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SELECTING A SUITABLE MODEL FOR ROUNDABOUT ENTRANCE CAPACITY ESTIMATION: A CASE STUDY

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Abstract

In India, urban vehicular traffic is highly heterogeneous; it appears to be extremely challenging to accurately anticipate roundabout capacity. The main objective of this paper is to develop two models which are predicting the capacity of roundabouts in the Indian scenario. One is Weighted Least Square Regression (WLSR), a linear regression is carried out using weights of each data variable while the other one is Self Adaptive Segregative Genetic Algorithm with Simulated Annealing (SASEGASA), which is a combination of Segregative Genetic Algorithm (SEGA) and self-adaptive selection pressure with the application of simulated annealing. The coefficient of determination (R^2) and Nash-Sutcliffe model efficiency coefficient (E) for the models like SASEGASA and WLSR were obtained as (0.947, 0.949) and (0.906, 0.905) respectively. Ranking among the proposed models is carried out using a complex phenomenon known as Modified Ranking Index (MRI), where the highest rank generated from five estimates is chosen as the best model for this study. SASEGASA is ranked as the appropriate model to estimate the roundabout capacity as per MRI. As compared to previously used models, SASEGASA model is quite relevant for field application.

Keywords: heterogeneous traffic, roundabout, capacity, artificial intelligence

1. INTRODUCTION

Roundabouts are a particular kind of unsignalized intersection where traffic flows predominantly in one direction across Central Island. It contains merely 8 conflict points, as opposed to 32 at an unsignalized intersection, and these are points where traffic is merging, diverging, and crossing even making it less prone to accidents. Roundabouts are extremely effective in controlling environmental pollution, reducing vehicle speed, boosting pedestrian safety[1], minimizing delay time[2], and lessening the number of major fatal accidents[3].

Vehicles maneuvering at roundabouts outperform stop-and-go traffic in terms of energy and environmental efficiency, emitting fewer harmful gases and burning less fuel[4]. The efficient operation of traffic flow can be improved by using roundabouts instead of complex signal systems[5], [6]. Even roundabouts can be influenced by automated motor vehicles, and it could render urban intersections more efficient and safer[7], [8]. It is, therefore, pertinent to determine the roundabout entrance capacity, or the number of vehicles that can swiftly maneuver through the entrance lane per unit time at a certain Level of Service (LOS).

In India, the traffic situations are considered as heterogeneous in which drivers do not adhere to lane discipline. Regardless of their size, Heavy Vehicles (HV) were expected to impede the flow of traffic on the central island, tempting queuing conditions. Here, gap acceptance behavior can't be studied properly. In homogeneous traffic, all the variables are assumed to be constant including drivers' behavior towards the road, so the critical gap can be taken as a constant parameter throughout. While in heterogeneous traffic streams, critical gap varies significantly from driver to driver. The space headway between vehicles significantly influences capacity computation in heterogeneous traffic conditions[9]. The choice of vehicles owned by a commuter, either for personal use, or public transit is a critical parameter in estimating traffic capacity at roundabouts and even urban intersections[10]. Consequently, the analysis of the Indian scenario is a complex phenomenon that ought to be studied in depth.

Due to increased use of roundabout as a facility, for the focus is on the improvement of operational efficiency under heterogeneous traffic flow scenarios. The study of roundabout in terms of calculation of entrance capacity has been classified in three different categories as empirical method, gap-acceptance, and micro-simulation method. The former model (empirical method) is based on the mathematical approach considering entrance capacity as output dependent variable and other geometric parameters as independent variables[11]–[13]. The entrance capacity of a roundabout and mega-elliptical intersection can be computed by queuing theory with two vehicle streams, was analysed by employing gap acceptance theory[14]. As a result, the capacity value derived from the critical gap of the stochastic function is more sophisticated and realistic [15]. HCM 2000 uses the concept of gap acceptance to calculate the above two variables [16]. HCM 2010 uses the above principle for the determination of LOS of roundabouts [17]. Relation among the vehicles around Swiss roundabout is done in a simulated networking basis in micro simulation method. Authors analysed the relationship between independent and dependent variables of roundabout using normal regression method and found some difficulties due to scatter type of data [18]. In addition, the authors applied mathematical modelling and microscopic simulation to examine roundabout capacity. The findings suggest that the minimal gap time has a substantial effect on approach capacity [19]. Even while, roundabout capacity declines as non-resident vehicles engage more in traffic flow. Multiple linear regression was used to anticipate the effects of non-resident drivers on roundabout capacity [20].

