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GEOMETRIC FACTORS INFLUENCING ENTRY CAPACITY OF ROUNDABOUTS UNDER HETEROGENEOUS TRAFFIC CONDITIONS

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Abstract:

Roundabout entry capacity is influenced by geometric features of the roundabout, traffic flow characteristics, vehicle and driver characteristics, as well as, environmental conditions. The major methods for estimating roundabout entry capacity are based on either gap acceptance theory or on empirical relations. Roundabout geometry is the sole aspect which can be entirely manipulated by the designers to improve the entry capacity. Limited studies have been conducted to analyze the influence of geometric elements of a roundabout on its capacity, for heterogeneous traffic conditions. Many developing countries like India, Malaysia, Indonesia etc., have heterogeneous traffic conditions on their roads. Data is collected from twenty-one entries of six roundabouts, where heterogeneity in traffic is observed. Seven different vehicle categories are considered such as motorised two wheeler, three wheeler, car, mini bus, light commercial vehicle (LCV), heavy commercial vehicle (HCV) and bus. A non-linear regression model is proposed to predict entry capacity, based on the nature of variation with individual geometric elements. Various combinations of independent variables are used to estimate entry capacity. The non-linear correlations among the geometric variables are checked. In comparison with the existing empirical models such as the LR942 regression model and German empirical model, the proposed regression model produced better estimates and much lower RMSE values. Approach width is found to have the highest impact on entry capacity. The entry capacity is found to be negatively influenced by entry angle. Circulating flow is considered in terms of per metre width against the usual convention. This modification incorporates the effect of circulatory roadway width also into consideration. The circulatory roadway width has a diverse effect on entry capacity at different levels of circulating flow. Modification of inscribed circle diameter and circulatory roadway width is suggested as a potential solution for improving entry capacity. Sensitivity analysis is carried out to quantify the effect of variation of entry angle, circulatory roadway width, inscribed circle diameter and approach width on entry capacity based on the non-linear model. The sensitivity plots can be used to make subtle geometric modifications to improve capacity at congested roundabouts.

Keywords: *roundabout, entry capacity, geometry, heterogeneous traffic, regression*

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1. Introduction

Roundabouts are passive traffic control devices which are popular in many developed and developing countries. The traffic speed reduction and lesser number of conflict points make roundabouts more desirable than other unsignalised and signalised forms of intersections (Brilon and Vandehey, 1998; Chodur and Bak, 2016; Ren et al., 2016; Patnaik et al., 2017). At high traffic volumes, roundabouts undergo lockdown. Such lockdowns can be prevented by predicting the entry capacity. Capacity is defined as the maximum number of vehicles which can enter the roundabout through an entry in unit time under prevailing conditions (Transportation Research Board, 2000). Roundabout entry capacity is influenced by geometric features of the roundabout, traffic flow characteristics, vehicle and driver characteristics, as well as, environmental conditions. The approaches to estimate roundabout entry capacity are broadly classified into three categories: (i) Empirical approaches yielding regression models comprising of variables related to roundabout geometry, (ii) Gap acceptance theory based on parameters representing driver behaviour, and (iii) Simulation of traffic through roundabout at a microscopic level. Traffic volume, vehicle composition, roundabout geometrics and driver behaviour vary widely across the world. Reliable capacity prediction is possible only if the model is developed using the appropriate methodology and influencing factors. Therefore, an understanding of the strengths and weaknesses of different modelling approaches is important.

In 1957, Wardrop developed an equation (Troutbeck, 1984) pertaining to the capacity estimation of rotaries using weaving concept. Further studies dealt with the estimation of capacity based on the driver's acceptance of gap in the circulating flow (Akcelik et al., 1998; Transportation Research Board, 2000, 2010; National Cooperative Highway Research Program, 2006; Macioszek, 2010; Abhigna et al., 2016). From 1966 onwards, the offside (the side of a vehicle farthest from the kerb; in India, the right) priority rule was officially adopted and the capacity was calculated considering the driver's acceptance of gap in the circulating flow, rather than the weaving section (Kimber, 1989). The gap acceptance based models (Akcelik et al., 1998; Transportation Research Board, 2000, 2010; National Cooperative Highway Research Program, 2006) are sensitive to the values of gap parameters. They are also sensitive to the changes in headway distributions at higher values of circulating flows (Akcelik, 2007). Moreover, the varying driver behaviour and other factors result in weak relationships between gap parameters and geometric elements. The values of gap parameters that are obtained directly or indirectly, by field measurements which require some approximations, are inconsistent. For example, there are many methods of calculating critical gap, but they do not give consistent results (Brilon et al., 1999; Farah et al., 2009; Wu, 2012; Mohan and Chandra, 2017). The gap acceptance based models do not directly quantify the relationship between capacity and geometric elements, which can be completely controlled by the designer. Hence, a model incorporating the geometric aspects of roundabouts is essential for suggesting modifications to improve roundabout performance. This becomes pertinent for traffic flow conditions wherein heterogeneity in traffic composition exists.

Heterogeneous traffic conditions are characterized by vehicles having varied static and dynamic characteristics, without any lane discipline (Mohan and Chandra, 2017). Many of the developing countries like India, have heterogeneous traffic conditions on their roads. Some major empirical models are developed from data collected from developed countries such as UK, Germany, France and Switzerland. The traffic in developed countries is homogeneous, which implies that lane discipline is followed, and major proportion of the vehicles are passenger cars. Hence, the existing empirical models for entry capacity based on homogeneous and lane based traffic conditions are not appropriate for heterogeneous traffic conditions. Studies to analyze the influence of geometric elements of a roundabout on its capacity, for heterogeneous traffic conditions are limited. Some empirical models have been proposed by researchers in India, Malaysia, Indonesia etc.

