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MODELLING THE ENTRY CAPACITY REDUCTION FACTOR AND PEDESTRIAN MOVEMENT ANALYSIS AT ROUNDABOUTS: A CASE STUDY OF TIER-II CITIES IN INDIA

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Abstract

The present study is aimed at developing an entry capacity reduction factor model for roundabouts in developing countries. The study covers four Tier-II cities in India, namely, Ranchi, Rourkela, Bhubaneswar, and Nagpur. The explanatory variables are: the circulating vehicular traffic flow, pedestrian flow, and the diameter of the central island. A multiple non-linear regression (MNLR) analysis was utilised; it has an R^2 of 0.946 and 0.961 for the development and validation of the model. With an increase in influencing variable levels such as circulating vehicular traffic flow by [(50, 100, and 150) PCU/hr], pedestrian flow by [(50, 100, and 150) Ped/hr], and the diameter of central island by [10,20,30) m]; the Capacity Reduction Factor rises by (15%, 30% & 35%), (10%, 15% & 20%) and (25%, 35% & 45%) respectively. Further, the Equilibrium Probability Method (EPM) has been employed to analyse pedestrian movement patterns at roundabouts while they are crossing the streets. 'Children' and 'Seniors' cross the street almost at the same speed, but more slowly than 'Young People'. The study could be helpful for the operational evaluation of roundabouts by incorporating pedestrian behaviour.

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Key words

- Roundabout,
- Capacity Reduction Factor,
- Circulating Vehicular Traffic Flow,
- Pedestrian Flow,
- MNLR analysis,
- EPM approach.

1 INTRODUCTION

Developing countries like India are experiencing rapid urbanisation in Tier-II cities, leading to a significant reliance on motorised vehicles for mobility. The Roundabouts are a prominent transportation infrastructure where motorized vehicles have a complete spatial advantage to perform efficient manoeuvres. Nevertheless, pedestrian activity along and across roundabout premises often disrupts the streamlined flow of vehicles. Thus, roundabouts cannot accommodate the intended number of vehicles. In a city with a diverse land use pattern, its traffic is likely to be heterogeneous, with a wide range of vehicles exhibiting static and dynamic features. Narrow-width vehicles and small vehicles such as two-wheelers consistently look for lateral and longitudinal gaps between wide vehicles. Consequently, heterogenous traffic flow conditions more efficiently utilize space for motorised traffic than homogenous conditions. However, essential utilities such as lane markings, zebra crossings, refuge islands, and grade-separated sidewalks are lacking. In such congested traffic, pedestrians rarely have adequate space for getting around and crossing the street. Hence, an attempt has been made to assess pedestrian crossing behaviour at roundabouts.

Capacity at a roundabout has been evaluated through gap acceptance and empirical methods. Traffic flow and geometric variables were considered by the two existing methodologies to infer the influence factor, regardless of pedestrian activity. The reduction in roundabout capacity attributed to frequent pedestrian interruptions needs an in-depth study. When scrutinizing the existing literature, it has been observed that limited research has been conducted in this regard in a developing country such as India. The primary objective of this study is to develop a methodology that can be used to estimate the reduction in entry capacity of roundabouts because of pedestrian interruptions to the normal flow of traffic. The present study highlights the extent of the impact of pedestrian activity on a roundabout's capacity.

The present study has been carried out in two steps. In the first step, employing a Multiple Non-Linear Regression (MNLR) analysis for modelling the capacity reduction factor by integrating two factors i.e. the circulating vehicular traffic flow and the diameter of the central island, with additional pedestrian factors that influence the roundabout's capacity. In subsequent steps, the gap acceptance theory, i.e., the Equilibrium Probability Method (EPM), was considered to assess the behaviour of pedestrians. Moreover, the data splitting method and error measuring variables technique were employed in the model's validation process to observe the predicted performance of a new model that could be applied to new data sets. Four roundabouts in four cities (Bhubaneswar, Ranchi, Nagpur, Rourkela) in India are considered for the study.

The paper consists of six sections: the first provides an overview of the research. Section 2 describes a detailed literature review regarding various aspects relating to the effect of pedestrians at the roundabout. The subsequent section addresses the location of the study area and the data collection process. The methodology adopted for modelling the capacity reduction factor considering the impact of the pedestrian is developed in section 4. The results and discussion are described in section 5. The final section of this study i.e., section 6, contains the summary and conclusion.

2 REVIEW OF THE LITERATURE

The effect of the entry of pedestrians on a roundabout's capacity reduction has garnered relatively little attention. The queuing theory was used to develop a capacity reduction factor model for crosswalks and entry flow at roundabouts under the influence of pedestrians (Marlow and Maycock 1982). The model assumed that pedestrian flow has a priority over motorised vehicles (Griffiths 1981). The capacity reduction factor is additionally evaluated as a function of the circulating traffic and pedestrian flow (Brilon et al. 1993). Using gap acceptance theory, a microscopic simulation model for assessing the effect of a roundabout on vehicular traffic indicated that pedestrian delays increase nonlinearly with the volume of vehicles (Rouphail et al. 2005). The capacity of a roundabout is evaluated in light of pedestrian and vehicle interactions, including situations where pedestrians yield to vehicles and instances where vehicles yield to pedestrians (Rodegerdts and Blackwelder 2005). The effect of pedestrian volume and crosswalk-yield line distances on roundabout capacity was studied by Duran (2010). Cyclists and pedestrians close to roundabout intersections can impede the roundabout's effectiveness and make it difficult for analytical traffic models to determine its level of service (Bergman et al. 2011). Pedestrian impedance appears to be dependent on the following factors while traversing a multilane roundabout: conflict area, vehicle speed, pedestrian walking speed, pedestrian behaviour, pedestrian route selection decisions, and vehicle turning movements (Schroeder et al. 2012). Pedestrian movements, splitter islands in roundabout intersections, and vehicle queues at downstream exits were even considered to assess roundabout entry capacity (Kang and Nakamura 2014).

