
Circulating road width (meter)	6.62	29.20	12.34	4.21
Inscribed circle diameter (meter)	29	70.40	43.05	13.15
Approach width (meter)	3.00	13.60	6.62	2.48
Departure width (meter)	3.00	14.37	6.69	2.66
Entry angle (degree)	7.00	131.00	40.45	25.77
Exit angle (degree)	5.00	123.23	39.33	22.27
Entry radius (meter)	4.12	221.00	35.37	35.07
Exit radius (meter)	5.39	301.00	49.71	59.64
Entry width (meter)	4.23	27.80	10.51	4.16
Exit width (meter)	4.13	29.00	11.67	4.74
Weaving width (meter)	7.0	43.15	14.49	5.48
Weaving length (meter)	9.10	70.91	28.75	12.50
Angle to next leg (degree)	32.85	178.00	104.81	32.55
Splitter island length (meter)	0.0	70.0	12.69	17.05
Splitter island width (meter)	0.0	15.80	3.41	4.22
ADT at junction (PCU/Day)	30 469	10 4967	60 016	22 728
Categorical variables				
Number of circulating lanes	2 lanes (84.7%), 3 lanes (15.3%)			
Number of legs	3 leg (25.35%), 4 leg (67.60%), 5 leg (7.04%)			
Number of lanes in approach	Single lane (23.8%), 2 lanes (67.9%), 3 lanes (8.1%)			
Number of lanes in a departure	Single lane (24.7%), 2 lanes (66.28%), 3 lanes (9%)			
Presence of pedestrian cross marking	No (64.5%), Faded (35.5), Yes (0%)			
Presence of road lane marking	No (72.5%), Faded (27.4%), Yes (0%)			
Presence of traffic signboard	No (85.4%), Faded (12.9%), Yes (3.2%)			
Presence of road surface condition	Bad (5.06%), Medium (91.3%), Good (3.8%)			
Presence of street light conditions	Yes (42%), No (58%)			
Type of land use	Mixed land use (26.5%), Commercial (48.2%), Residential (21.6%), Institutional (3.6%)			
Day-Night (crash Statistics)	Day (69.8%), Night (30.2%)			

Note: PCU—passenger car units (IRC 2017)

For each roundabout, crash data for five years (2015–2019) was obtained from the State Crime Records Bureau (SCRB) and the respective police stations by referring to the filed first information reports (FIRs). The crash-related information was retrieved around the vicinity of the roundabout from each study location. It consists of individual crash-related information such as type of collision, vehicle age, severity, number of vehicles involved, gender, causes of accidents, time of occurrence, location of accidents, type of vehicle, weather conditions, etc. A total of 1 088 crashes were collected from 19 roundabouts which were twelve four-legged, one five-legged, and six three-legged roundabouts respectively. Detailed descriptive statistics of the studied roundabouts is presented in Table 1.

Further, accident data severity distribution (IRC 2012) of five years was analysed for the roundabouts. The results revealed that grievous injury was most dominant at the roundabout vicinity followed by minor and fatal injuries. Of the total crashes (2015–2019), 6.27% are fatal, 61.87% are grievous, and 31.8% are minor crashes. In addition to this, we can clearly say that collisions involving four-wheelers (4W) and powered two-wheelers (PTW) were dominant. Around 30% of accidents are due to 4W–PTW collisions, followed by PTW–PTW (15.85%) and PTW–pedestrian (10%) collisions. These crashes occur due to the disordered nature of traffic which can be in the form of smaller vehicles often undertaking risky manoeuvres like lane changing, sudden deceleration or junction overshooting. In addition, we can say that the crashes could be either due to non-compliance behaviour, inadequate geometric design, or failing to judge another person's path or speed.