The capacity estimates produced by existing empirical models, even after calibration, are incomparable to the observed entry flow (Al-Madani, 2013; Ahmad and Rastogi, 2016; Patnaik et al., 2016, 2017, 2018; Mathew et al., 2017). Among the different factors influencing entry capacity, geometric aspects of roundabouts can be truly quantified and modified. Models in terms of geometrics are useful as tools for traffic engineers, for analysis and improvement of roundabout performance. This work is an attempt to study the influence of geometric elements on roundabout entry capacity and to develop entry capacity models based on geometric elements applicable for heterogeneous traffic conditions. A sensitivity analysis is also conducted to understand the effect of variation of geometric elements on entry capacity of roundabouts. The discussion on empirical modelling of capacity using geometric variables as predictors is given in the next section.

2. Background

Among the various empirical models, the LR942 regression model proposed by Kimber in 1980 (National Cooperative Highway Research Program, 2006) , given in equation 1, is used by the U.K. Department for Transport. Also, the LR942 regression model forms the core of the TRL Software, which is known as ARCADY /Junctions.

$$Q_e = \left(1 - 0.00347(\varnothing - 30) - 0.978\left(\frac{1}{r} - 0.05\right)\right) \times \left(\begin{array}{l} 303 \times \left(v + \dfrac{e-v}{1+2\left(\dfrac{e-v}{l'}\right)}\right) - 0.21 \times \left(1 + \dfrac{0.5}{1+e^{\left(\frac{D-60}{10}\right)}}\right) \times \\ \left(1 + 0.2 \times \left(v + \dfrac{e-v}{1+2\left(\dfrac{e-v}{l'}\right)}\right)\right) \times Q_c \end{array} \right) \tag{1}$$

where Q_e = entry capacity (veh/h), $\emptyset$ = entry angle (in degrees), r = entry radius (m), v = approach half-width (m), e = entry width (m), l' = effective flare length (m), D = inscribed circle diameter (m) and Q_c = circulating flow (veh/h). The German empirical model (Bared et al., 1997) , given in equation 2, has an linear regression form which describes the relationship between maximum entry flow and circulating flow.

$$Q_e = A - B \times Q_c \tag{2}$$

where Q_e = entry capacity (pcu/h), Q_c = circulating flow (pcu/h), $A = 1379.9$ and $B = 0.497$. A and B are parameters which were determined through regression techniques applied to data collected from different roundabout entries in Germany. The French entry capacity model (Bared et al., 1997) is a linear regression model, which has separator island width, entry width, circulatory roadway width, circulating flow and exiting flow as predictor variables. The Swiss also developed a linear regression model (Patnaik et al., 2016) for predicting the entry capacity with splitter island width, circulating flow and exiting flow as predictors.

Al-Masaeid and Faddah (1997) found that central island diameter, entry width, circulatory roadway width and circulating flow have a strong effect on capacity. They developed a non-linear regression model with power and exponential functions. Al-Madani and Pratelli (2014) modelled entry capacity using circulating and exiting flows, number of entry and circulating lanes, entry and circulating widths, inscribed circle diameter and flare length. The variables were considered either individually or in combination with one another. They combined linear, logarithmic and quadratic functions to model entry capacity. Yap et al. (2015) developed linear regression model and exponential regression model with additive error for predicting capacity. The predictor variables used for modelling were circulating flow, inscribed circle diameter, exiting flow, entry curvature, entry-exit separation and circulatory roadway width. They also used combinations of some of these variables. Patnaik et al. (2016) found that weaving length, entry radius, diameter of central island, entry width, weaving width and circulating flow were the significant factors affecting capacity. Patnaik et al. (2018) also used gap parameters as predictor variables in regression analysis. Ahmad and Rastogi (2016) proposed a non-linear model with central island diameter, circulatory roadway width and circulating flow as influencing factors.

Both linear and non-linear model forms are considered by the researchers for empirical modelling of capacity. All the models include circulating flow as a predictor variable, in addition to the significant geometric elements of the roundabout. However, there is ambiguity in the model form. The relationship between individual geometric elements and entry capacity has not been explored to the required extent. The non-linear models have not considered correlation ratio (Ayres, 1920). The nature and extent of correlation between the geometric variables is a critical factor influencing prediction accuracy of non-linear models (Crathorne, 1922; Roche et al., 1998). The geometric elements (Anjana and Anjaneyulu,

2015) are vital to the efficient operation and design of roundabouts, since traffic and environmental aspects can only be sparingly manipulated. Figure 1 shows the geometric elements of a roundabout.
Entry width is one of the most significant factors which influence capacity (Bared et al., 1997; Federal Highway Administration, 2000). Entry width is the width of entry road where it meets the inscribed circle (Federal Highway Administration, 2000). Entry width has a positive correlation with entry capacity (Crown, 1987). One-lane increase in the entry width (from one to two lanes) was found to improve the estimated capacity by about 30 percent (Al-Masaeid and Faddah, 1997). For a four-legged roundabout, entry capacity is between 2,400 and 2,600 vehicles per hour (veh/h) with single lane approaches, and greater than 4,000 veh/h with two-lane approaches (Bared et al., 1997).
Inscribed circle diameter is the diameter of the circle that can be inscribed within the outer line of the circulatory roadway or the largest diameter circle that can be drawn inside the roundabout (National Cooperative Highway Research Program, 2010). Capacity changed to a lesser extent, by widening the inscribed circle diameter (Crown, 1987; Bared et al., 1997). Increase in central island diameter provides a substantial improvement in entry-capacity values (Al-Masaeid and Faddah, 1997; Ahmad and Rastogi, 2016). An increase in central island diameter from 15 to 35 m, and from 55 to 75 m results in an increase in estimated capacity of about 30 percent and 10 percent respectively (Al-Masaeid and Faddah, 1997). It is recommended that the shape of the central island be circular (not oval) to prevent speeding and to provide skewed entry angles (Bared et al., 1997). Circulatory roadway width is the width between the outer edge of the circulatory roadway and the central island (National Cooperative Highway Research Program, 2010). Circulatory roadway width significantly influences capacity (Yap et al., 2015; Ahmad and Rastogi, 2016). The two-lane roundabout entries have 20% to 30% higher capacities than single-lane roundabout entries, when the circulatory roadway has an extra width (Lindenmann, 2006). An increase of one lane in the circulatory roadway increases the entry capacity by 6 to 10 percent (Al-Masaeid and Faddah, 1997).
Entry radius is the minimum radius of curvature of outside curb at the entry (National Cooperative Highway Research Program, 2010). Capacity changed to a lesser extent by enlarging the entry radius (Crown, 1987; Bared et al., 1997). According to LR942 regression model, entry capacity increases with increase in entry radius. Studies conducted by Patnaik et al. (2016) and Yap et al. (Yap et al., 2015) revealed a contrasting trend, where entry capacity reduced with increase in entry radius. Approach width is the one-way width of the road approaching the roundabout (National Cooperative Highway Research Program, 2010). The capacity increases with increase in approach width (Crown, 1987). Entry angle is the angle between the entering traffic and the circulating traffic (National Cooperative Highway Research Program, 2010). The capacity linearly decreases with increase in entry angle (Crown, 1987).