A regression analysis for the Level of Service (LOS) model analysed pedestrian perceptions on urban arterial routes and characteristics such as age, gender, walking experience, and residence location (Petritsch et al. 2007). The impact of guardrails on crossing behaviours of pedestrians on roundabouts varied by type of guardrail, traffic volume, anticipated age group, gender, road type, and crosswalk style (Cohen et al. 2013). A logistic regression model for signalised intersections was constructed by analysing pedestrian crossing behaviours such as their passing through speed, awareness of signals, and pedestrian-vehicle interactions (Marisamynathan and Perumal 2014). A roundabout with a slip lane enhances traffic flow, speeds up the right turn, and lowers conflicts. A microscopic multimodal traffic flow simulation software such as PTV VISSIM is used and its simulations show that pedestrians incur the most delay in free-flow slip lanes at higher traffic volumes (Al-Ghandour et al. 2012). Analyses of pedestrian behaviour at signalised intersections indicate that group pedestrians move at a slower pace i.e. they have a lower value of average and 15th percentile speeds than the individuals. The findings also suggest that crossing alongside or against other pedestrians affects pedestrian crossing speeds (Shaaban 2019).

In consideration of pedestrian safety, a study conducted on visually impaired pedestrians indicates that they overlook more crossing opportunities and make riskier decisions than sighted pedestrians (Ashmead et al. 2005). A Stated Preference (SP) survey was used in another study to examine pedestrian preferences at roundabouts, and results showed that perception of a pedestrian, vehicle speeds, traffic volume, and pedestrian island all affect pedestrian preferences. (Perdomo et al. 2014). Crossing times increased slightly while reaction times increased by 84% when pedestrians were distracted by their phones while crossing a road at roundabouts (Gruden et al. 2021). The result of a driver's reaction time in traffic showed that longer reaction times lead to higher capacity declines (Calvert et al. 2018). The driver's reaction was significantly determined by the moment the pedestrian arrived and the driver's field of vision (Dozza et al. 2020). The average travel time delay varied with a pedestrian's age and gender and ascended linearly with pedestrian volume in unsignalized and mid-block sections (Govinda et al. 2020).

In accordance with the Highway Capacity Manual (HCM 2010), the pedestrian-vehicle interaction model can serve as a variant to deterministic roundabout analysis methods. From a review of the pertinent literature, it can be inferred that pedestrian and vehicular flows, as well as geometric variables, have a significant impact on the entrance capacity of roundabouts. Therefore, the study is framed to assess pedestrian crossing behaviour and to develop the capacity reduction factor at roundabouts for developing countries.

3 STUDY AREA AND DATA COLLECTION

Traffic flow and road design parameters of four roundabouts in India have been used to model the entry capacity reduction factor of roundabouts under heterogeneous traffic flow conditions in developing countries. Such roundabouts are Albert Ekka Square (Ranchi, Jharkhand), Master Canteen Square (Bhubaneswar, Odisha), Birsa Square (Rourkela, Odisha) and Medical Square (Nagpur, Maharashtra), as depicted in Fig. 1. These roundabouts have strategic significance and are influenced by commercial, industrial, residential, and municipal offices, while remaining unaffected by heavy vehicles during peak hours. The circulating and entrance stream approaches to these roundabouts consist of two lanes. Two high-resolution cameras on a tripod were used to record the video data clearly for the simplified collection of data sets at the sites. A significant and reliable data set was gathered during peak morning hours (9:00 a.m. - 11:00 a.m.) and evening hours (5:00 p.m. – 7:00 p.m.) of the traffic flow. The geometric parameters of the roundabout depicted in Fig. 2 are measured with measuring tape in the early morning hours to avoid traffic congestion. The following aspects were considered throughout the site observations:

- **i)** Congestion of vehicles at the entrance of the roundabout due to high traffic volume.
- **ii)** Moderate to large number of vehicles in the circulating flow of a roundabout.
- **iii)** Variation in pedestrian counts, each of which presents a unique obstacle for vehicles navigating in the circulating flow.
- **iv)** Vehicles manoeuvring in the circulation zone arrive at the roundabout's potential conflict points.
- **v)** Vehicles proceeding through the route of the exit path in a roundabout.
- **vi)** Classification of vehicle (two-wheeler, standard or large cars, three-wheeler, etc.)
- **vii)** Conflicts occurring during pedestrian entries and exits.

The recorded videos were observed on large screen monitors to distinguish the circulating vehicular traffic flow from the pedestrian flow to obtain the entry capacity reduction factor. The circulating vehicular traffic flow, pedestrian flow, number of approach legs, and the central island's diameter of these roundabouts are presented in Tab. 1.