3.2 Research framework

3.2.1 Safety performance function

SPFs are one of the effective safety tools for expressing the safety quantitatively, their potential for determining both frequency of crash occurrence and other contributing factors that transportation policies could address. Traffic accidents may have many contributing factors which can be related to driver behaviour, geometric characteristics, traffic characteristics, and environmental factors. Usually, an SPF is defined for typical network elements like road segments and intersections for the safety assessment. Mostly, count data is used for crash frequency analysis as the accidents number is nonnegative in nature. The Generalized Linear Model (GLM), which is the Poisson or Negative binomial with log link, is the recommended model (Pande *et al.* 2017; Abdul Manan *et al.* 2013; HSM 2010; Lord & Mannering 2010). A GLM model generalizes linear regression by allowing the linear model to have a link function that connects it to the response variable, and the magnitude of variance of each measurement to depend on the predicted value. One limitation of the Poisson regression model is that the variance of the data is constrained to be equal to the mean. When this equality does not hold the data is said to be under-dispersed if $E[x_i] > var[x_i]$ and to be over-dispersed if $E[x_i] < var[x_i]$. In order to overcome the overdispersion, the Negative Binomial (NB) distribution will take care of the condition of mean equals to variance, and hence overdispersion in the crash data counts can be taken into account. Hence, this model is widely accepted for SPF modelling. To obtain the NB-model (Gamma probability distribution), the Poisson regression is modified by adding an error term ε_i, along with number of crashes expected as shown in equation (1).

$$\lambda_i = \exp\,(\beta \cdot X_i + \varepsilon_i), \tag{1}$$

where $\exp(\varepsilon_i)$ is a gamma-distributed error term with mean 1 and variance α. In addition to this, the term allows the variance to differ from the mean as $var[x_i] = E[x_i]\cdot(1 + \alpha \cdot E[x_i]) = E[x_i] + \alpha \cdot E[x_i]^2$. The negative binomial probability density function form is shown in equation (2):

$$P(x_i) = \left[\frac{\frac{1}{\alpha}}{\frac{1}{\alpha}+\lambda_i}\right]^{\frac{1}{\alpha}} \frac{\Gamma\left(\left(\frac{1}{\alpha}\right)+x_i\right)}{\Gamma\left(\frac{1}{\alpha}\right)x_i!} \left[\frac{\lambda_i}{\frac{1}{\alpha}+\lambda_i}\right]^{x_i} \tag{2}$$

where Γ(.) is a gamma function; x_i is observed crash frequencies for unit i; and λ_i is expected crash frequencies for unit i.

The NB model has some limitations due to its inability to handle of under-dispersion (when the mean of the crash counts is higher than the variance). The other modelling approach is the zero-inflated negative binomial model. However, it is inappropriate here because of not many excessive zeroes in traffic accident data counts.

For selected sites, the SPFs at unsignalized roundabouts vicinity were analysed using negative binomial regression with log-link function, which is the most suitable method for explaining the SPFs (Pande *et al.* 2017; Lord & Mannering 2010). In this present study, the generalized linear negative binomial regression model is formulated as shown in equation (3).

$$Y = \exp\left(\beta_0 + \sum_{i=1}^{n} \beta_i \cdot x_i + \varepsilon_i\right) \tag{3}$$

where Y is the expected number of crashes at the vicinity of roundabouts; β_0 is the intercept; x_i is the explanatory variable; β_i is the model coefficients linked with x_i; n is the total number of variables; and ε_i an error term which will follow the gamma-distributed error.

The modelling was carried out with the help of the statistical software IBM-SPSS.

3.2.2 Goodness-of-fit and model validation

Evaluating the performance of best-fitted model assessments, the ρ^2 statistic and the Akaike's Information Criterion (AIC) are employed as the goodness-of-fit measures.

The ρ^2 statistic can be calculated using below equation (4):

$$\rho^2 = 1 - \frac{LL(C)}{LL(0)} \tag{4}$$

where LL(0) is the log-likelihood function when all parameters are zero, and LL(C) is the log-likelihood at convergence.

Akaike's Information Criterion (AIC) test was used to measure the goodness-of-fit of each model relative to each of the other models (Akaike 1974). This test is defined as shown in equation (5):

$$AIC = -2 \cdot \log L + 2 \cdot P \tag{5}$$

where log L is the maximum log-likelihood of the model and P is the number of estimated parameters in the model. In general, the smaller AIC values are more preferred in the model (Abdul Manan *et al.* 2013; Young & Park 2013; Cafiso *et al.* 2010).

Pearson chi-square and deviance test was used to check whether the NB assumption is acceptable for this study. These statistics divided by its degree of freedom (df) will give the estimation results. The obtained results are in the allowable range implying that the NB distribution assumption is acceptable.

Moreover, Mean Squared Prediction Error (MSPE) and Mean Absolute Deviation (MAD) are employed as the prediction performance measures (Young & Park 2013; Washington *et al.*

2010). The difference between observed crashes and predicted crashes variance is determined by MSPE as given in equation (6):

$$MSPE = \frac{1}{n} \cdot \sum_{i=1}^{n} (y_i' - y_i)^2 \tag{6}$$

where y_i' is the predicted crashes number; y_i is the observed crashes number at i-th roundabout; and n is the sample size. In addition, MSPE typically evaluates the error associated with a validation dataset.

