Safety Evaluation of Urban Roundabouts in India: A Safety Performance Function based Approach

Vinayaraj V S [1], Vedagiri Perumal

Department of Civil Engineering, Indian Institute of Technology Bombay, Mumbai, India-400076
vinayaraj4u@gmail.com
Department of Civil Engineering, Indian Institute of Technology Bombay, Mumbai, India-400076
vedagiri@civil.iitb.ac.in

Abstract

Safety Performance Function (SPF) is a suitable tool for explaining safety at roundabouts. However, such safety performance measures are very limited in heterogeneous traffic conditions. So, this study develops an SPF model for assessing the safety evaluation at roundabouts considering the geometric characteristics, traffic characteristics, and historical crash data. For model formulation, data corresponding to crashes in twenty roundabouts with different geometric and traffic characteristics was used. 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. Results revealed that the average daily traffic at the junction, percentage of two-wheelers, percentage of heavy vehicles, entry-angle, and weaving-length were significantly associated with the increased crash occurrences at roundabouts. 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. The developed SPF would best explain the relationship between geometric and traffic characteristics and the crash occurrence rate in heterogeneous 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: Roundabouts; Negative binomial; Safety performance function

1. Introduction

Safety on roads is a major concern for developed and developing countries because it affects their economy and people's welfare. Road accidents have been increasing drastically over the past few years owing to several reasons. Hence, road traffic safety has been gaining increasing importance within our country and around the globe. As per the Ministry of Road Transport, and Highways [1], there were approximately 449,002 total 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 was around 11% of total road accidents worldwide.14% of these crash occurrences were reported in roundabouts as compared to other type of intersections in India [1]. These road accidents may lead to enormous losses to society and the economy, particularly in developing countries like India. A roundabout is a specialized form of at grade intersection, where vehicles from the conversing arms are forced to move around a central island in one direction in an orderly and regimented manner and move out of the roundabout into their desired direction. Generally, roundabouts are associated with a positive impact on traffic safety compared to other types of at-grade intersections [2]. Roundabouts may reduce delay and provide safer vehicle movement under moderate traffic conditions compared to signalized or uncontrolled intersections. Reported inadequate safety considerations during the design and operation of roundabouts have led to the overall depreciation in traffic stream safety [3]. However, most of these roundabout studies were globally grounded on the estimation of capacity and point towards gap acceptance behavior using various techniques [4-7]. There is a lack of comprehensive research in roundabout safety, mainly due to the limited access to crash data from heterogeneous traffic conditions. Because of this, detailed information about the factors causing crashes at the roundabouts is essential for planners and designers to identify existing deficiencies and refine the design criteria. Therefore, the objective of this study is to develop a safety performance function (SPF) model for assessing the safety evaluation at roundabouts.

[1] * Corresponding author.
E-mail address: vinayaraj4u@gmail.com

2. Literature Review

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. Researchers were used by regression techniques like log-linear regression [8], negative binomial regression [9], multiple logistic regression [10] and zero-inflated negative binomial regression [11]. These models were used to predict the crash frequency at a road segment, and the function was following the log-linearity [12-13]. Furthermore, crash prediction methods were used to predict the crashes in different road entities, including urban and suburban arterials, rural two-lane highways, rural multi-lane highways, and freeway ramp terminals. They were considered major and minor roads traffic volume used as predictors to estimate the crash counts. Dixon and Zheng [14], Bagdade et al. [15], Rodegerdts et al. [16], Kamla et al. [17], Al-Marafi et al. [18], and Novak et.al [19] developed SPF for roundabout intersection level and approach level. They found that traffic flow was the most influencing variable. In addition to this Maycock and Hall [20], Arndt [13], Harper and Dunn [20], and Turner et al. [21] developed total crashes-based SPF for roundabouts at approach level. Further, researchers were considered geometric variables, but it showed an inconsistent relationship with the other crash occurrence cases [13,22]. Recently, Anjana and Anjaneyulu [23] and Kim and Choi [24] investigated the approach level of roundabout safety based on the geometric elements and traffic conditions. Results revealed that geometric parameters are contributing the crash occurrence on roundabout approaches. To date, very few studies have analyzed crash-based safety performance function outcomes at uncontrolled intersections and roundabouts. Therefore, it is a discernible research gap to explain the safety aspects of roundabouts using the safety performance function model using the field crash data. A comprehensive crash dataset is required to investigate the potential factors associated with the crashes occurring at roundabouts. Therefore, the detailed understanding of further investigation on this subject is still pertinent, especially in developing countries like India. However, it is also evident that studies related to safety performance function modelling for safety assessment of roundabouts, particularly under heterogeneous traffic scenarios, are minimal. Hence, it is worth studying the appropriateness of the safety performance function model while explaining the contributing factors of crashes at roundabouts in India. In this context, this study aims to develop a safety performance function model for assessing the safety evaluation of roundabouts, especially at approach and intersection level, while considering the geometric design features, traffic characteristics, and historical crash occurrence data.