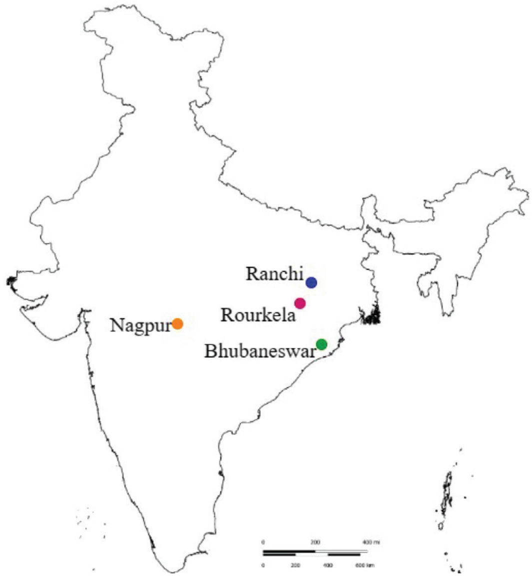

Fig. 1 *Location of the Study Area*

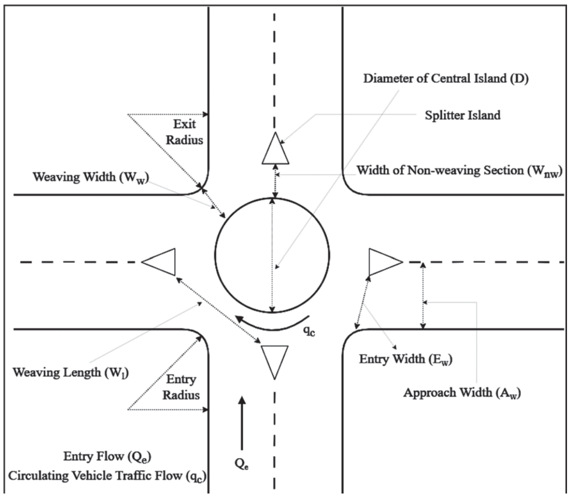

Fig. 2 *Geometric Parameters of a Roundabout*

4 METHODOLOGY

The methodology section is composed of two parts. The first part describes the development of the capacity reduction factor of the roundabouts, while the crossing behaviour of pedestrians is discussed in the second part.

4.1 Capacity Reduction Factor of Roundabouts

In heterogeneous traffic flow conditions, there is a composition of different types of vehicles with varying manoeuvrability skills, and the pedestrian impact is notably influential at the roundabouts. Vehicle space is occupied by the substantial movement of pedestrians at the roundabout, which consequently affects its capacity. As to what extent, the impact of the pedestrians affects the capacity of roundabouts, the assumption regarding the entry capacity of a roundabout considering pedestrians is provided in Equation 1.

$$Q_{max} = q_{max} \times F \tag{1}$$

Where, Q_{max} = Reduction of entry capacity of a roundabout while considering pedestrians.

q_{max} = Maximum entry capacity at a roundabout without considering pedestrians.

F = Entrance capacity reduction factor.

The entrance capacity reduction factor based on the percentage of space occupied by pedestrians is represented by Equations 2 and 3 (Meneguzzer and Rossi 2013).

$$P_{occ} = 0.0052\, v_p{}^{0.699} \tag{2}$$

$$M = \sqrt{(1 - P_{occ})} \tag{3}$$

Tab. 1 *Traffic Flow and Geometric Variables Measured at Roundabouts*

Roundabout	Approach Leg	Circulating Vehicle Traffic Flow (PCU/h)	Pedestrian Volume (Ped/h)	Diameter of Central Island (m)
Albert Ekka Square, Ranchi	Leg1	436	150	10.76
	Leg2	290	130	
	Leg3	257	122	
Master Canteen Square, Bhubaneswar	Leg1	882	252	46.87
	Leg2	789	254	
	Leg3	760	280	
	Leg 4	533	198	
Birsa Square, Rourkela	Leg1	394	192	44.21
	Leg2	773	245	
	Leg3	711	262	
	Leg4	411	276	
Medical Square, Nagpur	Leg1	686	282	41.22
	Leg2	483	231	
	Leg3	993	298	
	Leg4	554	223	
	Leg5	432	268	
	Leg6	508	122	

where, v_p = Pedestrian volume (Ped/h)
P_{occ} = Pedestrian occupancy
M = Entry capacity reduction factor

In order to develop a traffic model for roundabouts using a MNLR Analysis, it is necessary to collect data on an array of traffic-influencing factors, including entrance and exit flows, the roundabout's geometry, and pedestrian movements. Subsequently, these data undergo an analysis employing non-linear regression techniques to ascertain the correlation between these characteristics and traffic performance measures such as capacity, delay, and queuing. Iterative modelling assesses parameters such as the entry volume, circulating flow, and size of the roundabout, allowing planners to estimate roundabout performance under different conditions and to optimize designs for efficient traffic flow (Patnaik et al. 2018). The present study focuses on pedestrian occupancy in the vicinity of roundabouts while formulating the entry capacity reduction factor. However, the entry capacity reduction factor is dependent on other variables, such as the circulating vehicular traffic flow, pedestrian flow, and geometric variables, as assessed by the study. Hence, the study has been carried out by applying an empirical approach as an MNLR analysis to develop the entry capacity reduction factor model as a function of the circulating vehicular traffic flow, pedestrian volume and geometric variables, i.e., the diameter of the central island at the roundabout.