Recent studies are based on artificial intelligence techniques, where it has been found that these types of models fit better than normal regression models. In addition, Artificial Intelligence (AI) technique has increased its recognition for its simplicity nature of model expression. Therefore, the study has been attempted to employ the concepts of regression and AI technique such as WLSR and SASEGASA to develop entrance capacity of Indian roundabouts.

2. STUDY OBJECTIVES AND WORK OUTLINES

Considering the effect of heterogenous traffic and the application of regression and AI technique, the following study objectives are outlined as:

- To calculate the gap acceptance parameters using Influence Area for Gap Acceptance (INAGA) method.
- To develop two roundabout entrance capacity models using WLSR and SASEGASA technique of regression and AI method respectively.
- To determine the most prominent model using MRI technique and to select the most important variable using sensitivity analysis respectively.

This paper is divided into different sections in which 'Methods' section deals with study area and data collection part, determination of driver behavior parameters and modelling approach such as WLSR and SASEGASA respectively. The 'Result and Discussion' comprises of mathematical expressions of the roundabout entrance capacity models, significance of proposed models and sensitivity analysis of suggested model. The summary of the whole study has been covered along with the possible future extensions of the proposed study are given in last section 'Conclusions'.

3. METHODS

The methodology section comprises two parts. The first part describes data collection and an extraction procedure, second part defines the modelling approach such as WLSR and SASEGASA technique respectively.

3.1 Data collection and extraction procedure

To carry out the capacity studies pertaining to heterogenous traffic, 27 un-signalized roundabouts from 8 different states are considered for this study, i.e., depicted in Figure 1. The pedestrian hinderances, effects of curvature, side friction, parking areas and bus stops are eliminated during the data collection. And even, these roundabouts are located at-grade, with no rise or descent.

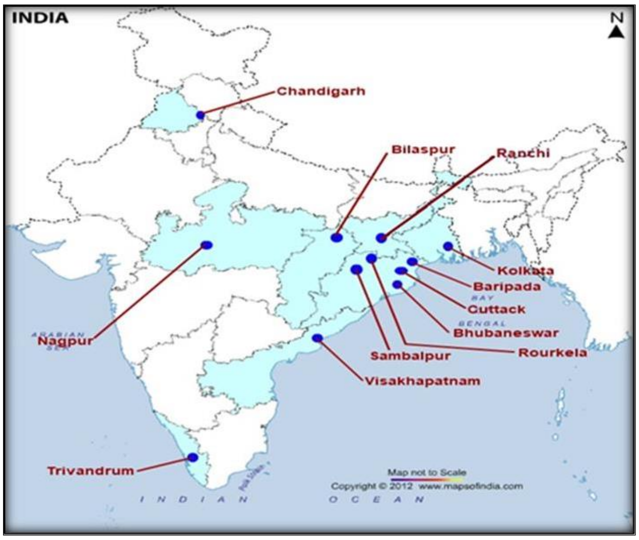

Figure 1. Study area of roundabouts.