The average magnitude of the prediction variability was measured by using MAD values. The smaller value of MSPE and MAD indicates the model's lower prediction error. The MAD is calculated as:

$$MAD = \frac{1}{n} \cdot \sum_{i=1}^{n} \left| y_i' - y_i \right|. \tag{7}$$

4 Results and discussion

4.1 Development of SPF

A negative binomial model (NB) with a log-link function was used to develop an SPF. In this model, we formed a database of 19 roundabout (comprising of 71 approaches/legs) locations, containing the number of crashes, traffic and geometry characteristics, and environmental factors. The model includes the number of crashes deliberated as the dependent variable, and geometric elements, environmental factors, and traffic characteristics as independent variables. A total of 29 variables were considered for this study, 18 variables as continuous, and the rest as categorical. A Pearson correlation matrix has been developed to check the relationships between independent and dependent variables for choosing appropriate variables for model development. Significant variables (when the correlation coefficient is greater than 0.5 and p-value less than 0.05) which do not exhibit multicollinearity (Variance Inflation Factor > 10 and Tolerance < 1) were considered for the model development, and others were discarded from this model. After these steps, remaining 10 variables were used for model development with many trials and with different combinations of independent variables. Finally, statistically significant variables have been retained based on the p-values for the final model.

In order to better understand the effects of variables on crash frequency, SPFs of roundabout are divided into two sections: (*i*) entry approach level SPF, and (*ii*) the intersection level SPF. These will give an in-depth understanding of traffic characteristics, environmental factors and geometric elements and their influence on the roundabout safety performance.

4.2 SPF at roundabout entry approach level

While considering the roundabout at entering approach level, the estimation results of safety performance function model as shown in Table 2. The sign of the coefficients β_i denotes the directions of influence of individual variables on response variables. Parameter having a positive sign indicates that increase in the variables increases the crash frequency and vice-versa. The model results were found that exit radius, average daily traffic at junction, entry angle, and weaving length were positively associated with increase in the propensity of crash occurrence. On the other hand, inscribed circle diameter, and road lane marking are negatively associated with the increased crash occurrence rate at roundabout approaches. A greater exit radius was more associated with higher crash risk at roundabouts approaches. However, with significant pedestrian traffic across the exit road, the radii will be provided more or less similar to entry radii; accordingly, the crash occurrence is reduced.

Table 2 Estimates of SPF model for entry approach

	Parameters	Coeff.	St. error	*t*-stat.	Sig.
Entry approach level SPF	Constant	2.732	-	-	-
	Average daily traffic at junction (ADT_JN)**	0.400	0.142	2.816	0.005
	Inscribed circle diameter (ICD)**	-0.340	0.164	-2.073	0.045
	Entry Angle (EA)*	0.202	0.90	0.224	0.026
	Exit radius (EXR)**	0.286	0.092	3.11	0.002
	Weaving length (WL)**	0.241	0.105	2.29	0.022
	Presence of road lane marking (PRLM)**	-0.448	0.22	-2.03	0.050
Goodness' of fit & Validation	Dispersion parameter				0.40
	log-likelihood ratio (ρ^2)				0.117
	Deviance & Pearson chi-square				1.15 & 1.03
	AIC				473.31
	MSPE & MAD				0.14 & 0.31

Notes: **Significant at 95% confidence level; *Significant at 90% confidence level
AIC: Akaike's Information Criterion
MSPE: Mean squared prediction error
MAD: Mean absolute deviation