4.2 Pedestrian Movement Patterns at Roundabouts

In areas where pedestrian crossings are not available, pedestrians have to cross the roundabout while interacting with passing vehicles. The intricacy and adaptability of pedestrian behaviour at roundabouts are more evident than that of vehicles when traffic signals and markers are absent (Bari and Dhamaniya 2022). Even at unsignalized intersections, pedestrian crossing behaviour is examined and classified into four stages such as one stage, two-stage, in-perpendicular directions, and in-oblique directions (Jain et al. 2014). The Gap Acceptance theory is a fundamental concept used in traffic flow analysis, particularly at crossings and merging points where vehicles have to determine the optimal moment to enter a traffic stream. The theory examines the actions of drivers when they encounter gaps (i.e. in terms of time or distance) in traffic that enable them to enter or cross the flow of vehicles without any risk. The fundamental concept is that a driver assesses the extent of gaps in the flow of traffic (between two successive vehicles) and determines whether to accept or decline the gap considering whether it is suitable to proceed safely. The accepted gap refers to the situation when the driver perceives the gap between vehicles as sufficiently large to safely perform the desired manoeuvre and proceeds accordingly. On the other hand, the rejected gap occurs when the driver feels the gap between vehicles is too small or unsafe to proceed, leading them to reject it and wait for a larger gap. The present research primarily observes gap acceptance behaviour to quantify the impact of crossing pedestrians on motorised vehicles. As a consequence, pedestrians are classified into three distinct groups of ages. Those under the age of 15 (commonly referred to as 'children'), those between the ages of 15 and 45 ('Young People'), and those older than 45 ('Seniors') make up the three categories of pedestrians. Here, the gap acceptance theory, i.e., the Equilibrium Probability Method (EPM) was considered to assess the behaviour of pedestrians.

4.2.1 Equilibrium of Probability Method (EPM)

The microscopic equilibrium of the accepted gap [$Fa(t)$] and rejected gap [$Fr(t)$] is considered in this analysis (Wu 2012). The observed probability of not being accepted with the gap length of time "t" is taken as [$1 - Fa(t)$] and the observed probability of not being rejected with the gap length of time "t" is taken as [$1 - Fr(t)$]. The critical gap that is to be estimated is written as $F_{tc}(t_j)$.

The critical gap $F_{tc}(t_j)$ and frequency of critical gap $P_{tc}(t_j)$ is estimated as in Equations 4 and 5 respectively.

$$F_{tc}(t_j) = \frac{Fa(t_j)}{Fa(t_j)+1-Fr(t_j).} \quad (4)$$

$$P_{tc}(t_j) = F_{tc}(t_j) - F_{tc}(t_{j-1}) \quad (5)$$

Finally, an average value of the critical gap $t_{c,avg}$ can be estimated by a summation of the multiplication of the time gap and the frequency of the critical gap as per Equation 6.

$$t_{c,avg} = \sum(t_{dj} * P_{tc}(t_j)) \quad (6)$$

where, $t_{dj} = \frac{t_j + t_{j-1}}{2}$

Further, the graph is plotted on the rejected gap, accepted gap, and the critical gap to a time interval (seconds); the critical gap should lie between an accepted gap and a rejected gap.

5 RESULTS AND DISCUSSION

5.1 Model Development

Empirical modelling was adopted by employing regression analysis to study the entry capacity reduction factor of roundabouts. A preliminary assessment regarding the model's development should determine the dependency of independent variables with the dependent variables meaning up to what extent the variables are correlated. As a result, it is determined from all roundabout entries that the capacity reduction factor (a variable on the y-axis) varies to the power of circulating vehicular traffic flow and pedestrian flow (different set of variables on the x-axis) with coefficients of determination (R^2) values of 0.875 and 0.685, respectively, as depicted in Figs. 4(a) and 4(b). It has additionally been found that the capacity reduction factor varies exponentially with the diameter of the central island for which R^2 equals 0.649, indicating that it best fits the capacity reduction factor as shown in Fig. 4(c). Henceforth, considering the above three variables such as the circulating vehicular traffic flow, pedestrian flow, and diameter of the central island, the MNLR analysis is utilized to develop a new capacity reduction factor model. Geometric variables such as the approach width, entry width, weaving length, weaving width, and width of the non-weaving section did not show any significant relationship with the capacity reduction factor. Hence, these variables are ignored for the study.

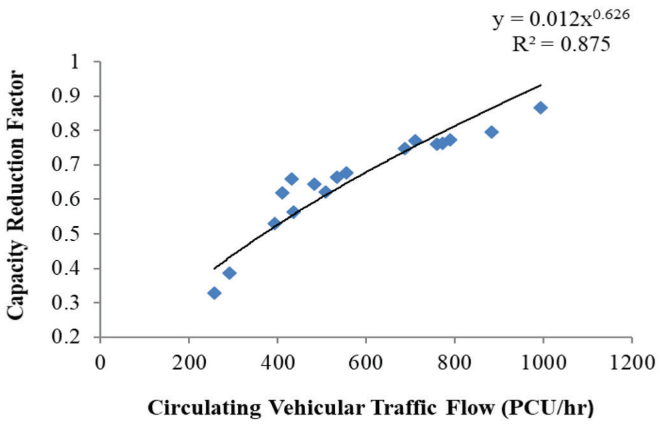

Fig. 4 (a) *Capacity Reduction Factor Variation with Circulating Vehicular Traffic Flow*