3. Methodology

SPFs are the effective safety tool 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 related to driver behavior, geometric features, traffic characteristics, and environmental factors. Mostly, count data is used for crash frequency analysis because 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. One limitation of the Poisson regression model is that the variance of the data is constrained to be equal to the mean. This equality does not hold, then the data is said to be (E[xi] > var[xi]) under dispersed or over-dispersed (E[xi] < var[xi]). If the variance of crash data is usually greater than the mean, which is called overdispersion [25]. In order to overcome the problem of over-dispersion, the Negative Binomial (NB) distribution will take care of the condition of mean equals to variance, and hence over-dispersion in the crash data counts can take into account; so, this model is widely accepted for SPF modelling. To obtain the NB-model (Gamma probability distribution), modify the Poisson regression by adding an error term (εi), its number of crashes expected, and shown in equation (1).

$$\lambda_i = \exp(\beta X_i + \varepsilon_i) \quad (1)$$

Where, exp(εi) is the error term with mean one and variance α of gamma-distribution. SPFs at unsignalized roundabouts vicinity, for selected sites, were analyzed using negative binomial regression with log-link function, which is the most suitable method explaining the SPFs [25-26]. In this present study, the generalized linear negative binomial regression model is formulated as shown in (2).

$$Y = \exp\left(\beta_0 + \sum_{i=1}^{n} \beta_i x_i + \varepsilon_i\right) \quad (2)$$

Where Y is the number of crashes expected at the roundabout vicinity, β_0 is Intercept, xi is the explanatory variables for the roundabout vicinity, β_i is the model coefficients associated with x_i, n is a total number of variables, and εi error term, it will follow the gamma-distributed error. Modelling will be done with the help of the statistical software IBM-SPSS.

4. Data Collection

The present study roundabouts were selected at 20 different locations from two states, Kerala and Maharashtra, India. All study sites were un-signalized roundabouts with varying traffic volume and geometric features, ensuring sufficient variability for modelling purposes. The last five years of each roundabout crash data from 2015 to 2019 was obtained from the State Crime Records Bureau and the respective police stations by referring to the filed first information reports (FIRs). The collected crash data 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 1100 crash data were collected from 20 roundabouts. 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 the required variables were extracted from that software. Further, a video graphic survey was also conducted at each roundabout at different time slots to get the mixed traffic-flow related information.

5. Analysis and Results

5.1 Development of Safety Performance Function

A negative binomial model (NB) with log-link function was used to develop a safety performance function. The model includes the number of crashes deliberated as the dependent variable, and geometric elements, environmental factors, and traffic characteristics as the independent variables. A Pearson correlation matrix developed to check the relationships between independent and dependent variables. The statistically significant variables (If the correlation coefficient is greater than 0.5 and P-value less than 0.05), which do not exhibit multicollinearity (Variance Inflation Factor>10, Tolerance <1) were considered for the model development. The model estimates results are shown in below tables 1 and 2. The roundabout SPFs are divided into two categories for in-depth understanding of traffic characteristics, environmental factors and geometric elements and their influence on the roundabout's safety performance. The different models considered are for: I) Entering approach level, II) the whole roundabout (Intersection level).

