MODIFICATION IN HCM DELAY MODEL FOR ROUNDABOUT FOR MIXED TRAFFIC CONDITIONS - A PILOT STUDY

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Resume

Roundabouts have proven to be an effective intersection design method for smooth traffic flow movements and improved safety. Previous studies show that VISSIM, commercial traffic simulation software, can be used as a proficient tool for modeling and efficiently analyzing roundabouts. This paper focuses on developing a methodology for modeling roundabouts in India using VISSIM. Three typical roundabouts were chosen from the northern part of India. Calibration and validation of the model were performed to ensure the correctness of the model. The average delay and volume to capacity ratio (v/c ratio) were compared for developing the level of service (LOS) thresholds for Indian conditions. The thresholds are compared with existing guidelines provided by the HCM 2010 and AUSTROADS. In addition, the methodology for determining modification factors for applying HCM 2010 delay model in Indian traffic conditions is defined.

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1 Introduction

The presence of vehicles of various kinds with significantly diverse physical and operational features characterizes traffic in developing countries like India, which is essentially random and haphazard. Apart from that, moving vehicles might take up any convenient lateral position on the road without any regard for the lane discipline. The current state of traffic adds to the safety concerns at intersections. A roundabout may reduce delays and enable safer movements under moderate traffic conditions as the traffic flow merges and diverges at comparatively small angles and lower speeds [1]. A higher degree of safety is achieved partially due to a reduction in the speed of the vehicles entering the roundabout. Typically, at signalized intersections, vehicles waiting for the green light do not stop the engine and hence, besides safety, roundabouts provide an advantage of reduced pollution at intersections since the waiting time is comparatively very small for the entering vehicles. However, the movement of traffic and vehicular interactions at the roundabout has been a major concern to the researchers since the parameters of the traffic flow have a major impact on efficiency of any road facility. Hence, for planning safe and efficient movements, understanding the operational performance of roundabouts is essential. This warrants the need for analyzing a multitude of roundabouts in terms of geometric and traffic conditions. Developing countries like India, face challenges due to inadequate number of the standard roundabouts, which could help in understanding and analyzing traffic behavior. Hence, Simulation is widely acknowledged as one of the most effective approaches for modelling the traffic flow in heterogeneous conditions. The VISSIM is a widely used micro-simulation software that helps to model various roadway facilities. Since VISSIM imparts provision for creating links without lane discipline, the developed model can be admissible to represent Indian roadway conditions.

Most discussions, related to roundabout or network modelling, call attention to the need for addressing the calibration and validation of roundabouts. Calibration can be performed by changing the conflict areas or priority rules, speed distribution and fine-tuning is attained by changing driving behavior parameters [2]. The reliability of the model thus developed is examined by validation of the results obtained from the model. Validation can be done by considering microscopic and/ or macroscopic parameters. The model used in the study has been validated using the microscopic and macroscopic parameters of the traffic flow.

Performance evaluation is essential for the effectiveness of a facility. Delay can be feasibly considered as a critical performance measure of roundabouts. It is the extra time spent by vehicles before clearing the intersection. Delay results in the loss of time to the vehicle's occupants, increased fuel consumption and additional air pollution [3-4]. This delay value considers the extra time that an average vehicle encounters in the roundabout, either directly or indirectly. The total delay includes geometric delay, queuing delay, acceleration and deceleration delay and stopped delay. A new approach is introduced in the current study for estimating average delay by using the trajectory data of entry vehicles obtained from the VISSIM output.

Further, plots for the delay value obtained from the field data through the trajectory and the delay value by the HCM 2010 model are compared and modification factor for applying the HCM 2010 model in Indian condition is attempted as a part of the pilot study. The HCM introduced the term level of service (LOS) to describe the level of quality that may be achieved under various operational conditions and traffic volumes. Methodology to develop the LOS thresholds and thus the performance evaluation is designed as a part of this pilot study on three different roundabouts. The same can be adopted for planning and designing efficient roundabouts under heterogeneous traffic flow conditions.