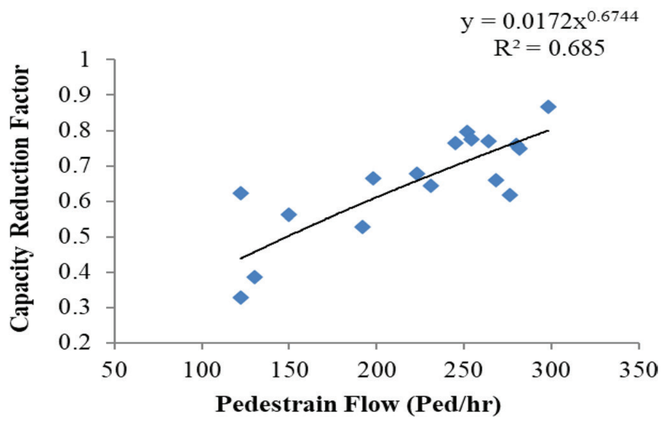

Fig. 4 (b) *Capacity Reduction Factor Variation with Pedestrian Flow*

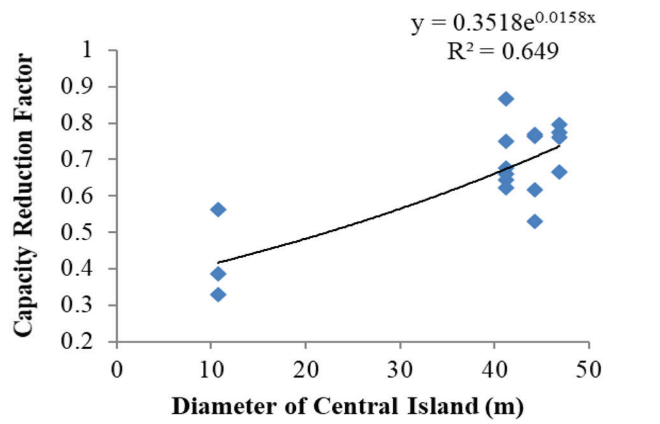

Fig. 4 (c) *Capacity Reduction Factor Variation with the Diameter of the Central Island*

For modelling the entry capacity reduction factor, independent variables such as the circulating vehicular traffic flow and pedestrian flow are measured on a logarithmic scale, while the diameter of the central island is measured on a linear scale; the dependent variable (capacity reduction factor) is measured on a logarithmic scale. After the regression analysis, Equation 7 was found to be best fitted by considering all the variables together. Descriptive statistics of the variables used in the model's development showing several data samples (N) and their mean and standard deviations is represented in Tab. 2.

$$F = 0.00130 \times C_f^{\,0.413} \times P_f^{\,0.439} \times e^{0.004D} \quad [R^2 = 0.94] \tag{7}$$

where, F = Entry capacity reduction factor
C_f = Circulating vehicular traffic flow (PCU/hr)
P_f = Pedestrian flow (Ped/hr)
D = Diameter of central island (m)

Tab. 2 *Descriptive Statistics of Variables Used in the Model's Development*

Specifics	Mean	Standard deviation	Number of samples (N)
ln *F*	0.4472	0.256	17
ln C_f	6.30	0.383	17
ln P_f	6.94	0.117	17
D	37.87	13.12	17

The Pearson correlation coefficient measures the linear dependence among the variables, thereby defining the sample's correlation. The Pearson correlation is obtained using Equation 8. The values close to '-1' and '+1' in the Pearson correlation indicate a significant relationship between the two variables. It was seen from the analysis that the correlation between the variables ranges between 68% to 93%, which appears to be good for the model's development; it is presented in Tab. 3. The significance of a correlation is measured against the possibility that it was merely coincidental. It can be observed in Tab. 3 that the significant values of the various variables in the model are all less than 5%, indicating that the chance of occurrence is no more than 5 out of 100.

$$r = \frac{N\sum xy - (\sum x \times \sum y)}{[N\sum x^2 - (\sum x)^2] \times [N\sum y^2 - (\sum y)^2]} \tag{8}$$

where,
N = Number of paired variables.
$\sum xy$ = Sum of products of paired variables.
$\sum x$ = Sum of x variables.
$\sum y$ = Sum of y variables.
$\sum x^2$ = Sum of squared of x variables.
$\sum y^2$ = Sum of squared of y variables.

Tab. 3 *Correlation among Variables after Regression*

Specifics		In *F*	In C_f	In P_f	*D*
Pearson Correlation	In *F*	1.000			
	In C_f	.936	1.000		
	In P_f	.828	.724	1.000	
	D	.806	.688	.689	1.000
Significant Value	In *F*	-			
	In C_f	.001	-		
	In P_f	000	.001	-	
	D	000	.001	.001	-

The statistical characteristics of the capacity reduction factor model are detailed in Tab. 4, and the model is significant at the 95% confidence level if all the constituent variables are considered altogether. The R^2 of the capacity reduction factor model is 0.946. The R^2 represents the linear relationship between the dependent and independent variables. The larger the R^2 value, the better will be the fitness of the model. The analysis of variance (ANOVA) tests the reliability of a model statistically. The model's significance level, which is less than 0.05, is 0. Thus, the model is significant by considering all the variables together in detail, as given in Tab. 4. After the regression analysis, different statistical tests, such as standard error, t-statistics, and measures of significance, were developed. The standard error is the average deviation of the input value from the regression line, which provides insight into the accuracy of the regression model constructed by considering the response variable. A smaller value gives a better result because it indicates that the input that was taken to develop the model is closer to the regression line. From Tab. 4, it is clear that the standard error for different variables is nearly equal to zero. Hence the three variables which have been taken in the model's development contributed with a fair degree of accuracy in the prediction process. The *t*-statistic values vary for each case since they are calculated by dividing the coefficient by the standard error of the regression variables included in the model. It follows that the t-statistic value listed in Tab. 4 is equally important for creating the model, considering the significance of the standard error. From Tab. 4, it is observed that all the significant values for the different variables are less than 5%. Hence the new model is far more reliable.