5.2 SPFs at Entry Approach Level

While considering the roundabout at entering approach level, the results found that average daily traffic at junction, entry angle, exit radius, weaving length, inscribed circle diameter, and road lane marking are significantly contributed to the crash occurrence. The estimation results are shown in Table 1. A greater exit radius was more associated with higher crash risk at roundabouts approaches. However, with significant pedestrian traffic across

Table 1: Estimates of Safety Performance Function Models for entry approach

Category wise SPFs	Parameters	Coefficients	St. Error	t-Stat.	Sig:
Entry Approach level	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
Approach level 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 and MAD	0.14 & 0.31			

Note: *Significant at 95% confidence level**; Akaike's Information Criterion (AIC), Mean squared prediction error (MSPE), Mean absolute deviation (MAD)*

the exit road, the radii could be provided more or less similar to entry radii. Accordingly, we can reduce the speed reasonably. In other words, we can say that, if the traffic is medium or low, most of the drivers drive vehicles at high speed even if road condition was good or not. It led to more accidents at approaches. Further, the presence of proper road lane markings was also negatively influencing the crash occurrences. Suppose at present road lane marking condition is good, most of the drivers may wish to drive at their desired speed (driver behaviour will change depending upon the situations) without considering traffic rules and regulations (this result might be controversial since road condition was not good). While considering the inscribed circle diameter of a roundabout, if the diameter of the circle is reduced, the crash occurrence at the roundabout increases. Thereby, diminishing the roundabout safety. In other words we can say that for safer movement, a wider inscribed circle diameter is preferable. Accordingly, we can reduce traffic congestion and ensure smooth traffic flow through the roundabout. 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 increases. Due to the wider weaving length, most of the vehicles attempted to close to pass each other, resulting in increased crash risk due to negligent driver behavior. During the design stage, it is necessary to limit the maximum weaving length to discourage speeding. The entry angle serves as a geometric proxy for the conflict angle between entering and circulating traffic streams. While considering the entry angle, a large entry angle was associated with higher entry speeds, and it caused more crashes at the roundabout entering-circulating areas.The goodness of fit of approach level model was investigated using AIC, ρ^2 statistic, deviance, and Pearson Chi-Square statistics. The obtained results of this model were 473.31,0.11,1.15 and 1.03 respectively. Models having smaller AIC values perform better, and this model's dispersion (0.40) parameter was significantly different from zero. Overall, it indicates that 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. This shows that the model has produced reasonably good predictive performance.

5.3 SPFs at Intersection Level

The intersection level SPFs were developed and estimated safety performance function as publlished in table 2. The obtained results indicated that average daily traffic at the junction, number of circulatory lanes, percentage of

Table 2: Estimates of Safety Performance Function Models for Intersection level

Category wise SPFs	Parameters	Coefficients	St. Error	t-Stat.	Sig:
Intersection level	Constant	2.533	-	-	-
	Average daily traffic at junction (ADT-JN) **	0.441	0.133	3.31	*0.001*
	Two-Wheeler (%) (TW) **	3.09	1.57	1.96	*0.050*
	Number of circulatory lane (NCL)**	-1.02	0.36	-2.83	*0.005*
	Heavy vehicle (%) (HV)*	7.74	4.57	1.69	*0.09*
Intersection level Goodness' of fit & Validation	Dispersion parameter		0.207		
	log-likelihood ratio (ρ^2)		0.10		
	Deviance & Pearson Chi-Square		1.4 & 1.39		
	AIC		*213.35*		
	MSPE and MAD		0.94 & 1.1		