The paper is divided into 11 sections. Section 1 is introduction of the content of the paper. Section 2 concentrates on the literature review for the research papers based on analysis of various parameters of the roundabout with a prime focus on simulation. Section 3 mentions the objectives of the analysis presented in the paper. Section 4 discusses the methodology adopted for the data collection and Section 5 highlights the heterogeneity in traffic at study areas along with turning movement counts. Section 6 is dedicated to the critical gap analysis on the selected study areas. Sections 7 and 8 are dedicated to development of the simulation model and its validation. Section 9 focuses primarily on the development of the delay model. Section 10 is an attempt to suggest a modification factor for the HCM 2010 delay model, while applying the same in heterogeneous traffic conditions. Section 11 presents the conclusions drawn based on analysis and observations made through the field data and data obtained from the simulation model.

2 Literature review

The majority of simulation studies on roundabout performance evaluation were conducted in developed countries where traffic is homogeneous and the priority rules, as well as lane discipline, are voluntarily observed. Studies are limited under heterogeneous traffic conditions where vehicles occupy the entire road space without any lane discipline and priority rule. Simulation tends to be a helpful practice in such cases. Xiang et al. [5] applied the microsimulation model for capacity estimation at the roundabout in China. The model was calibrated and validated using the gap acceptance criteria. Due to flexibility offered for the lack of lane discipline and priority rules [6], VISSIM is used in the present study for developing a simulation model. The VISSIM calibration in mixed traffic conditions was presented as an approach by Manjunatha et al. [7] and a multi-parameter sensitivity analysis was used to identify calibration parameters. Li et al. [8] investigated the effect of the VISSIM parameters on the critical gap and follow-up headway and used the sensitivity analysis to quantify their findings. Based on the sensitivity analysis results, recommendations were made for calibrating VISSIM roundabout models. These suggestions were employed in the current study for simplified model calibration, with some modifications to make it more suitable for heterogeneous traffic conditions.

Gallelli and Vaiana [9] studied the variation of stop-line delay for geometric elements, characteristics of traffic flow and behavioral features. Results provide an insight into the sensitivity of the model to different input parameters. Kang and Nakamura [10] studied the impact of conflicting pedestrians in estimation of a roundabout entry capacity. Sisiopiku and Oh [11] conducted studies for evaluating roundabout performance using SIDRA. The performance of roundabouts was evaluated concerning delay and capacity. Akcelik et al. [12] discussed issues related to the calibration of models for analyzing roundabout capacity and performance and studied the delay criteria for the level of service definition of roundabouts. In addition, they added various methods for queue calculation and showed how it varied with different flow rates. Asaithambi et al. [13] developed the Passenger Car Unit (PCU) at Signalized Intersections using a microsimulation model for the mixed traffic conditions. Praticò et al. [14] used the microsimulation approach for prediction of operating speeds at the roundabout.

In summary, the existing literature suggests that studies concentrated on data based on homogeneous lane-based traffic conditions. Previous calibration researches have used qualitative analysis to study the impact of VISSIM parameters on roundabout capacity and performance evaluation. Furthermore, studies are limited under mixed traffic conditions for the analysis of unsignalized intersections and roundabouts. Most of the literature focus on the performance evaluation of roundabouts which are limited to the service delay estimations of signalized intersections. This study focuses on tackling this issue by developing a methodology for defining the LOS thresholds for roundabouts under Indian conditions using the control delay as a measure.