As indicated in Tab. 4, three influential variables, consisting of the circulating vehicular traffic flow (C_f), pedestrian flow (P_f) and the diameter of the central island (D) were found to have measured values of 0, 0.043, and 0.035, respectively, thereby satisfying the significance criteria of being less than 0.05. Thus, the model is shown to be statistically significant, and the analysis reveals that the circulating flow () is the most influential of the three existing variables in the proposed model.

5.2 Assessment of the Significance of the Model

The proposed model's predictive ability is measured throughout the training and testing phase by employing five statistical parameters. The detailed results of the statistical parameters such as the Nash–Sutcliffe coefficient (E), Average-Absolute Error (AAE), Root Mean-Square Error (RMSE), Mean (μ), and Standard deviation (σ) are set out in Tab. 5. The 'E' values are found to be greater than 0.8 which denotes that proposed model is statistical fit. In addition, the 'μ' and 'σ' values tend towards '1' and '0' respectively, implying the better fitness of the model.

Tab. 5 *Model Significance Test*

Specifics	E	AAE	RMSE	μ	σ
Training Data	0.84	279.78	358.08	1.11	0.22
Testing Data	0.81	207.13	294.61	0.96	0.16

The Model's validation involves deciding if the numerical findings measuring the derived relationships between the variables obtained through the regression analysis are appropriate as representations of the data. It serves to evaluate the perfor-

Tab. 4 *Statistical Characteristics of the Entry Capacity Reduction Factor Model*

Analysis of Variance (ANOVA)					
Model	**Sum of squares**	**Degree of freedom**	**Mean square**	**F**	**Significant value**
Regression	0.999	3	0.333		
Residual	0.057	13	0.004	76.379	0.000
Total	1.056	16	0.337		
	$R^2 = 0.946$	Adjusted $R^2 = 0.934$			

Variable Estimation by Multiple Non-Linear Regression Analysis				
Model variables	**Variable's Co-Efficient**	**Standardized Error**	**t-statistic Value**	**Significant Value**
Constant	-6.638	1.339	-4.959	0
$\ln C_f$	0.413	0.067	6.135	0
$\ln P_f$	0.493	0.22	2.243	0.043
D	0.004	0.002	2.354	0.035

mance of the model in the light of the new data. The method may also involve verifying that the regression residuals are indeed random by performing a goodness-of-fit analysis. If the model's predictive accuracy significantly declines once it is applied to a new data set, the model's estimation is invalid for the study.

In the present study, the data set is sliced into two sets, and the data splitting approach is used to validate the model. The first set is used for the model's creation, while the latter is utilised to validate the model by measuring the prediction's accuracy. Hence, 70% of the total data are initially used for the model's development, while the remaining 30% of the data is used for the validation of the model. Thus, 30% of the data indicates that seven approach legs of four roundabouts were chosen at random from a total of 17 approach legs for the validation purposes. Further, the scatter plot was developed in between the observed capacity reduction factor obtained using Equation 3 and the predicted capacity reduction factor obtained using Equation 7 to observe the validity of the model as depicted in Fig. 5. The R^2 acquired from this validation is 0.961. Consequently, the model has been validated and found to be significant in developing countries with heterogeneous traffic flow conditions.

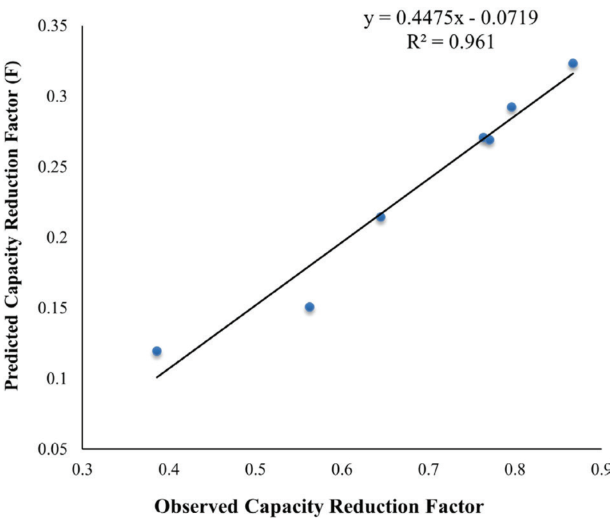

Fig. 5 *Validation of the Model*

5.3 Effect of Change in the Capacity Reduction Factor with the Influencing Variables

The three influencing variables, i.e. the circulating vehicular traffic flow, pedestrian flow, and diameter of the central Island act as major contributing variables in the determination of the roundabout capacity reduction factor. Each one of the aforementioned variables profoundly impacts the capacity reduction factor. Accordingly, the study has been conducted to observe the variation of capacity reduction factor per increase in the individual variables.

5.3.1 Variation of the Capacity Reduction Factor with Respect to the Circulating Vehicular Traffic Flow, Pedestrian Flow and Diameter of the Central Island

It has been found that the capacity reduction factor (in the y-axis) varies with the power of circulating vehicular traffic flow being a variable (in the x-axis). As illustrated in Fig. 6(a), increasing the circulating vehicular traffic flow by 50 PCU/hr, 100 PCU/hr, and 150 PCU/hr increases the predicted capacity reduction factor by 15%, 30%, and 35%, respectively. The capacity reduction factor (on the y-axis) is directly proportional to the pedestrian flow (on the x-axis) raise to a certain exponent. For a 50 Ped/hr, 100 Ped/hr, and 150 Ped/hr increase in the pedestrian movement, the predicted capacity reduction factor increases by 10%, 15%, and 20%, respectively, as depicted in Figure 6(b). The capacity reduction factor at roundabouts scales exponentially with the size of the island in the centre. As indicated in Fig. 6(c), increasing the diameter of the central island by 10 m, 20 m, and 30 m results in an increase in the predicted capacity reduction factor of 25%, 35%, and 45%, respectively.