Further, the presence of proper road lane markings was also negatively influencing the crash occurrences. If the road lane marking condition is good, most of the drivers may wish to drive at their desired speed (driver behaviour might change depending upon the road environment) without considering traffic rules and regulations (this result might be controversial since road condition was not good) thereby leading to accidents. In other words, if the road lane marking is faded or not available, the driver might get confused while driving through the roundabouts. It leads to accidents at the roundabout area because the road marking is controlling factor and guiding the traffic direction. Focussing on the inscribed circle diameter (ICD) of a roundabout, it is seen that reducing the diameter of the circle increases the crash occurrence at the roundabouts, diminishing the roundabout safety. In other words, we can infer that for safer movement, a wider inscribed circle diameter (as per IRC (2017), ICD ranges from 28 to 70 m) is preferable for reducing the traffic congestion and ensuring smooth traffic flow through the roundabout. Traffic volume (ADT) is the other significant variable for safety studies (HSM 2010). The crash risk increases with the increase in traffic volume at junction due to the heterogeneous traffic condition in the form of the smaller vehicles often taking the risky behaviour or manoeuvring inside the roundabouts leading to crash occurrence at roundabouts. Mostly, diverging, merging, and lane changes occur between the vehicles at weaving length sessions in roundabouts. If the length of the weaving section increases, the likelihood of a crash also increases (Anjana & Anjaneyulu 2015). Owing to the wider weaving length, most of the vehicles attempt to come closer to each other subsequently increasing crash risk as a result of negligent driver behaviour.

During the design stage, it is necessary to constrain the maximum weaving length to discourage the speeding of vehicles at roundabouts. Generally, entry angle serves as a geometric proxy for the conflict angle between entering and circulating traffic streams. Focussing on the entry angle, a wide entry angle is related to higher entry speeds leading to more collisions at the roundabout entering-circulating sections. As per IRC (2017), the entry angle is recommended to be maintained between 20 and 60 degrees. Accidents and delays occur in the roundabout vicinity if the entry angle is not designed correctly during the implementation stage.

The goodness of fit for the roundabout approach level model was investigated using AIC, ρ^2-statistic, deviance, and Pearson chi-square statistics. The obtained results of this model were 473.3, 0.11, 1.15 and 1.03, respectively. Model having smaller AIC value (different trials with several combinations of variables were conducted in this model) perform better, and this model's dispersion parameter having a value of 0.40 was significantly different from zero. Specifically, the test values are within the allowable range, so the NB distribution assumption is acceptable for this model. In order to check the accuracy level of prediction results, MAD and MSPE indicators were used. The results obtained are 0.31 and 0.14 respectively. This shows that the model has produced reasonably good predictive performance because of the smaller value of these refers to lower prediction error (Washington *et al.* 2010).

4.3 SPF at intersection level

The intersection level SPF was developed to inform design decisions at a similar level. The estimated SPF is presented in Table 3. The obtained results indicate that average daily traffic at the junction, number of circulatory lanes, and percentage of powered two-wheeler and heavy vehicles (bus and trucks) mainly contribute to the crashes at roundabouts. However, it was also noticed that the parameters such as the percentage of powered two-wheeler and heavy vehicles highly impact on the accidents occurring at roundabouts. Results obtained from the preliminary analysis showed that the percentage of PTW was dominant in all the roundabouts. Powered two-wheelers were considered a vulnerable vehicle class component; it has high manoeuvrability power, risky behaviour and filtering behaviour and the nature of traffic conditions is too heterogeneous. These might be the reason for more accidents at roundabout junctions. On the other hand, as compared to powered two-wheeler, heavy vehicles required more time to accept the gap (Abhigna *et al.* 2016) to cross the roundabouts. This more time gap leads to more congestion and delay at the roundabout vicinity. Similar results are supported by previous research findings (Kamla *et al.* 2016). Traffic volume was the most important factor in road safety studies (HSM 2010; Kennedy *et al.* 2005). In this study, increasing the average daily traffic at the junction will likely increase the crash risk at roundabout intersections. During the high traffic flow condition at junctions, the vehicles are unable to manoeuvre/move properly to the inside of the roundabouts due to geometric constraints or high traffic heterogeneity thus leading to accidents. The other reasons for a crash occurring at a roundabout could be poor night visibility of roads, absence of proper signboard, and human errors such as late reaction time, inadequate brake pedal force application, misapplication of accelerator/brake pedal, etc. Due to above mentioned reasons the drivers cannot get the proper attention to controlling the vehicle at short time which leads to crashes at roundabouts. Another geometric factor, the number of the circulatory lanes (NCL), negatively influences road crashes, i.e. if the number of circulating lanes increases, the crash associated risk decreases. If the circulating lane is too narrow, the manoeuvrability power of the vehicle gets reduced (less turning radius), which may lead to accidents occurring in the circulating section. Here, NCL also an important factor for the planners to take the decision related to safety aspects of roundabouts. The circulating traffic flow will depend on the NCL. If the NCL decreases, it leads to crashes at roundabout vicinity.