3 Objective of the study

The performance of roundabouts under mixed traffic conditions needs attention as the specifications developed for homogeneous traffic are extremely different from Indian conditions. The collection of required data from the field is difficult under Indian conditions due to inadequate standard study areas with varied traffic flow characteristics. This necessitates developing simulation models for various analyses. The foremost objective of this study aims to calibrate the VISSIM model in

***Table 1** Inventory details*

	R1(Chandigarh)	R2(Chandigarh)	R3(Jaipur)
Inventory details (m)			
	30°43’45.98”N 76°45’26.51”E	30°43’19.78”N 76°44’45.36”E	26°54’39.89”N 75°47’49.26”E
Entry Width	7	8.5	10
Exit Width	7	8.5	10
Approach Width	6.7	7.5	8.0
Departure Width	6.7	7.5	7.5
Circulating width	8	7	12
Weaving Length	28	33	28
Diameter	25	37	25
Perimeter	157	235	157

terms of the driver behavior attributes, conflict area setting, priority rule, etc. In addition, an attempt has been made to validate the VISSIM model with respect to travel time (microscopic validation) and critical gap (macroscopic validation). As the delay estimation (a measure of performance for assessing the level of service) was difficult from the field, this study evaluates the suitability of microscopic simulation model for the same and develop a methodology for defining the LOS thresholds and modification factor to delay model suggested in HCM 2010 for heterogeneous non-lane based traffic conditions.

4 Data collection

For the present study, three conventional four-legged roundabouts with diameters ranging from 25 to 40 meters were selected (R1, R2 and R3). The most important factor to consider while choosing a roundabout was that it would be free of the effects of parked vehicles, curves, gradient, pedestrian movement and any other side friction. For all the selected roundabouts, the approach roads are four-lane divided.

On a typical weekday, data was collected using the high-resolution video cameras positioned at vantage positions on surrounding high-rise buildings to capture the full camera view of selected roundabouts during the peak and off-peak hours. During the morning and evening peak hours, significant queue development was noticed, causing significant delays in traffic flows at all the roundabouts. Inventory data for the selected roundabouts are tabulated as shown in Table 1.

5 Traffic composition and Turning Movement Count (TMC)

To quantify the traffic operations in the roundabout area, the traffic composition and TMC are usually used. For the present study, turning movement count was carried out manually by observing the recorded video playing it repeatedly for various times. Vehicles were classified as Two-wheelers (2W), 3-Wheelers (3W), small cars (4WS) and big cars (4WB), Light commercial vehicles (LCV) and Busses and Truck (Bus). Being urban intersections, heavy commercial vehicles (Trucks) were observed in negligible proportion and hence are merged with Buses. The proportion of bicycles and pedestrians was less than 1% and hence not considered. The traffic composition and turning movement count details are shown in Figure 1.

6 Estimation of the critical gap

One of the essential criteria that represent the aggression of the drivers is the critical gap. It has an impact on roundabout capacity and delay and is defined as the smallest gap (shortest feasible time period) that an entering vehicle can take up before safely merging into the circulating stream. Estimation of the critical gap is studied by various researchers and different deterministic and probabilistic methods were proposed, as well. A critical gap can be defined as the intersection point of the cumulative distributions of accepted and rejected gaps [15]. Under heterogeneous traffic conditions, it would be appreciated when the