5.4 Pedestrian Crossing Behaviour at Roundabouts

To ascertain pedestrian safety and the provision of adequate pedestrian facilities, an attempt has been made to analyze pedestrian crossing behaviour. Pedestrian safety is an important aspect of pedestrian crossing behaviour. Therefore, pedestrian crossing behaviour was observed in the traffic stream in which the Equilibrium of Probability Method (EPM) was

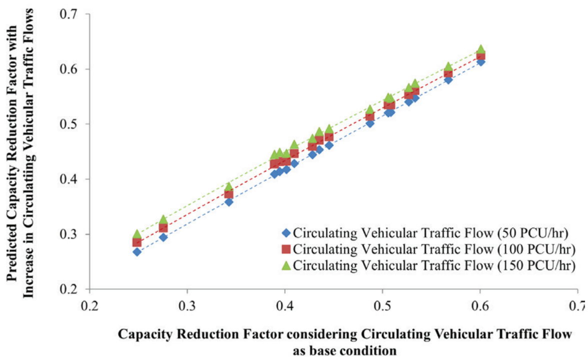

Fig. 6 (a) *Capacity Reduction Factor variation with Circulating Vehicle Traffic Flow as the base condition*

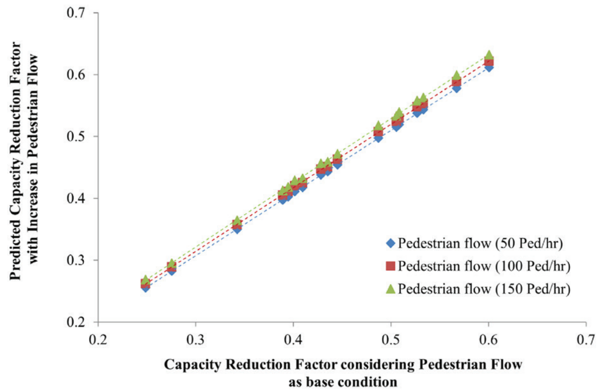

Fig. 6 (b) *Capacity Reduction Factor variation with Pedestrian Flow as the base condition*

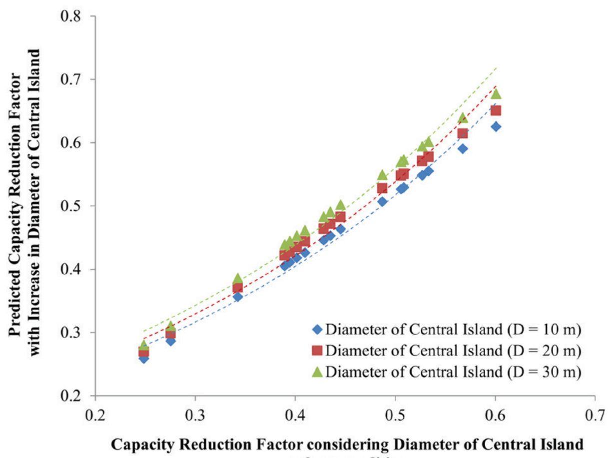

Fig. 6 (c) *Capacity Reduction Factor variation with the diameter of the central island as the base condition*

considered in this study. In general, a pedestrian crossing on a road relates to pedestrian behavioural attributes and existing traffic environments. Here, in the present study pedestrian behavioural attributes are judged through the gap acceptance behaviour (critical gap) of pedestrians and the average crossing length of pedestrians. The critical gap is defined as the least available time for which a vehicle can safely merge into the traffic stream (Mohan and Chandra 2018). Here, the critical gap of pedestrians is determined where the pedestrian intends to cross the approach lane of the roundabouts. The EPM approach was considered for calculating the critical gap as the accuracy of its measurement seemed acceptable (Sahani et al. 2018). The method considers both values of the accepted gap and rejected gap; based on the cumulative distributive functions of both gaps, finally, the critical gap values are precisely determined. Due to the considerable presence of pedestrians, the maximum likelihood method fails to determine the critical gap values because of a wide spread of accepted and rejected gaps under heterogeneous traffic conditions. In the four locations of Albert Ekka Square, Master Canteen Square, Birsa Square, and Medical Square, the critical gap of pedestrians is determined based on their respective three age groups as 'Children', 'Young People' and 'Seniors'. Considering the aforementioned three groups at Albert Ekka Square, Ranchi, the probability density functions of the critical gap lay between the functions of the accepted gap and the rejected gap, as shown in Figure 7.

According to Fig. 7, the critical gap values for Children, Young People, and Seniors in Albert Ekka Square, Ranchi were 7.64 seconds, 6.1 seconds, and 7.12 seconds, respectively. Similarly, taking into account the aforementioned three groups of pedestrians, Tab. 6 displays the critical gap values for the remaining three sites.

In assessing the mutual interaction of pedestrians and vehicles, the analysis shows that pedestrian delays grow non-linearly with the number of vehicles on the street. Moreover, the results indicate that 'Young People' takes less time than 'Children' and 'Seniors' concerning the volume of traffic at the roundabout. 'Children' and 'Seniors' cross the street at about the same speed, though at a slower pace than 'Young People'. The discrepancies in the critical gap levels are attributable to physiological factors. Regarding pedestrian-vehicle interaction, a pedestrian traverses a street in less time and with a shorter crossing distance.