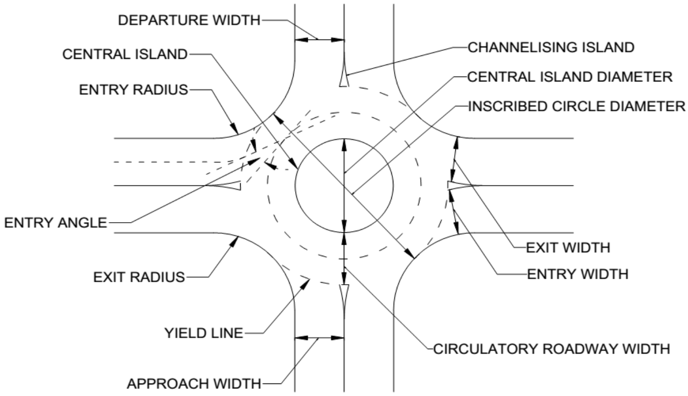


Fig. 1. Geometric elements of a roundabout for Keep Left driving conditions

The geometric variables are inevitable in predicting capacity according to previous studies. Some models have used combination of geometric variables as predictor variables (Al-Madani and Pratelli, 2014; Yap et al., 2015). The nature of influence of the geometric variables and the correlation between variables is crucial for model formulation. The subsequent section details out the data collection and data extraction effort.

3. Data collection and extraction

The geometric details and videographic data of traffic entering and circulating the roundabouts were collected from twenty-one roundabout entries of six roundabouts. The video recording was carried out during typical peak hours of weekday traffic. The camera was placed on top of adjacent tall structure, from where all entries of the roundabout were visible. The location and number of approaches at each roundabout are given in Table 1. The geometric details of roundabout entries are given in Table 2. The geometric elements selected for study are entry width, entry radius, entry angle, circulatory roadway width, approach width, inscribed circle diameter and central island diameter. The central island diameter ranges from 7.71 to 30.80 metres and the inscribed circle diameter ranges from 20.81 to 46.20 metres. The entry width ranges from 4.15 to 10.80 metres. The maximum values of entry radius and entry angle are 71.55 metres and 70 degrees respectively.

Table 1. Location and number of approaches of roundabouts chosen for the study

Roundabout	Number of approaches	Location
1	Four	Ramanattukara Junction, Calicut city
2	Four	Mission Quarters Junction, Thrissur city
3	Four	Yogasala Junction, Kannur city
4	Three	Birla Mandir circle, Hyderabad city
5	Three	Near Indo American Hospital, Banjara Hills, Hyderabad city
6	Three	Kottappady Junction, Malappuram city

Table 2. Geometric details of roundabout entries

Roundabout	Central island diameter (m)	Inscribed circle diameter (m)	Circulatory roadway width (m)	Entry	Entry width (m)	Entry radius (m)	Entry angle (degrees)	Approach width (m)
1	11.84	33.18	8.96	1A	5.35	25.90	46	5.00
				1B	4.98	19.53	67	4.82
				1C	5.52	30.58	57	5.08
				1D	5.92	34.13	42	5.30
2	7.71	20.81	6.58	2A	7.50	20.21	50	7.10
				2B	4.57	13.84	70	2.50
				2C	8.30	25.56	32	7.93
				2D	4.15	5.90	60	2.50
3	9.20	27.40	9.10	3A	6.23	12.13	34	5.85
				3B	8.97	8.20	36	8.44
				3C	4.25	9.80	60	2.00
				3D	8.60	9.46	51	8.11
4	14.20	32.23	9.10	4A	10.80	19.46	31	8.00
			10.00	4B	10.80	45.48	18	10.40
			11.6	4C	9.00	20.52	24	9.50
5	30.80	46.20	7.80	5A	9.50	71.55	19	9.00
			7.90	5B	7.20	29.22	21	7.20
			7.70	5C	7.60	64.60	25	7.00
6	12.14	32.38	10.15	6A	8.60	25.00	29	7.50
				6B	8.14	26.00	32	7.00
				6C	9.04	24.00	35	7.50

Table 3. Traffic details of roundabout entries

Roundabout	Entry	Maximum entry volume during peak period (pcu/h)	Circulating flow (pcu/h)
1	1A	891	466
	1B	757	316
	1C	1041	745
	1D	1987	341
2	2A	1544	119
	2B	678	754
	2C	1506	247
	2D	428	733
3	3A	324	1780
	3B	2093	304
	3C	335	1471
	3D	1869	601
4	4A	1664	1405
	4B	3000	607
	4C	3189	695
5	5A	1672	211
	5B	1890	153
	5C	1045	414
6	6A	1522	1099
	6B	1061	835
	6C	1253	1109