Table 3 Estimates of SPF model for intersection level

	Parameters	Coeff.	St. error	*t*-stat.	Sig.
Intersection level SPF	Constant	2.533	-	-	-
	Average daily traffic at junction (ADT-JN)**	0.441	0.133	3.31	0.001
	% powered two-wheelers (PTW)**	3.09	1.57	1.96	0.050
	Number of circulatory lane (NCL)**	-1.02	0.36	-2.83	0.005
	% heavy vehicles (HV)*	7.74	4.57	1.69	0.09
Goodness of fit and validation	Dispersion parameter				0.207
	log-likelihood ratio (ρ^2)				0.10
	Deviance & Pearson chi-square				1.3 & 1.29
	AIC				213.35
	MSPE & MAD				0.94 & 1.1

Notes: **Significant at 95% confidence level; *Significant at 90% confidence level
AIC: Akaike's Information Criterion
MSPE: Mean squared prediction error
MAD: Mean absolute deviation

Using the goodness-of-fit tests, the best fit for this model based on AIC, ρ^2 statistic, deviance, and Pearson chi-square statistics are estimated as 213.3, 0.10, 1.4 and 1.39 respectively. The dispersion parameter was 0.207. Overall, the estimated values are in allowable range and indicate that this model with an assumption of NB distribution is a good fit. Finally, validation was carried out based on 10% of the remaining data set as well. For validation purpose, MAD and MSPE were used as performance indicators. The smaller MAD (1.1) and MSPE (0.94) values generally refer to lower prediction error which shows that the model has produced reasonably good predictive performance.

5 Conclusions

The present study developed safety performance measure for the evaluation of safety at roundabouts considering geometric characteristics, traffic characteristics, and historical crash occurrence data. The developed SPF model predicts the total number of crashes at the roundabout's vicinity based on measurable explanatory variables. A negative binomial model with a log link function was used to estimate the model parameters. Two SPF models were developed for a roundabout at entry approach level and an intersection level to obtain in-depth understanding of the impact of geometric and traffic variables on safety. It was found that the percentage of PTW, percentage of heavy vehicles, average daily traffic at the junction, entry angle, and weaving length were significantly associated with increased crash occurrences at roundabouts, whereas the number of circulatory lanes, inscribed circle diameter, and presence of road lane marking were negatively associated with the increased crash occurrences. The other finding attained from this study is that the average daily traffic was the most influencing risk factor across the roundabout intersection level and entry approach level. Beside this, impact of some of the risk factors on accidents vary significantly across developed SPF models. Hence, the overall crashes significantly vary across roundabout sections due to the asymmetric effects of geometric and traffic characteristics. In a nutshell, we can say that the traffic and geometric characteristics have statistically significant influence on roundabout safety. Further, it is a simple and effective safety evaluation tool for explaining the insights for selecting geometric and traffic variables for reducing crash safety treatment. Goodness-of-fit was investigated using AIC, ρ^2-statistics, deviance, and Pearson chi-square statistics. Results indicate that the model developed using NB distribution assumption is acceptable. Furthermore, the Performance evaluation of the model was estimated based on MAD and MSPE indicators respectively. The study also shows that obtained values are in the allowable range.

The potential contributions of this study can be two-fold. Firstly, this study gives an in-depth analysis of roundabout safety based on geometric and traffic characteristics in developing countries like India. Though many studies have been conducted in western (developed) countries (Ferguson *et al.* 2019; Rodegerdts *et al.* 2010), limited studies were reported on the influence of geometric and traffic variables on roundabout safety in Indian conditions. These study findings may not be directly applicable to other countries with non-lane-based traffic environments. Secondly, the study findings support the need to relook at the existing design decisions parameters and traffic parameters of roundabouts, thereby improving the existing facilities to enhance road users' safety. The proposed SPFs tool will help safety engineers to examine the safety treatments of roundabouts in terms of design adequacy, quantifying the crash contributing factors, and future crash predictions.

The present study has some limitations, i.e. the variables such as speed and acceleration at the time of the accident are not considered in this study due to the unavailability of these variables from the FIR records. In future research, the calibration of developed models and verification of the applicability of the models to different regions with similar traffic and geometric characteristics need to be carried out.

CRediT contribution statement

V S Vinayaraj: Conceptualization, Data curation, Formal analysis, Methodology, Validation, Writing—original draft, Writing—review & editing. **Vedagiri Perumal:** Conceptualization, Supervision, Writing—review & editing.