The data was collected using a high-resolution mega pixel camera. Observations were conducted for a minimum of two hours, with at least half an hour wasted in vehicle queuing at each approach leg. In the months of September through November 2022, data collection was done, duration in which traffic was least affected by environmental condition. Two peak hour periods (9AM-11AM and 5PM-7PM) were chosen to get the data from study areas and were analysed in the laboratory computer to extract the data. To avoid traffic disturbance, the geometric variables of the roundabout were measured at dawn with a tape measure and wheel. Google Earth Pro software was used to verify those geometric variables. As per Indian Road Congress manual (IRC: 65-1976)[21], The total stream flow i.e., entrance and circulating flow are modified by converting them into static Passenger Car Unit (PCU) form, which takes account for vehicle shape, size, category, composition also varies from country to country [22]. Three-wheel pedal-cycle rickshaw carrying with a limitation of carrying two passengers or three-wheel pedal-cycle to haul certain quantity of goods over small distance are included in the category of Manually Pulled Vehicles (MPV). These MPV travel alongside motor vehicles on the mainstream carriageway, with no physical separation or designated areas for them. Average length of Light Motor Vehicles (LMV) varies from 4-4.5 m while width of the same varies from 1.6-1.7 m respectively. The percentage of volume pertaining to any one type of vehicle was observed to be no more than 80%, which concludes the traffic condition is highly heterogeneous in India[23]. After obtaining data regarding traffic flow, gap acceptance parameters, and geometric variables, then WLSR and SASEGASA models are developed for roundabout entrance capacity. Explanatory variable data are mentioned in Table 1.

Table 1. Explanatory variables in the study area.

Variable abbreviations	Variables	Mean	Maximum	Minimum	Standard Deviation
Q_e	Entrance capacity (PCU/h)	1820	4587	240	937.51
q_c	Circulating flow (PCU/h)	951	3421	209	701.42
W_l	Weaving length (m)	42.39	55.22	27.76	5.95
W_w	Weaving width (m)	16.95	19.25	8.1	4.89
E_w	Entrance width (m)	14.98	19.22	4.74	3.7
D	Diameter of central island (m)	42.53	59.22	11.66	10.88
T_c	Critical gap (seconds)	1.83	2.87	0.54	0.59
T_f	Follow-up time (seconds)	1.58	2.99	0.92	0.53

3.2 Modelling approach

Normal regression assumes the error term variance is homoscedastic throughout all conceivable combinations of predictor and explanatory variable values and each data point yields equally precise information. In order to lower the standard error term and to enhance the precision of individual term by varying standard deviation, Weighted Least Square Regression (WLSR) is employed in this study. In conventional Genetic algorithm (GA), a major drawback is premature convergence, which occurs when genetic operators can no longer generate progeny that outperform their parents. To avoid this problem of premature convergence and to get a single global optimum, a combination Segregative genetic algorithm (SEGA) and self-adaptive selection pressure is carried out named as SASEGASA for this study.

4. RESULTS AND DISCUSSION

In this section, the WLSR and SASEGASA techniques are used to discuss the model development for determining roundabout entrance capacity. Based on MRI, the most appropriate model is selected among the developed models. Similarly, sensitivity analysis is employed to determine the contribution of different explanatory variables in the selected model. Furthermore, the proposed model's prediction capabilities in heterogeneous scenarios are obtained by comparing it with some of the finest international existing models to ascertain the prediction capability.

4.1 Modelling of roundabout capacity models

The study comprises a total of 110 data points gathered at each entrance leg of a roundabout, of which 70% (77 points) are used for training and 30% (33 points) are used for testing purpose respectively. The relation between each explanatory variable and the outcome variable has been determined beforehand through a preliminary evaluation. Weaving length (W_l), weaving width (W_w), entrance width (E_w), critical gap (T_c), circulating flow (q_c), follow-up time (T_f) and central island diameter (D) serve as independent variables, while entrance capacity (Q_e) acts as a dependent variable, yielding the mathematical equation for each model like WLSR and SASEGASA respectively.