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

two-wheeler (TW) and heavy vehicles (HV-bus and trucks) mainly contributes to the crashes at roundabouts. However, it can also be noticed that the parameters such as the 2W and HV highly impact on the accidents occurring at roundabouts. Results obtained from the preliminary analysis showed that the percentage of TW was dominant in all the roundabouts. Mostly TW were considered a vulnerable vehicle class component; it has high manoeuvrability power and filtering behaviour. It may be due to more accidents at junctions because of the complex traffic behaviour at roundabouts. Traffic volume was the most important factor in road safety studies [23]. In this study, increasing the average daily traffic at the junction will likely increase the crash risk at roundabout intersections. Even though the high traffic flow conditions at the junction, the vehicle cannot manoeuvre/move properly to inside the roundabouts because of geometric constraints.it will also lead to minor accidents. The other reason for a crash occurring at roundabout might be night visibility of roads, no proper signboard, human error including late reaction time, inadequate brake pedal force application, misapplication of accelerator/brake pedal, etc. Here, best fit is based on AIC, and ρ^2 statistic. The dispersion parameter of this model was 0.207. The deviance and Pearson Chi-Square statistics were estimated as 1.4 and 1.39 for this model. Finally, validation was done based on 10 percentage of the remaining data set. The smaller MAD (1.1) and MSPE (0.94) value generally refers to lower prediction error. This shows that the model has produced reasonably good predictive performance.

6. Conclusions

The present study developed performance measures for the safety evaluation of roundabouts considering geometric elements, traffic characteristics, and historical crash occurrence data. A negative binomial model with a log link function was used to estimate the model parameters. The results were found that the percentage of two-wheelers, percentage of heavy vehicles, average daily traffic at the junction, entry angle, and weaving length, number of circulatory lanes, inscribed circle diameter, and presence of road lane marking significantly contributes to the crash occurrence at the roundabout vicinity. Average daily traffic was the most influencing factors across the entire roundabout vicinity. The impact of some of the risk factors on accidents varies significantly across developed models. Goodness-of-fit was investigated using AIC, ρ^2 statistic, deviance, and Pearson chi-square statistics. Performance evaluation of the model was estimated based on MAD and MSPE indicators, respectively. The potential contributions of this study can be two-fold. First, this study gives an in-depth analysis of roundabout safety issues in developing countries like India. Studies conducted in western countries on roundabout study are in the area of crash prediction models based on crash data. These findings may not be directly transferable to other countries with heterogeneous traffic environments. Second, the study's findings support the need to relook at design parameters for better movement at the roundabouts, thereby improving the existing facilities to enhance road users' safety. The proposed SPFs tool will help engineers to examine the safety treatments of roundabouts in terms of design adequacy, quantifying the crash contributing factors, and future crash predictions.

Acknowledgment

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 data set to support the research work.