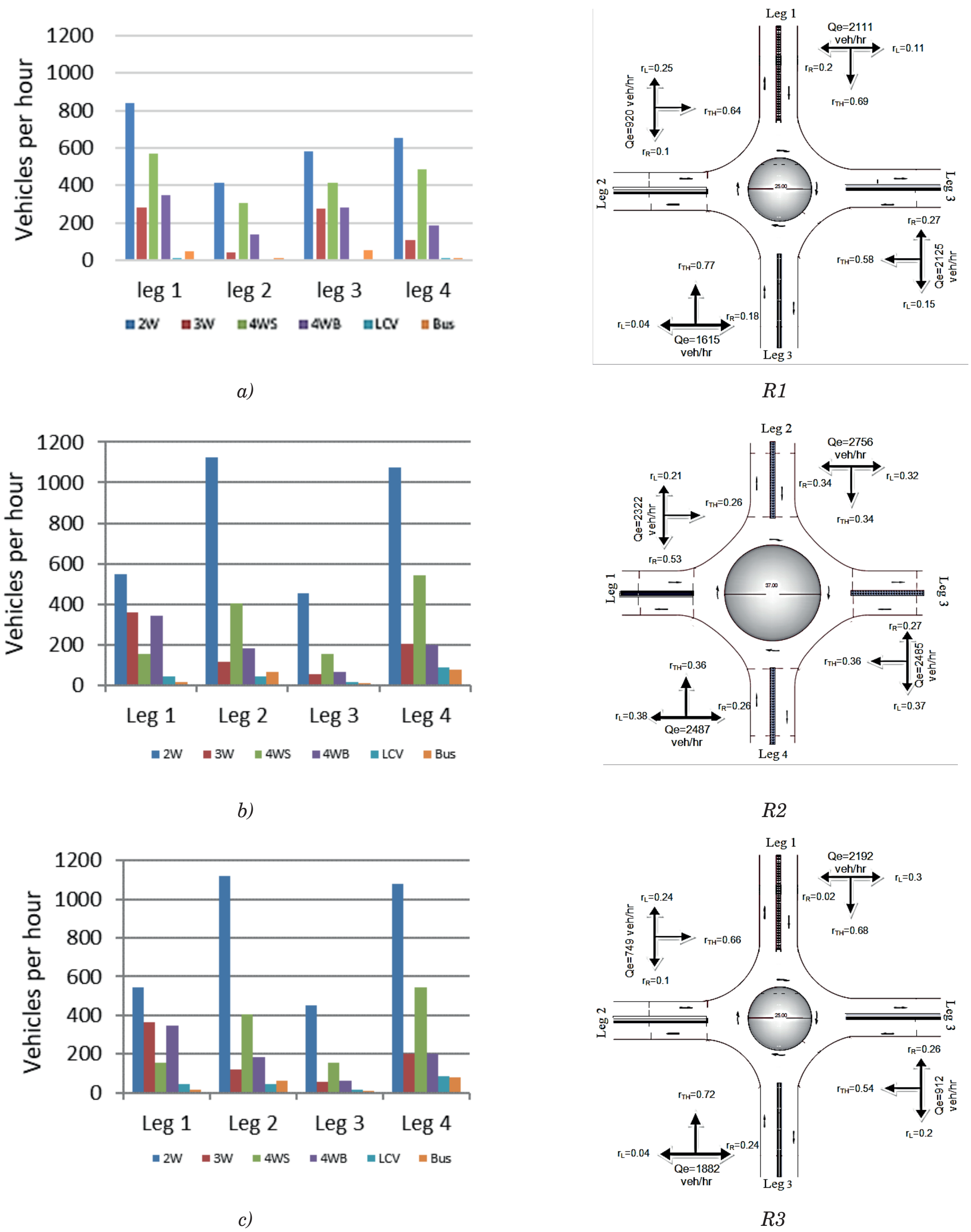


***Figure 1** TMC and classified vehicle count for (a) R1 (b) R2 (c) R3*

***Table 2** Critical gap in seconds estimated using the Raff's method*

Vehicle Type	R1	R2	R3
Two- Wheeler	1.2 s	1.4 s	1.2 s
Three- Wheeler	1.2 s	1.3 s	1.5 s
Small Car	1.5 s	2.0 s	1.9 s
Big Car	1.7 s	2.1 s	1.5 s
All	1.5 s	1.8 s	1.6 s

critical gaps are estimated for various vehicle categories, as it can be observed from the field that critical gap value increases with an increase in vehicle dimensions. The combined critical gap value is further used for validation of the simulated model. The critical gaps obtained for various vehicle types are shown in Table 2.

Bus and Trucks have a smaller proportion which may lead to erroneous values and hence are excluded from Table 2.

7 Calibration of the VISSIM model

The major goal of simulation model development is to create a model that accurately represents the design and operational attributes of roundabouts in a simulation software. Geometric elements of roundabouts can be design attributes, while the vehicle or driver characteristics and traffic flow data can be an operational attribute. Simulation models of all the study locations were developed using the VISSIM 8.0 Software.