The traffic data such as the classified traffic volume of flow entering through each approach and corresponding circulating flow were manually extracted from the video recording. The vehicles are classified into motorised two wheeler, three wheeler, car, mini bus, light commercial vehicle (LCV), heavy commercial vehicle (HCV) and bus. Since no vehicle class constitutes more than 80% of the traffic composition, the traffic can be termed as heterogeneous (Arasan and Krishnamurthy, 2008). Two wheelers constitute the major share of the traffic ranging from 31 to 57 percent. The traffic volume, was expressed in terms of passenger car units per hour using the PCU values recommended by Indian Highway Capacity Manual (CSIR - Central Road Research Institute, 2017) as 0.32 for two-wheeler, 0.83 for three-wheeler, 1.0 for car, 1.88 for LCV and minibus, and 3.65 for HCV and bus. Table 3 gives the traffic details.

4. Effect of geometric elements on roundabout entry capacity

The relationship between geometrics of the roundabouts under study and the observed roundabout entry capacity are explored in detail.

Figure 2 shows the nature of variation of entry capacity with respect to different geometric elements. Similar to the findings in literature (Kimber, 1980; Al-Masaeid and Faddah, 1997; Bared et al., 1997; Polus and Shmueli, 1997; Hagring, 2001; National Cooperative Highway Research Program, 2007; Macioszek, 2015; Yap et al., 2015), entry capacity increases with increase in entry width (e), entry radius (r), approach width (v), circulatory roadway width (c), inscribed circle diameter (D_i), central island diameter (D) and decreases with increase in entry angle (φ).

The relation between entry capacity and geometric variables such as entry width, approach width, entry radius, circulatory roadway width, central island diameter and inscribed circle diameter are best represented by power functions. According to Al-Masaeid and Faddah (1997), Patnaik et al. (2016) and Ahmad and Rastogi (2016) power function denotes the best fit between central island diameter and entry capacity. Contrary to the slight variation in entry capacity with respect to entry radius as reported by previous studies (Kimber, 1980; Bared et al., 1997), Figure 2(c) shows a considerable increase in entry capacity. These high values of capacity corresponding to entry radius are prominent in cases of roundabout 4, 5 and 6, which are three-legged roundabouts and have lesser entry angles when compared to four-legged roundabouts. Hence, the combined effect of high entry radius and lesser entry angles is found to result in higher entry capacity. Entry capacity varies exponentially with respect to entry angle, in contrast with the linear trend reported in the literature (Kimber, 1980). This seems rational due to two reasons, the first one being that, a non-linear trend is more logical since entry capacity is also influenced by other geometric elements, and the second, being the wider range of entry capacity observed.