Declaration of competing interests

The authors report no competing interests.

Acknowledgement

The authors would like to express sincere gratitude to the Department of Kerala police and Bhadrakali Police Station for sharing the crash data for this study. The authors would like to thank the National Transportation Planning and Research Centre (NATPAC), Thiruvananthapuram, Kerala, India, for providing the detailed traffic volume and total station-based geometry dataset to support this research work. The authors received no financial support for this research, authorship, and publication of this article.

An early version of this paper was presented at the 8th Road Safety & Simulation International Conference, held in Athens, Greece, on 8–10 June 2022.

References

Abdul Manan, M. M., T. Jonsson, A. Várhelyi (2013), 'Development of a safety performance function for motorcycle accident fatalities on Malaysian primary roads', *Safety Science*, 60, 13–20, https://doi.org/10.1016/j.ssci.2013.06.005.

Abhigna, D., S. Kondreddy, K. V. R. R. Shankar (2016), 'Effect of vehicle composition and delay on roundabout capacity under mixed traffic conditions', *Archives of Transport*, 40 (4), 7–14, https://doi.org/10.5604/08669546.1225456.

Akaike, H. (1974), 'A new look at the statistical model identification', *IEEE Transactions on Automatic Control* 19 (6), 716–723, https://10.1109/TAC.1974.1100705.

Al-Marafi, M. N., K. Somasundaraswaran, R. Ayers (2020), 'Developing crash modification factors for roundabouts using a cross-sectional method', *Journal of Traffic and Transportation Engineering (English Edition)*, 7 (3), 362–374, https://doi.org/10.1016/j.jtte.2018.10.012.

Anjana, S., M. V. L. R. Anjaneyulu (2015), 'Development of Safety Performance Measures for Urban Roundabouts in India', *Journal of Transportation Engineering*, 141 (1), https://doi.org/10.1061/(ASCE)TE.1943-5436.0000729.

Arndt, O. K., R. J. Troutbeck (1998), 'Relationship between Roundabout Geometry and Accident Rates', presented at *International Symposium on Highway Geometric Design Practices* (Boston, MA, USA: 30 August–1 September 1995).

Avidemux (n/d), 'Avidemux: Free video editor', https://avidemux.sourceforge.net/, accessed 4 October 2022.

Bared, J. G., W. Prosser, C. Tan Esse (1997), 'State-of-the-Art Design of Roundabouts', *Transportation Research Record: Journal of the Transportation Research Board*, 1579 (1), https://doi.org/10.3141/1579-01.

Bauer, K. M., D. W. Harwood (2000), 'Statistical Models of At-Grade Intersection Accidents' (McLean, VA, USA: Federal Highway Administration), FHWA-RD-99-094, https://www.fhwa.dot.gov/publications/research/safety/99094/99094.pdf, accessed 4 October 2022.

Cafiso, S., A. Di Graziano, G. Di Silvestro, *et al.* (2010), 'Development of comprehensive accident models for two-lane rural highways using exposure, geometry, consistency and context variables', *Accident Analysis & Prevention*, 42 (4), 1072–1079, https://doi.org/10.1016/j.aap.2009.12.015.

Charly, A., T. V. Matthew (2019), 'Estimation of traffic conflicts using precise lateral position and width of vehicles for safety assessment', *Accident Analysis & Prevention*, 132, 105264, https://doi.org/10.1016/j.aap.2019.105264.

Dixon, K., J. Zheng (2013), 'Developing safety performance measures for roundabout applications in the state of Oregon' (Oregon Department of Transportation and Federal Highway Administration), FWHA-OR-RD-13-08, https://www.oregon.gov/odot/Programs/ResearchDocuments/SPR733_Roundabout.pdf, accessed 4 October 2022.

Ferguson, E., J. Bonneson, L. Rodegerdts, *et al.* (2019), 'Development of Roundabout Crash Prediction Models and Methods' (Washington DC, USA: National Cooperative Highway Research Program, Transportation Research Board), NCHRP Research Report 888, https://doi.org/10.17226/25360.

Greibe, P. (2003), 'Accident prediction models for urban roads', *Accident Analysis & Prevention*, 35 (2), 273–285, https://doi.org/10.1016/S0001-4575(02)00005-2.