From the collected field data, it is observed that the traffic flow is highly heterogeneous and gives low consideration to the priority rules. As a general regulation, a minor stream vehicle has to stop and wait for an acceptable gap in the major stream so that it can safely negotiate the intersection. However, the software will always have some pre-defined assumptions underlying it. Hence, calibration is done with extreme precision to adjust the model to accurately replicate observed traffic flow conditions, while taking into account the actual field conditions. Parameters of the car-following model Wiedemann 74 were calibrated from earlier studies conducted in similar traffic conditions to replicate the behavior of Indian traffic [16-19].

Desired speed values were obtained for each vehicle type from the travel time and the distance travelled by them. The cumulative distribution of desired speed was plotted for R1, R2 and R3 and it was given as input to the simulation model. Figure 2 shows the cumulative distribution of desired speeds at roundabout R1. It is to be noted that due to the small proportion of Trucks, Bus and Truck are combined for further analysis.

Conflict areas at the roundabout are those locations where merging and diverging of vehicles occur. As a general rule, vehicles in the circulating flow (major stream) are given higher priority than entering flow (minor stream). VISSIM facilitates the prioritization accordingly by setting the conflict areas. Conflict areas in the simulation model are the areas at which two links or two connectors or a link and connector intersect with each other. These conflict areas are to be modelled carefully for avoiding vehicular conflicts.

There are four types of conflict areas in the VISSIM model namely 1 waits for 2, 2 waits for 1, undetermined and passive. First, two states are to be used when the major stream crosses the minor stream. When the two major streams intersect, either undetermined or passive are to be used. Undetermined state implies that vehicles in both intersecting streams act as if they were in the same link. This state of conflict areas was considered for modelling the traffic movement at the merging and diverging sections. Passive state implies that the

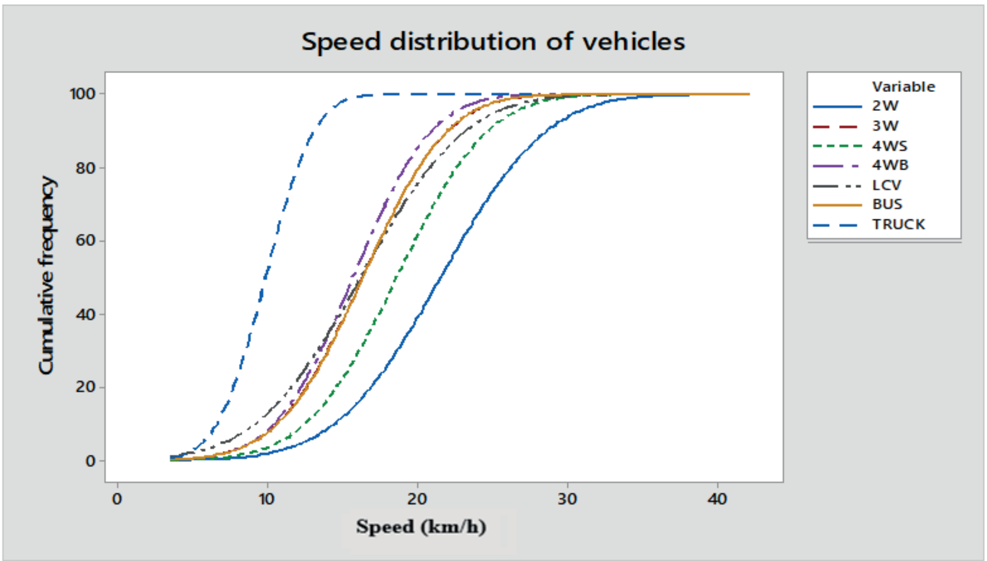


Figure 2 *Cumulative distribution of speeds at roundabout R1*

Table 3 *Conflict areas for R1 and R2*

Parameter	Default (m)	Calibrated (m)
Front gap	0.5	0.1
Rear gap	0.5	0.1
Meso critical gap	3.0	2.5
Safety distance factor	1.5	0.6
Additional stop distance	0	0