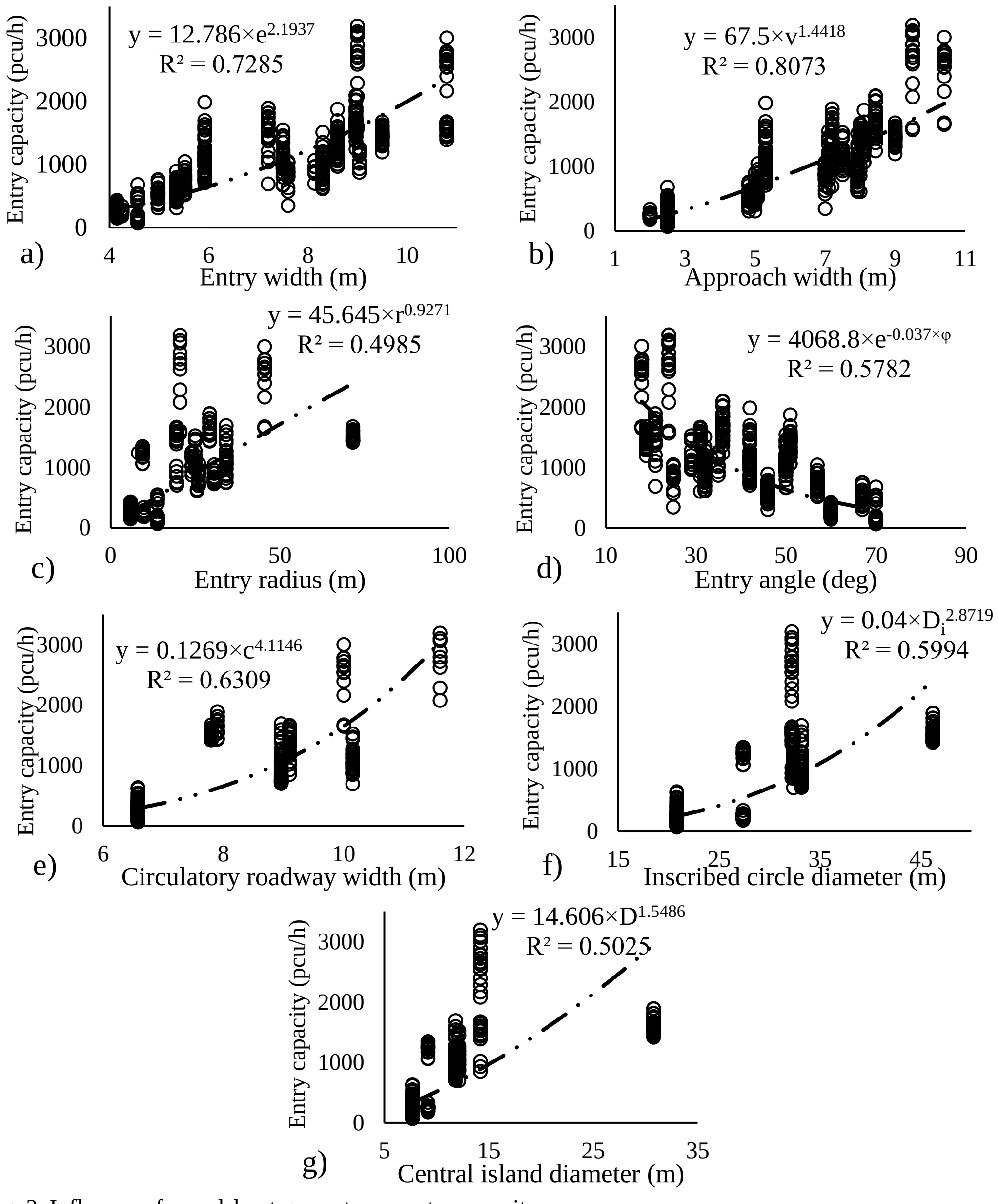


Fig. 2. Influence of roundabout geometry on entry capacity

In order to identify candidate variables for model development, the correlation ratio is used. Correlation ratio denotes the non-linear correlation between two variables (Ayres, 1920; Crathorne, 1922; Roche et al., 1998). A correlation ratio value of 0.5 or higher is considered as indication of medium non-linear correlation. The circulatory roadway width is found to have medium correlation with all other candidate variables, as shown in Table 4. The entry width has medium non-linear correlation with central island diameter, inscribed circle diameter, circulatory roadway width and entry radius. The entry radius has substantial non-linear correlation with circulatory roadway width, entry width and approach width.
Before proceeding further, the capacity estimates of the roundabouts under consideration were estimated using existing entry capacity models. This was taken up to verify the suitability of the existing models to the heterogeneous traffic conditions. Moreover, efforts are made to modify the existing models for their use in heterogeneous traffic conditions. This would aid to check their suitability for heterogeneous traffic conditions.

5. Capacity estimates using existing entry capacity models

The observed entry capacity at each approach is compared with the estimates from the LR942 regression model and German empirical model. Observed entry capacity and capacity estimates from existing models were plotted against circulating flow for all the twenty-one roundabout entries. It is understood from the Figure 3 that the existing model estimates do not consistently reflect field conditions across all variations of traffic and geometry. The reason for the better performance LR942 model compared to German empirical model could be attributed to the inclusion of more number of geometric variables. Even though the LR942 model is relatively close to the field values in the range of 1000 to 2000pcu/h, as observed in Figure 3(d), the difference is pronounced in the range of 250 to 1000pcu/h. Hence a new model incorporating geometric variables is necessary.
Circulating flow is another variable included in most of the existing empirical models. It is seen that the effect of circulating flow on entry capacity is similar (exponential variation) across different roundabout entries. This indicates circulating flow is a significant contributing factor under the current conditions. The varying values of entry capacity for similar values of circulating flows can be attributed to diverse geometric features of the roundabouts.
On comparing the RMSE values of the existing empirical models, shown in Table 5, the estimates from German empirical model were found to be only slightly better. Hence, both LR942 model and German empirical model were calibrated for the study sites. The calibrated values of parameters of the LR942 model are given in Table 5. While comparing the values of parameters before and after calibration, it is observed that significant changes have occurred only to values of certain parameters such as a, c, f and h. The parameters a, c, f and h corresponds to parts of the LR942 model involving entry angle, entry radius, entry width, approach width and inscribed circle diameter respectively. The change in values of parameters can be attributed to the site conditions and traffic conditions. Hence it is established that entry angle, entry radius, entry width, approach width and inscribed circle diameter have an important role in estimation of entry capacity.

Table 4. Correlation ratio between candidate variables and entry capacity

	Entry capacity	Central island diameter	Inscribed circle diameter	Circulatory roadway width	Entry width	Approach width	Entry radius	Entry angle
Entry capacity	1.00							
Central island diameter	0.55	1.00						
Inscribed circle diameter	0.55	0.09	1.00					
Circulatory roadway width	0.40	0.91	0.59	1.00				
Entry width	0.17	0.56	0.62	0.56	1.00			
Approach width	0.13	0.43	0.48	0.50	0.05	1.00		
Entry radius	0.69	0.15	0.18	0.94	0.63	0.57	1.00	
Entry angle	0.24	0.26	0.33	0.56	0.19	0.18	0.40	1.00