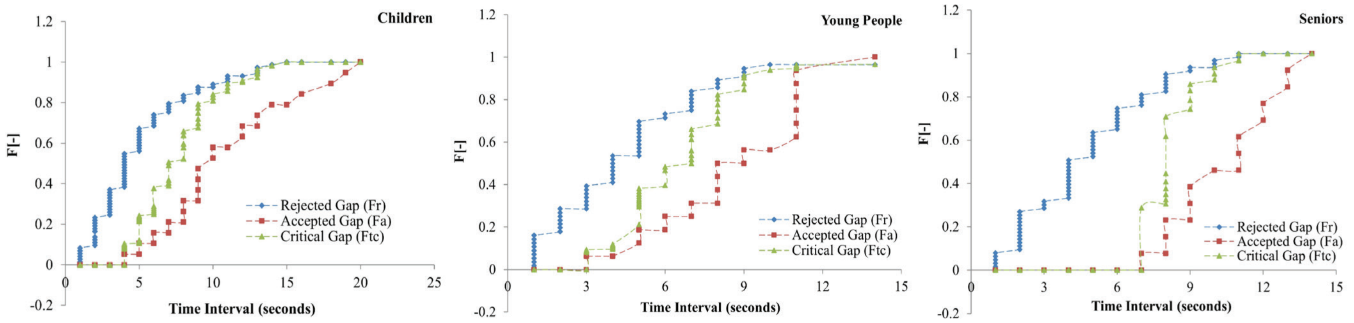

Fig. 7 *Schematic representation of accepted gap, rejected gap, and critical gap by EPM method at Albert Ekka Square, Ranchi*

Tab. 6 *Summary of the critical gap of three pedestrian groups*

Specifics	Average crossing length (m)	Critical Gap (seconds)		
		Children	Youth	Seniors
Albert Ekka Square, Ranchi	12.15	7.64	6.10	7.12
Birsa Square, Rourkela	13.49	8.64	7.14	8.16
Medical Square, Nagpur	13.18	6.68	5.58	6.46
Master Canteen Square, Bhubaneswar	21.03	8.10	6.40	7.52

6 SUMMARY AND CONCLUSION

The study was conducted in two steps. In the first step, an empirical roundabout capacity reduction factor model was developed by assuming the circulating vehicular traffic flow , pedestrian flow, and a geometric variable identified as the diameter of the central island as explanatory variables; data was collected from four cities in India, including Ranchi, Bhubaneswar, Rourkela, and Nagpur. Subsequently, the crossing behaviour was observed through the EPM method to assess the level of risk for pedestrians.

In urban centres of developing countries such as India, surplus two-wheelers, auto-rickshaws, and varied types of light motor vehicles around roundabouts contribute to circulating vehicular traffic flow. An assessment determines the capacity reduction factor's dependence on influencing variables for model development. It was found that the capacity reduction factor (in the y-axis) varies with the power of circulating vehicular traffic flow and pedestrian flow (R^2 = 0.875, 0.685) (variables in the x-axis), and exponentially with the central island's diameter (R^2 = 0.649). Considering these explanatory variables, the MNLR model was applied to develop the capacity reduction factor model under a heterogeneous traffic flow. In addition, its ability to accommodate a heterogeneous traffic flow distinguishes it from simpler models; its probabilistic approach even facilitates the estimation of an effective entrance potential, thereby leading to more accurate capacity estimates.

In the regression analysis, the Pearson correlation coefficient indicates that the correlation among the influencing variables varies from 68% to 93% respectively. The statistical characteristics of the capacity reduction factor model showed that the model is significant at a 95% confidence level by constituting all the aforementioned explanatory variables. An R^2 of 0.946 suggests that the model provides a better fit under heterogeneous traffic flow conditions. The ANOVA confirms that the model is significant as the significance level is below 0.05 for all the variables. The data splitting method is utilised in the model's validation, with 70% and 30% of the total data used for the model's development and validation, respectively. The model has been validated and shown to be effective, as assessed by an R^2 of 0.961. The capacity reduction factor rises by 15%, 30%, and 35% with increase in circulating flow for [(50, 100, and 150 (PCU/hr], respectively. Additionally, as pedestrian flow increases to [(50, 100, and 150) Ped/hr], the capacity reduction factor increases by 10%, 15%, and 20%, respectively. For central island diameters of 10, 20, and 30 m, the entry capacity reduction factor increased by 25%, 35%, and 45%, respectively.

Based on the results obtained from the EPM method to assess the pedestrian crossing behaviour ('Children', 'Young People', and 'Seniors'), the critical gap values in Ranchi were observed to be 7.64 seconds, 6.1 seconds, and 7.12 seconds, respectively. Similarly, the study was conducted for the remaining three sites. The critical gap values were found to be highest for 'Children' by considering all the sites, which implies 'Children' are more afraid while crossing the roundabouts.

Researchers, designers, engineers, and planners of transportation systems might recognise the model's data on the entry capacity reduction factor relevant to their efforts to enhance roundabout operations. Further, the critical gap values should be considered to determine the real time crossing behaviour of pedestrians. The limitation of the study is that the model is developed with due consideration of the geometric variable, circulating vehicular traffic flow and pedestrian flow without considering the impact of cyclists at roundabouts. Psychological factors could be studied separately to assess the fear while crossing streets. Consequently, a revised model could be created by incorporating the impact of cyclists alongside the three existing variables with a qualitative assessment of pedestrian behaviour under the prevalent heterogeneous traffic flow conditions in developing countries.

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