4.1.1 Weighted least square regression model (WLSR)

Using collected data, ordinary least square regression is carried out in SPSS software to develop entrance capacity model of roundabout. Considering the intercept and coefficients obtained from normal regression, weights of each data sample calculated to get the WLSR model. The mathematical equation for WLSR is provided by equation 1.

$$\boldsymbol{Q_e = -739.939 + 21.678D + 2.530 * (E_w * W_w) + 0.251 * \left(\frac{Q_c * T_f}{E_w}\right) + 74.311 * (T_c * \ln(W_l))} \qquad (1)$$

[Pearson's R^2 (training)=0.906, Pearson's R^2 (testing)=0.8591, RMSE=256.75]

The statistical features of the WLSR model after integrating all variables reveal that the model is statistically significant at a 95% confidence interval. The coefficient of determination R^2 is obtained as 0.906 that signifies the best fitness of the model. The model's statistical fitness was assessed by performing an Analysis of Variance (ANOVA) test, which yielded a standard error of estimate of 1.25 and a p-value of 0.000. Furthermore, the significance (p-value) values of all independent variables are 0.000, which is less than 0.05 (5%). Thus, variables contribute to model development at over 95% confidence.

4.1.2 Self adaptive segregative genetic algorithm with simulated annealing (SASEGASA)

SASEGASA model was developed using MATLAB programming till the number of subpopulation or village in a population changed from n to 1. Successive iteration has been carried out till it reaches its maximum generation size or smallest standard error possible. SASEGASA regression entails the creation of a tree-based model structure that precisely matches the dependent and independent variables. The following parameters (Table 2) are used to predict the roundabout entrance capacity by taking both dependent variable and explanatory variables. The following mathematical equation (2) and tree-based structure (Figure 2) are generated to determine the best-fit model with a maximum of 1000 iterations. The final mathematical expression of the best fit model of SASEGASA is represented in equation 2 as:

$$\boldsymbol{Q_e} = \frac{((c_0 * E_w) + (c_1 * D)) * \left((c_2 * W_w) + (c_3 * W_l) + \frac{c_4 * W_w}{c_5 * {T_f}^2}\right) * c_6}{\left(\frac{c_7}{c_8 * T_c} + \ln(c_9 * q_c) + \ln(c_{10} * T_c)\right)} + \boldsymbol{c_{11}} \qquad (2)$$

Where, c_0=2.6008, c_1=0.39264, c_2=0.64051, c_3=0.5385, c_4=0.64051, c_5=2.6728, c_6=5.9068, c_7=1, c_8=0.11313, c_9=0.14133, c_{10}=1.0933, c_{11}=261.93

[Pearson's R^2 (training)=0.9203, Pearson's R^2 (testing)=0.9492, RMSE=182.83]

Table 2. SASEGASA parameters

Parameters	Value
Mutation probability	5%
Population size	100
No. of villages	10
Maximum generations	1000
Maximum selection pressure	100
Final Maximum selection pressure	100
Selector	Proportional selector
Elites	1
Comparison Factor Lower Bound	0.3
Comparison Factor Modifier	Linear Discrete Double Value Modifier
Comparison Factor Upper Bound	0.7
Operators	+,-,*,/,power,log,root
Village Analyser	Multi Analyser
Cross over	Context Aware Cross over
Success Ratio	1
Mutator	Null

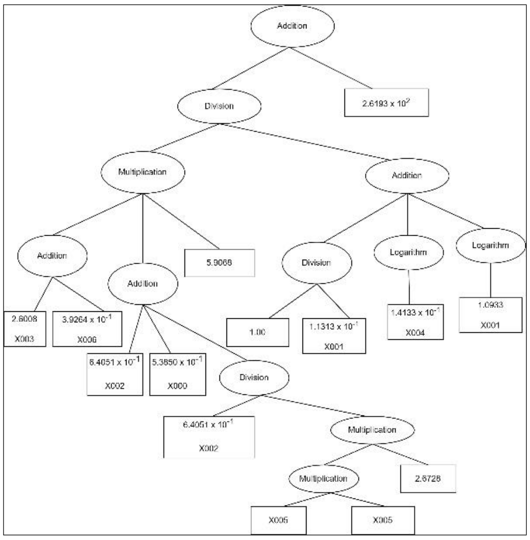

Figure 2. Tree based structure of SASEGASA model output.