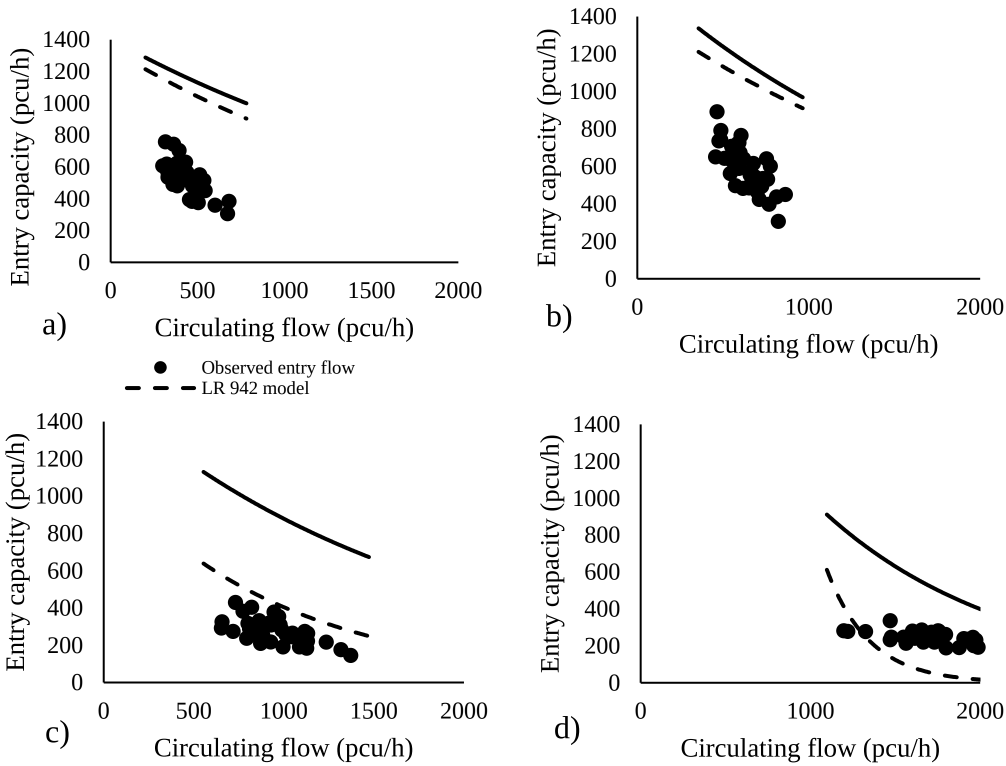


Fig. 3. Variation of observed entry capacity and model estimates with respect to circulating flow for roundabout entries (a) 1B, (b) 1A, (c) 2D, and (d) 3C

The values of parameters A and B for the calibrated German empirical model is given in Table 5. The RMSE of the German empirical model reduces slightly with calibration. After calibration, the RMSE value of LR942 regression model improved to a greater extent, as given in Table 5. So it is concluded that exploring further forms of models involving geometric variables and circulating flow can produce better results.

6. Model based on circulating flow and geometry

The relationship between entry capacity and influencing variables were distinctly found to be non-linear. Hence, regression modelling was carried out in the non-linear form, with entry capacity as the dependent variable. Various combinations of independent variables were used to estimate entry capacity. The non-linear correlations among the geometric variables were checked.

Table 5. Parameters and RMSE of LR942 regression model and German empirical model

Models	**LR942 model**							**German empirical model**	
Parameters	*a*	*b*	*c*	*d*	*f*	*g*	*h*	*A*	*B*
Values of parameters	0.00347	30	0.978	0.05	303	0.21	0.5	1379.9	0.497
Calibrated values	0.02	44	−1.34	0.04	154	0.14	−1.31	1281.02	0.334
RMSE	678							635	
RMSE after calibration	447							630	

The highly correlated variables such as entry width, circulatory roadway width and entry radius were excluded from the model to avoid multi-collinearity. Entry capacity was found to vary exponentially with respect to circulating flow and entry angle. Power functions denote the best fit between entry capacity and the geometric elements, approach width, inscribed circle diameter and central island diameter. The estimate of the parameter corresponding to central island diameter turned out to be negative, which is opposing the trend observed from the field, as per Figure 2(g), and from the literature (Al-Masaeid and Faddah, 1997; Ahmad and Rastogi, 2016). Hence the variable 'central island diameter' was excluded from the model. The final predictor variables considered were circulating flow, entry angle, inscribed circle diameter and approach width. The circulating flow was considered in terms of pcu/h/m indirectly to consider the effect of circulatory roadway width in the model.
Based on the form of German empirical model given in equation 2, the non-linear model, denoted as NLM01, was formulated. The NLM01 model does not include a parameter corresponding to 'A' as in equation 2. Instead, the product of the parameters associated with entry angle, inscribed circle diameter and approach width represents the term 'A' as in equation 2.

$$Q_e = exp^{-b\times\varphi} \times v^d \times (Di)^f - g \times Q_c \quad (3)$$

where Q_e = entry capacity (pcu/h), φ = entry angle (deg), Q_c = circulating flow (pcu/h/m), v = approach width (m), D_i = inscribed circle diameter (m), b, d, f and g = model parameters.

Table 6. Estimates of NLM01 model parameters

Model parameter	Estimate	Std. error	95% Confidence interval	
			Lower bound	Upper bound
b	−0.01	0.0009	−0.012	−0.009
d	2.45	0.06	2.33	2.57
f	0.52	0.04	0.44	0.60
g	−0.48	0.19	−0.86	−0.10

The parameters of the NLM01 model are given in Table 6. The signs of the parameters associated with circulating flow, entry angle, inscribed circle diameter and approach width are supporting the power and exponential trends observed in Figure 2 and 3. The R squared value for the NLM01 model is 0.72.

To examine if capacity estimates can be further improved, another form of non-linear regression modelling is also attempted. The form of the non-linear model was based on the non-linear nature of best fitting relationships between the independent variables and entry capacity, presented in Figure 2 and 3. The form of the non-linear model, denoted as NLM02, is given below.

$$Q_e = a \times exp^{-b\times\varphi - g\times Q_c} \times v^d \times (Di)^f \quad (4)$$

where Q_e = entry capacity (pcu/h), φ = entry angle (deg), Q_c = circulating flow (pcu/h/m), v = approach width (m), D_i = inscribed circle diameter (m), a, b, d, f and g = model parameters.

Table 7 shows the parameters of the NLM02 model. The signs of the parameters associated with circulating flow, entry angle, inscribed circle diameter and approach width are supporting the power and exponential trends in Figure 2 and 3. The R squared value for the NLM02 model is 0.76, which indicates good predictive capability.

Table 7. Estimates of NLM02 model parameters

Model parameter	Estimate	Std. error	95% Confidence interval	
			Lower bound	Upper bound
a	25.31	10.12	5.42	45.20
b	−0.001	0.002	−0.004	0.002
d	1.66	0.09	1.49	1.84
f	0.22	0.07	0.09	0.35
g	−0.001	0.0002	−0.002	−0.0008

Table 8. RMSE values of proposed regression models

Non-linear model	NLM01	NLM02
RMSE	350	333

The RMSE values shown in Table 5 and 8 indicate that the NLM01 model and NLM02 model give better results than the existing empirical models and the calibrated models. The NLM01 model was found to be underperforming considering the RMSE value in Table 8 and the R squared value of 0.72. Figure 4 shows the plot of entry capacity predicted by NLM02 model in equation 4 versus observed entry flow. The minimal scatter of the values about the 45 degree line confirms that the model predicted capacities and the observed entry flows are very much alike. Figure 5 shows the plot of residuals versus predicted entry capacity for the NLM02 model.