Harper, N. J., R. C. M. Dunn (2005), 'Accident Prediction Models at Roundabouts', presented at *ITE Annual Meeting* (Melbourne, Australia: 7–10 August 2005).

HCM (2010), 'Highway Capacity Manual' (Washington DC: Transportation Research Board).

HSM (2010), 'Highway Safety Manual' (Washington DC, USA: American Association of State Highway and Transportation Officials).

Indo-HCM (2017), 'Indian Highway Capacity Manual' (Council of Scientific and Industrial Research, Central Road Research Institute), https://crridom.gov.in/sites/default/files/files/Indo-HCM%20Snippets.pdf, accessed 4 October 2022.

IRC (2012), 'Road Accident Recording Forms A-1 and A-4 (Second Revision)' (New Dehli, India: Indian Roads Congress), IRC: 53-2012, https://www.roadsafetynetwork.in/wp-content/uploads/2019/01/irc-3-2012-road-accident-recording-forms.pdf, accessed 4 October 2022.

IRC (2017), 'Guidelines for Planning and Design of Roundabouts (First Revision)' (New Delhi, India: Indian Roads Congress), IRC: 65-2017, https://law.resource.org/pub/in/bis/irc/irc.gov.in.065.2017.pdf, accessed 4 October 2022.

Kamla, J., T. Parry, A. Dawson (2016), 'Roundabout Accident Prediction Model: Random-Parameter Negative Binomial Approach', *Transportation Research Record: Journal of the Transportation Research Board*, 2585 (1), https://doi.org/10.3141/2585-02.

Kennedy, J. V., J. Peirce, I. Summersgill (2005), 'Review of Accident Research at Roundabouts', presented at *National Roundabout Conference* (Vail, CO, USA: 22–25 May 2005), https://onlinepubs.trb.org/Onlinepubs/circulars/ec083/14_Kennedypaper.pdf, accessed 4 October 2022.

Kim, S., J. Choi (2013), 'Safety analysis of roundabout designs based on geometric and speed characteristics', *KSCE Journal of Civil Engineering*, 17, 1446–1454, https://doi.org/10.1007/s12205-013-0177-4.

Kumara, S. S. P., H. C. Chin (2010), 'Modeling Accident Occurrence at Signalized Tee Intersections with Special Emphasis on Excess Zeros', *Traffic Injury Prevention*, 3 (1), 53–57, https://doi.org/10.1080/15389580309852.

Lord, D., L. Mannering (2010), 'The statistical analysis of crash-frequency data: A review and assessment of methodological alternatives', *Transportation Research Part A: Policy and Practice*, 44 (5), 291–305, https://doi.org/10.1016/j.tra.2010.02.001.

Maycock, G., R. D. Hall (1984), 'Accidents at 4-Arm Roundabouts' (Workingham, UK: Transport Research Laboratory), Report 1120.

McIntosh, K., C. Redinger, J. Bagdade (2011), 'Evaluating the Performance and Safety Effectiveness of Roundabouts' (Michigan Department of Transportation), RC-1566, https://rosap.ntl.bts.gov/view/dot/24001, accessed 4 October 2022.

Montella, A. (2011), 'Identifying crash contributory factors at urban roundabouts and using association rules to explore their relationships to different crash types', *Accident Analysis & Prevention*, 43 (4), 1451–1463, https://doi.org/10.1016/j.aap.2011.02.023.

MoRTH (2019), 'Road Accidents in India 2019' (New Delhi: Transport Research Wing, Ministry of Road Transport and Highways, Government of India), https://morth.nic.in/road-accident-in-india, accessed 4 October 2022.

Novák, J., J. Ambros, J. Frič (2018), 'How Roundabout Entry Design Parameters Influence Safety', *Transportation Research Record: Journal of the Transportation Research Board*, 2672 (34), https://doi.org/10.1177/0361198118776159.

Pande, A., S. Chand, N. Saxena, *et al.* (2017), 'A preliminary investigation of the relationships between historical crash and naturalistic driving', *Accident Analysis & Prevention*, 101, 107–116, https://doi.org/10.1016/j.aap.2017.01.023.

Park, M., D. Lee, J. Jeon (2016), 'Random Parameter Negative Binomial Model of Signalized Intersections', *Mathematical Problems in Engineering*, 1436364, https://doi.org/10.1155/2016/1436364.