The scatter plot of the predicted and observed entrance capacity of the WLSR and SASEGASA models is depicted in Figure 3. Both models were confirmed to be statistically fit at a 95% confidence interval with the influence of heterogeneous traffic. The coefficient of determination (R^2) for WLSR and SASEGASA models utilizing training and testing data was (0.9063, 0.8591) and (0.9203, 0.9492), respectively. This proves there exist a strong correlation among the observed data sets (as $R^2 > 0.80$).

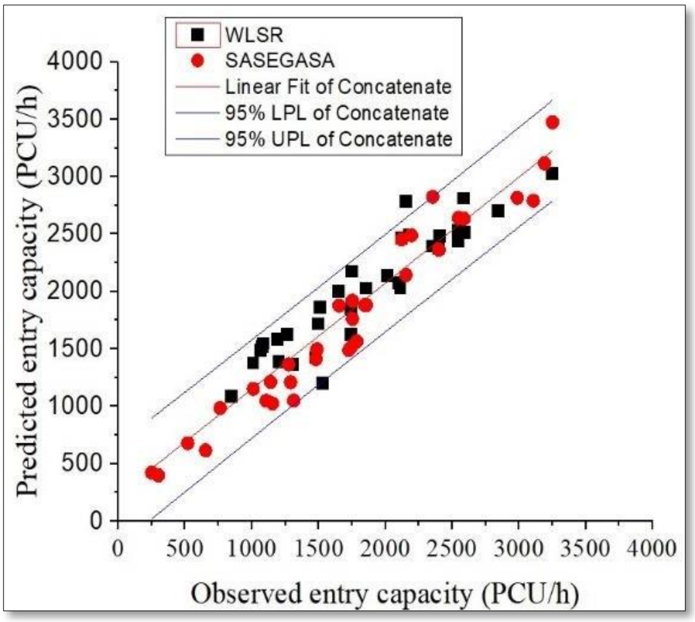

Figure 3. Scatter plot of the two observed models.

4.2 Significance test of the proposed models

MRI is used in this study to determine the overall prediction assessment of two developed models (WLSR & SASEGASA) and to rank them using several statistical variables. The following Appendix-1 has the MRI results. The following mathematical expression is presented as equation 3 to rank the models[24] .

$$\boldsymbol{MRI = R1 + R2 + R3 + R4 + R5} \tag{3}$$

According to literature, the mean ‘μ’ and standard deviation ‘σ’ of the EC_P/EC_O become equal to 1 and 0, respectively, when the estimated entrance capacity is exactly equivalent to the field-observed entrance capacity. Consequently, the performance of a model is enhanced for any model that nearly satisfies the above premise. P_{50} values below and above '1' indicate under and over predictions, respectively. The variation in EC_P/EC_O values across all observations is represented by the CP_{90} parameter. Therefore, values of the parameters CP_{50} and CP_{90} that are nearer to "1" imply better predictive model performance. The following Appendix 1 provides the MRI values that were obtained for each of the several entrance capacity models used in this study. As observed, the MRI values in the SASEGASA (1st rank) and WLSR (2nd rank) models are 5 and 10, respectively. Hence, it is ascertained that the SASEGASA model accurately predicts roundabout entrance capacity.

4.3 Sensitivity Analysis

Among the established entrance capacity models, the MRI analysis reveals SASEGASA to be the best fit under heterogeneous traffic scenarios. The model's sensitivity analysis is used to determine the percentage contribution of each explanatory variable to the outcome. While determining an input parameter's sensitivity, it is done so that its values are varied while the values of the other input parameters are held constant at their averages [25]. The following Table 3 ranks each input variable for the SASEGASA model.

Table 3. Sensitivity analysis of SASEGASA model

Sl. No.	Variables	Sensitivity (%)	Rank
1.	Weaving length (W_l)	12.41	4
2.	Critical gap (T_c)	21.42	2
3.	Diameter of central island (D)	11.75	5
4.	Weaving width (W_w)	15.07	3
5.	Entrance width (E_w)	24.73	1
6.	Circulating flow (q_c)	9.38	6
7.	Follow-up gap (T_f	5.24	7

From Table 3, it can be noticedthat entrance width, critical gap and weaving width contribute the maximum to the SASEGASA model development as 1st, 2nd and 3rd prominent input variables respectively. These three variables altogether contribute 61.22% to the entrance capacity model prediction. With 24.73% contribution, entrance width (E_w) is found to be the most prominent input variable. Sensitivity analysis shows that geometrical variables of roundabout play an important role in the prediction of entrance capacity.