Table 4 *Calibrated values of priority rule*

Element	Conflict marker 1		Conflict marker 2	
	Default	Calibrated	Default	Calibrated
Min. gap time (s)	3.0	0.0	3.0	1.8
Min. headway (m)	5.0	12.0	5.0	0.0
Max Speed (km/h)	180	14	180	180

(a) Conflict area settings for R1 and R3 *(b) Positions of the priority rule*

Figure 3 *Calibration of the VISSIM model*

priority is not assigned beforehand and this will result in the collision of the vehicles during the simulation run. This is the default status that the simulation model assigns itself, as soon as it detects the conflict areas where traffic from intersecting streams meet each other. This status also needs to be set based on the field observations and may vary from one road facility to the other. Depending on the location and type of conflict (merging or diverging), the status of conflict areas is set and modified according to the field behavior in a trial and error process. The exit priority was made as passive as shown in Figure 3(a), to replicate the field condition. The default and calibrated parameter values of conflict areas are shown in Table 3.

To suit the actual traffic behavior observed in the study area, priority rules are defined, as well. The priority rules are usually given when the conflict areas alone are not adequate to replicate the field conditions [20] also the application of priority rule provides consistent and repeatable gap acceptance behavior [21]. Especially in the case of some intersections, conflict areas alone may result in unnecessary queues in any of the arms of the intersection. So, the priority rules are used to avoid the tailback in the links at the intersections along with the conflict areas. For the present study, similar conditions of the tailback and unnecessary queues are observed for roundabout R3 and hence, conflict areas in this roundabout model are modelled using the priority rules.

The priority rules are placed using a trial and error method to produce vehicular priority behavior that is visually similar to observations from the field. The parameters of the priority rules considered for modelling and calibration are the minimum time gap, headway and maximum speed. The minimum headway signifies the distance from the conflicting zone and the first vehicle approaching the conflicting zone. The time it takes for the first upstream vehicle to reach the conflict zone is considered as the available time gap. The conflict zone is shown in Figure 3(a). Red marked zone indicates a priority zone where entering vehicles are required to stop and wait for a suitable gap before entering. The green marked zone shows the area considered for merging and the yellow-colored area indicates diverging. It is also required to enter the gap values for vehicles traversing the conflict areas. Conflict marker 1 is the green bar, which is in the downstream end and conflict marker 2 is the green bar in the upstream end of a priority rule. Figure 3(b) shows the positions of the priority rule and the calibrated parameter values of the priority rule have been given in Table 4.

Driving parameters are adjusted to replicate the actual behavior of different vehicle types while motion and standstill to an acceptable level of accuracy. The parameters of the inbuilt driving behavior model, Wiedemann 74, are calibrated and used in the present study. Various parameters are adjusted until the desired results are obtained through the trial and error process and the final values are shown in Tables 5 and 6. The lateral clearance values used for R1, R2 and R3 are finalized based on the study conducted in Indian traffic conditions by Arasan and Arkatkar [22].

Driving behavior at two study locations (R1 and R2) situated in the same city is identical and hence the same parameters are adopted for R1 and R2.

8 Validation of the VISSIM model

The model validation was performed by using the travel time (occupancy time) of vehicles from entry to exit

Table 5 Calibration parameters, [22]

Sl. No.	Vehicle category	Lateral clearance (m)	
		At speed 0 km/h	At speed 50 km/h
1	Two-wheeler	0.25	0.3
2	Three-wheeler	0.25	0.3
3	Car	0.3	0.5
4	LCV	0.3	0.5
5	Bus	0.4	0.7