Polus, A., Y. Shiftan, S. Shmueli-Lazar (2005), 'Evaluation of the Waiting-Time effect on Critical Gaps at Roundabouts by a Logit Model', *European Journal of Transport and Infrastructure Research*, 5 (1), https://doi.org/10.18757/ejtir.2005.5.1.4329.

Robinson, B. W., L. Rodegerdts, W. Scarborough, *et al.* (2000), 'Roundabouts: An Informational Guide' (Federal Highway Administration), FHWA-RD-00-067, https://www.fhwa.dot.gov/publications/research/safety/00067/00067.pdf, accessed 4 October 2022.

Rodegerdts, L., M. Blogg, E. Wemple, *et al.* (2007), 'Appendixes to NCHRP Report 572: Roundabouts in the United States. NCHRP Project 3-65' (Washington, D.C.: The National Academies Press), https://doi.10.17226/21999.

Rodegerdts, L., J. Bansen, C. Tiesler, *et al.* (2010), 'Roundabouts: An Informational Guide, Second Edition' (Washington DC, USA: National Cooperative Highway Research Program), NCHRP Report 672, https://doi.org/10.17226/22914.

Sawalha, Z., T. Sayed (2006), 'Traffic Accident Modeling: Some Statistical Issues', *Canadian Journal of Civil Engineering*, 33 (9), https://doi.org/10.1139/l06-056.

Sonu, M., A. Dhamaniya, S. Arkatkar, G. Joshi (2016), 'Time occupancy as measure of PCU at four legged roundabouts', *Transportation Letters*, https://doi.org/10.1080/19427867.2016.1154685.

Turner, S. A., A. P. Roozenburg, A. W. Smith (2009), 'Roundabout Crash Prediction Models' (Wellington, New Zealand: New Zealand Transport Agency), Report 386, https://www.nzta.govt.nz/assets/resources/research/reports/386/docs/386.pdf, accessed 4 October 2022.

Wang, X., M. Abdel-Aty (2006), 'Temporal and spatial analyses of rear-end crashes at signalized intersections', *Accident Analysis & Prevention*, 38 (6), 1137–1150, https://doi.org/10.1016/j.aap.2006.04.022.

Washington, S. P., M. G. Karalftis, F. Mannering (2010), *Statistical and Econometric Methods for Transportation Data Analysis* (New York: Chapman and Hall/CRC) 2nd Edition, https://doi.org/10.1201/9781420082869.

WHO (2018), 'Global Status Report on Road Safety 2018' (World Health Organization), https://www.who.int/publications/i/item/9789241565684, accessed 4 October 2022.

Wong, S. C., N. N. Sze, Y. C. Li (2007), 'Contributory factors to traffic crashes at signalized intersections in Hong Kong', *Accident Analysis & Prevention*, 39 (6), 1107–1133, https://doi.org/10.1016/j.aap.2007.02.009.

Yan, X., E. Radwan, M. Abdek-Aty (2005), 'Characteristics of rear-end accidents at signalized intersections using multiple logistic regression model', *Accident Analysis & Prevention*, 37 (6), 983–995, https://doi.org/10.1016/j.aap.2005.05.001.

Young, J., P. Y. Park (2013), 'Benefits of small municipalities using jurisdiction-specific safety performance functions rather than the Highway Safety Manual's calibrated or uncalibrated safety performance functions', *Canadian Journal of Civil Engineering*, 40 (6), https://doi.org/10.1139/cjce-2012-0501.

About the authors

V S Vinayaraj is a research scholar in the Department of Civil Engineering in the specialization in Transportation Systems Engineering, Indian Institute of Technology Bombay, India. His research mainly focuses on understanding the driver behaviour characteristics, analysing crash data, and safety assessment of roundabouts in disordered traffic conditions. His research interests include vehicle trajectory data analysis, crash data analysis, driver and pedestrian behaviour modelling, and traffic safety. He received his master's degree in Civil Engineering from SV National Institute of Technology (SVNIT), Surat, India.

Vedagiri Perumal is Professor in the Department of Civil Engineering, Indian Institute of Technology Bombay, India. His research interests include traffic safety, mixed traffic flow modelling and simulation, traffic monitoring, management and control, traffic facility design and evaluation, and public transit systems design and operations. He has over 40 international journal publications and 100 international and national conference publications. He has received IIT Bombay's Young Investigator Award in 2013 and Excellence in Teaching award in 2017. He is one of the Recognized Road Safety Auditor in the region. He has successfully completed various national and international research projects.