References

1. MoRTH-2019, Study on Road Accidents in India, Ministry of Road Transport and Highways (MoRTH), 2019. Transport Research Wing, New Delhi, India.
2. Polus, A., Shiftan, Y., and Shmueli-Lazar, S., Evaluation of the waiting-time effect on critical gaps at roundabouts by a logit model. European Journal of Transport and Infrastructure Research, 2005. 5(1): p.1-12.
3. Montella, Identifying Crash Contributory Factors at Urban Roundabouts and Using Association Rules to Explore Their Relationships to Different Crash Types. Accident Analysis and Prevention, 2011. 43 (4).
4. Highway Capacity Manual, Transportation Research Board of the National Academies, 2010. Washington, D.C.
5. Indian Highway Capacity Manual (Indo-HCM). 2017. Council of Scientific and Industrial Research. Central Road Research Institute, 2017. New Delhi.
6. Indian Roads Congress (IRC)-65. Guidelines for Planning and Design of Roundabouts. First Revision, 2017. New Delhi.
7. Sonu, M., Dhamaniya, A., Arkatkar, S. and Joshi, G, Time occupancy as measure of PCU at four legged roundabouts. Transportation Letters, 2016. p.1-12.
8. Bauer, K.M. and Harwood, D.W., Statistical Models of At-Grade Intersection Accidents, 2000. Addendum (No. PUBLICATION NO. FHWA-RD-99-094). United States. Federal Highway Administration.
9. Wong, S.C., Sze, N.N. and Li, Y.C., Contributory factors to traffic crashes at signalized intersections in Hong Kong. Accident Analysis & Prevention, 2007. 39(6): p.1107-1113.
10. Yan, X., Radwan, E., and Abdel-Aty, M., Characteristics of rear-end accidents at signalized intersections using multiple logistic regression model. Accident Analysis & Prevention, 2005. 37(6): p.983-995.
11. Kumara, S.S.P. and Chin, H.C., Modelling accident occurrence at signalized tee intersections with special emphasis on excess zeros. Traffic injury prevention, 2003. 4(1): p.53-57.
12. Kennedy, J., Peirce, J., and Summersgill, I., Review of accident research at roundabouts. Transportation research circular, (E-C083), 2005.
13. Arndt, O., and Troutbeck, R.J., Relationship between roundabout geometry and accident rates. Transportation research circular, (E-C003), 1998. p.28-1.
14. Dixon, K., and J. Zheng., Developing Safety Performance Measures for Roundabout Applications in the State of Oregon, 2013. Final Report, SPR 733, Oregon Department of Transportation, Salem, Oregon, and FHWAOR- RD-13-08, Federal Highway Administration, Washington, D.C.
15. Bagdade, J., B. N. Persaud, K. McIntosh, J. Yassin, C. A. Lyon, C. Redinger, J. Whitten, and W. A. Butch., Evaluating the Performance and Safety Effectiveness of Roundabouts. Michigan Department of Transportation, 2011. Report No. RC-1566, Lansing, Mich.
16. Rodegerdts, L., M. Blogg, E. Wemple, E. Myers, M. Kyte, M. Dixon, G. List, A. Flannery, R. Troutbeck, W. Brilon, N. Wu, B. Persaud, C. Lyon, D. Harkey, and D. Carter., Roundabouts in the United States, 2007. NCHRP Report 572: Transportation Research Board of the National Academies, Washington, D.C.
17. Kamla, J., Parry, T., and Dawson, A. Roundabout accident prediction model: random-parameter negative binomial Approach. Transportation Research Record, 2016. 2585: 11-19.
18. Al-Marafi, M.N., Somasundaraswaran, K., and Ayers, R., Developing crash modification factors for roundabouts using a cross-sectional method. Journal of traffic and transportation engineering (English edition), 2020. 7(3): p.362-374.
19. Novák, J., Ambros, J. and Frič, J., How roundabout entry design parameters influence safety. Transportation research record, 2018. 2672(34): p.73-84.
20. Maycock, G., and Hall, R. D., Accidents at four arm roundabouts, 1984. Rep. 1120, Transport and Road Research Laboratory, Berks, U.K.
21. Harper, N. J., and R. C. M. Dunn., Accident Prediction Models at Roundabouts, 2005. Proceedings of the 75th ITE Annual Meeting, Melbourne, Australia.
22. Turner, S. A., A. P. Roozenburg., and A. W. Smith., Roundabout Crash Prediction Models, 2009. NZ Transport Agency Research Report 386. Wellington, New Zealand.
23. Anjana, S., and M. V. L. R. Anjaneyulu., Development of Safety Performance Measures for Urban Roundabouts in India. Journal of Transportation Engineering, 2015. 141 (1): 4014066.
24. Kim, S., Choi, J., Safety analysis of roundabout designs based on geometric and speed characteristics. KSCE Journal of Civil Engineering, 2013. 17 (6): p.1446-1454.
25. Lord, D., & Mannering, F., The statistical analysis of crash-frequency data: A review and assessment of methodological alternatives. Transportation Research Part A: Policy and Practice, 2010. 44(5): p. 291–305.
26. Washington, S. P., M. G. Karlaftis, and F. L. Mannering., Statistical and Econometric Methods for Transportation Data Analysis, 2nd edition. 2011: Chapman and Hall/CRC, Boca Raton, Fla.