Lateral clearance share adopted based on the vehicle category

Table 6 Calibrated Wiedemann 74 parameters for R1 and R3

Sr. No.	Following vehicle category	Wiedemann 74 parameters for R1 and R2			Wiedemann 74 parameters for R3		
		AX	bx_add	bx_mult	AX	bx_add	bx_mult
1	Two-wheeler	0.5	0.3	0.35	0.3	0.25	0.3
2	Three-wheeler	0.5	0.4	0.45	0.3	0.35	0.4
3	Car	0.5	0.6	0.7	0.3	0.5	0.6
4	LCV	0.5	1.2	2.0	0.3	0.4	0.6
5	Bus	0.5	1.5	2.0	0.3	1	1

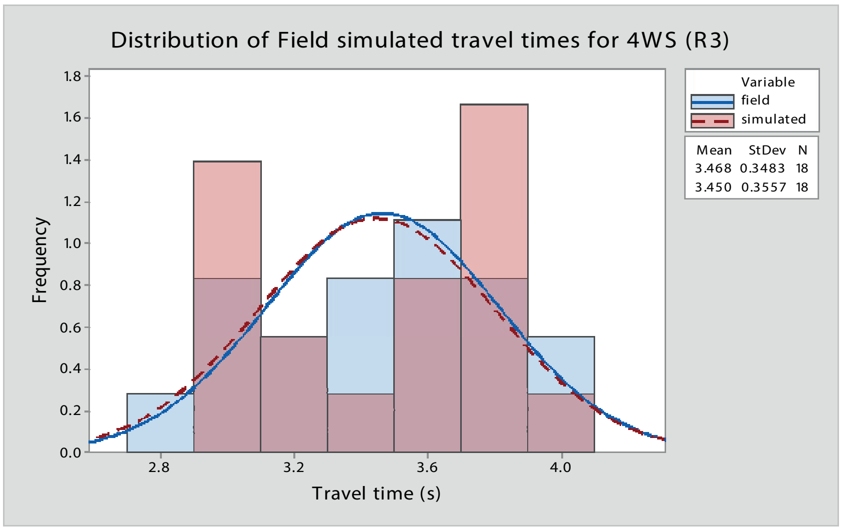


***Figure 4** Normal distribution of field and simulated travel times*

of the roundabout. The time taken by the subject vehicle to clear the roundabout is defined as the occupancy time in a particular direction of movement. Due to changes in the length traversed, it was observed individually for the left-movement, straight-movement and right-turn movement. As a result, the time difference between the two timestamps (entry timestamp at which the subject vehicle's front bumper enters the roundabout and exit timestamp at which the same vehicle's back bumper exits the roundabout) is considered to calculate the time occupied by each of the vehicle categories in the extraction process. It is worth noting that the time occupancy takes into account the impact of various roadway geometries and traffic conditions on a vehicle's movement in a roundabout. The data was collected in the field and compared to the model's travel time predictions. The sample distribution of the travel time derived from the calibrated model for small cars in R3 is shown in Figure 4.

To check the statistical significance of the trend, a two-tailed paired t-test has been performed. The null hypothesis is 'H0: There is no change in occupancy time in the simulation model. The alternative hypothesis is 'H1: The occupancy time significantly changed in the simulation model. It was observed that the model is performing reasonably well. Test results are summarized in Table 7.

Microscopic validation was performed using the critical gaps obtained from the field and simulation. Raff's method was employed for evaluating the critical gap from the observed, accepted and rejected gaps. Variation of the critical gap from the field and that

Table 7 *t-test results on travel time for (a) R1 and (b) R3*

Roundabout/Vehicle Category	R1			R3		
	Left	Straight	Right	Left	Straight	Right
	p-value	p-value	p-value	p-value	p-value	p-value
2w	0.551	0.879	0.258	0.44	0.978	0.53
3w	0.768	0.674	0.344	0.476	0.813	0.45
Small car	0.717	0.533	0.328	0.09	0.694	0.829
Big car	0.705	0.612	0.114	0.362	0.716	0.585
LCV	0.733	0.134	-	0.47	-	-
Bus	-	0.884	0.1	-		-