The symmetrical distribution of points and absence of a clear pattern in the residual plot again indicates the predictive strength of the NLM02 model.

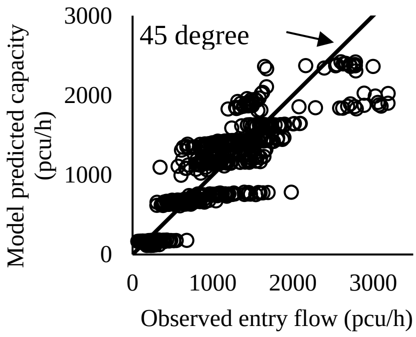


Fig. 4. Comparison of field entry capacity and predicted capacity of NLM02 model

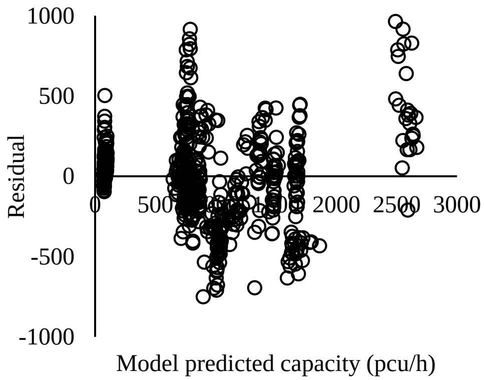


Fig. 5. Residual versus predicted capacity plot for NLM02 model

7. Sensitivity analysis

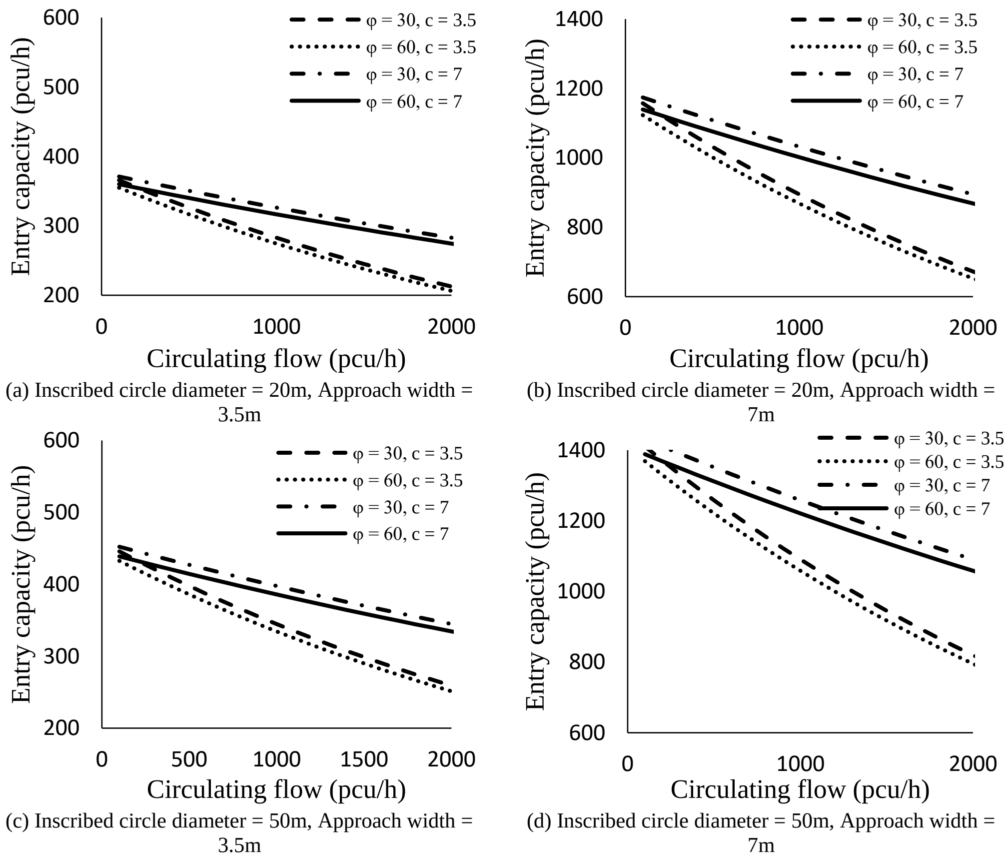
It is clear from the NLM02 model that the variations in geometric variables such as entry angle, inscribed circle diameter and approach width can significantly affect entry capacity. Sensitivity analysis was carried out to quantify the effect of variation of these variables on entry capacity based on the NLM02 model in equation 4. The range of values of the geometric variables is chosen corresponding to the typical values of entry angle, inscribed circle diameter and approach width. The values of entry capacity at different levels of circulating flow are plotted in Figure 6, for entry angle of 30 and 60 degrees, approach width of 3.5m and 7m, inscribed circle diameter 20m and 50m and circulatory roadway width of 3.5m and 7m. The effect of circulatory roadway width comes into effect through the circulating flow parameter expressed per metre width.

The significance of these plots is in the fact that they can be used to make subtle geometric modifications to improve capacity at congested roundabouts. For a roundabout to handle higher capacity, the entry angle, approach width and circulatory roadway width could be modified, for a specific inscribed circle diameter. For a congested roundabout, the circulating flow and entry flow could be measured from the field and the change in entry angle; approach width circulatory roadway width or inscribed circle diameter for achieving higher capacity can be estimated from the plots.