4.4 Comparison with existing models of entrance capacity

For assessment and prediction under heterogeneous traffic scenarios, the best fit model like SASEGASA needs to be compared with some existing capacity models such the Girabase formula (France), Brilon Wu formula (Germany), and HCM 2010. The measured capacity in the field is compared to the predicted capacity obtained from the models, as illustrated in Figure 4.

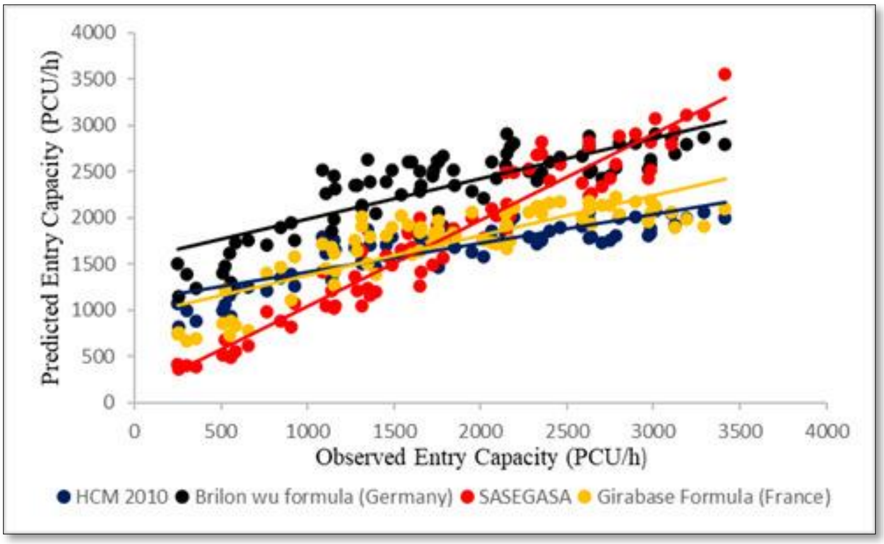

Figure 4. Comparison with existing model.

It is noticed that Brilon Wu formula (Germany) overestimates capacity at lower capacity values while underestimates capacity at higher capacity values. The observed entrance capacity is of the range (250-4500) PCU/h. Both Brilon-Wu formula and HCM 2010 fit the data linearly with coefficient of co-relation R^2 of 0.70. HCM 2010 gives relatively lower capacity values as compared to the observed one. Girabase Formula (France) linearly fits the data with R^2 value of 0.71. All the above three models fit exactly with the observed data under homogeneous traffic scenarios. The proposed model SASEGASA gives almost the same entrance capacity values as estimated from the field value with highest R^2 value as 0.94. Among the four models, SASEGASA model fits the best while HCM 2010 fits the worst under heterogeneous traffic condition. Hence, it proves the existence of a strong co-relation among the datasets in SASEGASA model. The presented model like SASEGASA neither underestimates nor overestimates the capacity values.

5. CONCLUSIONS

The entrance capacity estimation at roundabouts in heterogeneous traffic situations has been addressed so far in this study. The summary can be described in serial as follows:

- The traffic composition at roundabout is highly heterogeneous in India as the percentage contribution of each vehicle type are as follows: Heavy vehicles: HV (0.2 – 55.1) %, Light motored vehicles: LMV (6.8 – 84.7) %, Motorcycles & scooters: MCS (10.5 – 91.9) %, Bicycles: BS (0 – 36.5) % and Manually pulled vehicles: MPV (0 – 7.5) % at selected roundabouts.
- To reflect homogeneous in traffic condition, (as per Indian Road Congress manual: IRC 65-1976) observed traffic data are converted into static Passenger Car Unit (PCU). Again, by using the Influence Area for Gap Acceptance (INAGA) method, the gap acceptance parameters i.e., critical gap and follow up time are calculated. In this study, the range of critical gap is found to be 0.54-2.87 sec, while in other developed nations (USA and European countries), it is of the range like 4-4.6 sec. Hence, in India, almost half the value of critical gap is observed as compared to the developed nations and it is because of the presence of large number of two-wheeler vehicles. As two-wheeler vehicles require a marginally smaller gap as compared to other merging traffic around any roundabout.
- Two entrance capacity models, Weighted Least Square Regression (WLSR) and Self Adaptive Segregative Genetic Algorithm with Simulated Annealing (SASEGASA) were developed for the estimation of roundabout entrance capacity. SASEGASA model is obtained with a maximum generation size of 1000. Both the models are found to be statistically significant at 95% confidence interval. The Modified Ranking Index (MRI) is employed in this study to rank the proposed models to get the prediction values. The lower the MRI value, the better the developed model is. SASEGASA model is ranked as number 1 model with an MRI of 5 while WLSR holds 2nd position with an MRI value of 10.
- The contribution of each input variable to the model has been determined through sensitivity analysis. It shows that entrance width (E_w) is the most prominent variable followed by critical gap (T_c) and weaving width (W_w) respectively. Consequently, the SASEGASA model's geometric variables are its most vital parameters.

- In India, two-wheeler sharing is more prevalent than four-wheeler and large vehicle sharing. Two-wheelers hastily construct a gap to pass around the central island of the roundabout, which renders the gap to be rejected. Previously used models like HCM 2010, Brilon-Wu formula and Girabase formula assume homogeneous traffic behavior i.e., driver behavior is same for any type of vehicle and a single value of critical gap and follow up time is considered throughout the analysis. So, the existing models do not hold well under heterogeneous traffic scenarios.

Researchers, planners, designers, and professionals of transportation stream can use the proposed model SASEGASA as a valuable tool for estimating roundabout entrance capacity in other developing nations with comparable traffic conditions. This study provides three potential future research avenues:

- Impact of crossing traffic (through movement) at roundabout to calculate entrance capacity.
- Impact of natural parameters like weather, location of roundabout, disturbances due to other sources can be studied qualitatively.
- Use of micro-simulation technology in roundabout entrance capacity estimation.

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Appendix-1. Ranking of the models as per MRI

Model	Data	Best Fit Calculations			Error Measuring Parameters				Arithmetic Calculations of EC_P/EC_O			Cumulative Probability of EC_P/EC_O			±20% Accuracy (%)			Overall Rank	
		R^2	E	**R1**	AAE	MAE	RMSE	**R2**	μ	σ	**R3**	Ratio at CP_{50}	Ratio at CP_{90}	**R4**	Log-normal	Histogram	**R5**	MRI	**Final Rank**
WLSR	Training	0.906319	0.905212	**2**	205.137	589.8553	256.7589	**2**	1.021996	0.1557	**2**	1.001447	1.237353	**2**	82.13685	84.41	**2**	10	**2**
	Testing	0.859173	0.790763		225.5017	622.1194	274.0672		1.116139	0.163587		1.085843	1.37666		69.0719	63.64			
SASEGASA	Training	0.920311	0.920311	**1**	171.8483	541.1035	213.7688	**1**	1.017478	0.130504	**1**	1.012332	1.180227	**1**	87.95761	90.91	**1**	5	**1**
	Testing	0.949249	0.947014		146.0482	470.4916	182.8353		1.050232	0.172684		1.013725	1.299548		79.04906	84.85			

Note: R1, R2, R3, R4, R5 = Ranking of models according to different parameters
E = Nash–Sutcliffe model efficiency coefficient, AAE = Average absolute error, MAE = Maximum absolute error, RMSE = Root mean squared error, EC_P = Predicted entrance capacity, EC_O = Observed entrance capacity, MRI = Modified Ranking Index