The entry angle when varied from 30 degrees to 60 degrees, results in a 3 percent decrease in entry capacity. A 3.5 m increment in approach width, from 3.5m to 7m, improves the capacity almost 2.2 times. The rise in capacity of such proportion can be attributed to the fact that the increment of 3.5 m is in effect similar to the addition of an approach lane. The capacity improvement by increasing approach width is higher relative to results in the literature, which can be attributed to the large proportion of small vehicles. An 8 to 12 percent increase in capacity is observed with increase in inscribed circle diameter. The entry capacity has a distinct pattern of variation with respect to circulatory roadway width. At lower circulating flows, there is only a slight change in entry capacity with increase in circulatory roadway width. But as circulating flow increases, the circulatory roadway width has a prominent effect on entry capacity. For increase in circulatory roadway width from 3.5m to 7m, the entry capacity varies from 1 percent to 65 percent, for circulating flows ranging from 100 pcu/h to 3500 pcu/h. The observations from the analysis are explained in the next section.

8. Discussion

In this study, a non-linear regression model is proposed to estimate entry capacity, incorporating circulating flow, entry angle, inscribed circle diameter and approach width as independent variables. The NLM02 model is formulated from the nature of the relationships between the independent variables and entry capacity.



(a) Inscribed circle diameter = 20m, Approach width = 3.5m

(b) Inscribed circle diameter = 20m, Approach width = 7m

(c) Inscribed circle diameter = 50m, Approach width = 3.5m

(d) Inscribed circle diameter = 50m, Approach width = 7m

Fig. 6. Impact of entry angle (φ), circulatory roadway width (c), inscribed circle diameter and approach width on entry capacity

Circulating flow is expressed in terms of pcu/h/m, against the usual convention of pcu/h. This modification brings the effect of circulatory roadway width into consideration, since lane based traffic conditions do not prevail. Most of the previous studies consider central island diameter as a significant predictor variable (Al-Masaeid and Faddah, 1997; Ahmad and Rastogi, 2016; Patnaik et al., 2016). However, considering the fact that circulating flow is always a deciding factor for entry capacity, the circulatory roadway width and the inscribed circle diameter play a more important role. The proposed NLM02 model illustrates the effect of these geometric elements. The variation of entry capacity with change in circulatory roadway width at different circulating flow values shows a logical trend. The NLM02 model presents modification of inscribed circle diameter and circulatory roadway width as a feasible solution for improving entry capacity.

Entry angle has been observed previously, only in the LR942 regression model as an independent variable. There is a negative correlation between entry angle and entry capacity. The orientation of the entry and circulating vehicle streams depends on the entry angle. Some interaction between the entry and circulating streams are influenced by this orientation. But the modification of entry angle depends on the alignment of the approaches to the intersection. At capacity conditions, the approaches are saturated with

queued entry vehicles. Hence, greater approach width implies higher availability of entry vehicles. The modification of approach width depends on the classification of the particular road type, economic constraints and site specific geographic constraints.
The observed entry flow was not comparable to the capacity estimates from the existing empirical models such as LR942 and German models. The LR942 model and German empirical model were calibrated, but only a slight improvement over the existing models was observed. Circulatory roadway width, entry radius and entry width were excluded from the models to avoid multi-collinearity. The proposed NLM02 model produces capacity estimates comparable to the field values and also relatively better RMSE values than the existing empirical models and the calibrated models. The plots of observed entry flow vs model predicted capacity and the residuals emphasize the good predictive strength of the model. Moreover, the sensitivity analysis reveals the combined effect of entry angle, approach width, inscribed circle diameter, circulatory roadway width and circulating flow on entry capacity. The following section highlights the salient findings of the study.

9. Conclusions

Main conclusions can be formulated as follow:

- Among geometric variables, the effect of approach width on entry capacity is more pronounced. Increase in approach width from one lane to two lanes, improves the capacity by 2.2 times. The characteristics of motorised two wheelers and three wheelers such as sharing of lanes and executing a collective entry play a major role in capacity enhancement.
- The increase in entry angle from 30 degrees to 60 degrees resulted in 3 percent decrease in capacity. Higher entry angle makes it difficult for the vehicles to merge with the circulating traffic.
- The effect of inscribed circle diameter is much more pronounced than what is observed in the literature. Entry capacity increases by 8 to 12 percent for a 30m increase in inscribed circle diameter. This is a striking point considering the fact that inscribed circle diameter of a roundabout can be directly increased by widening the circulatory roadway, while the central island diameter is unchanged.
- The circulatory roadway width has a diverse effect on entry capacity at different levels of circulating flow. At circulating flow value of 100pcu/h, the entry capacity increases only by 1 percent with increase in circulatory roadway width from 3.5m to 7m. At a higher circulating flow of 3500pcu/h, the improvement in entry capacity is 65 percent.
- Hence it can be inferred that, inscribed circle diameter and circulatory roadway width together plays a significant role in improving entry capacity. Changing the approach width and entry angle may require major changes in the alignment of approaches and intersection geometry. However, inscribed circle diameter and circulatory roadway width maybe increased, subject to the constraints of space.
- The sensitivity charts can be used to suggest modifications to the roundabout entries, so as to improve their capacity. In the case of roundabout 1, the developed sensitivity charts in Figure 6 indicate that entries 1A, 1B and 1C could carry more traffic. In order to achieve higher entry capacity, the approach widths of 1A, 1B and 1C should be 7 m. With these modifications in the entries 1A, 1B and 1C, the capacity of the roundabout will be enhanced by 50 %. In the case of roundabouts 2 and 3, the entries 2B, 2D, 3A and 3C could carry twice the entry traffic, with a larger approach width of 7m.

The sensitivity plots can have extensive applications by obtaining data for more geometric and traffic conditions. This can also be made more robust by simulation. Further scope of this study may involve simulating roundabout entries with traffic and geometry over a wider range. It will be useful to verify and magnify the application of the current findings.

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