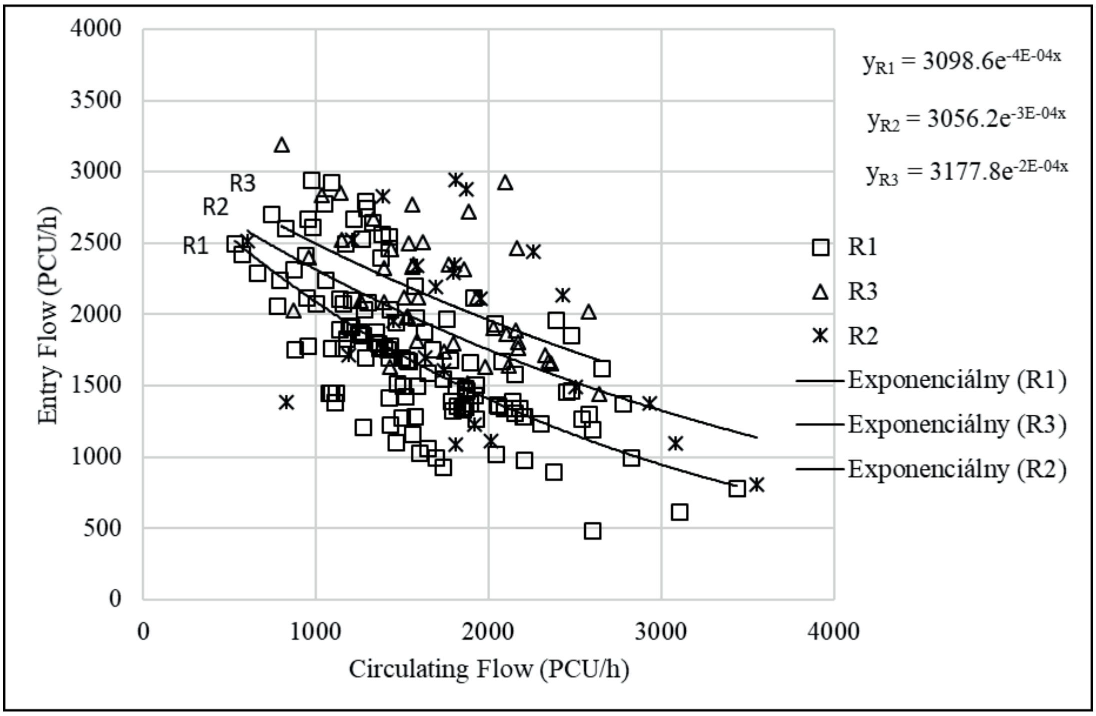


Figure 5 *Entry flow and circulatory flow plot*

obtained from simulations, follow a similar pattern in all the selected roundabouts. The major discrepancy in the critical gap is observed in two-wheelers where the critical gap value obtained from the field is 1.5 s, whereas, from simulation, it is reported as 1.7 s. The variation may be attributed to the abnormal behavior of the two-wheelers in the field. The two-wheelers are accepting all the possible gaps available for them, but in simulation, vehicles behave according to the predefined settings.

9 Performance evaluation of roundabout

The capacity and level of service are important indicators of the roundabout's performance. The maximum number of vehicles that can enter in unit time at a given entry leg for the flow in a circulating roadway is defined as the capacity of a roundabout. The relationship between entry capacity and circulating flow is developed from the simulated model. The dependent variable is the entry capacity, while the independent variable is the circulating flow. The entry capacity is estimated using the conflicting flow in the circulatory roadway area, which includes various turning movements for different vehicles categories from other approaches that pass in front of the subject approach leg for which the entry capacity is to be estimated. It is observed that the relationship between the entry capacity and circulatory flow is negative exponential. It means that as the circulating flow increases, the entry capacity decreases exponentially. Figure 5 depicts the relationship between the entry and circulatory flow observed in the study areas.

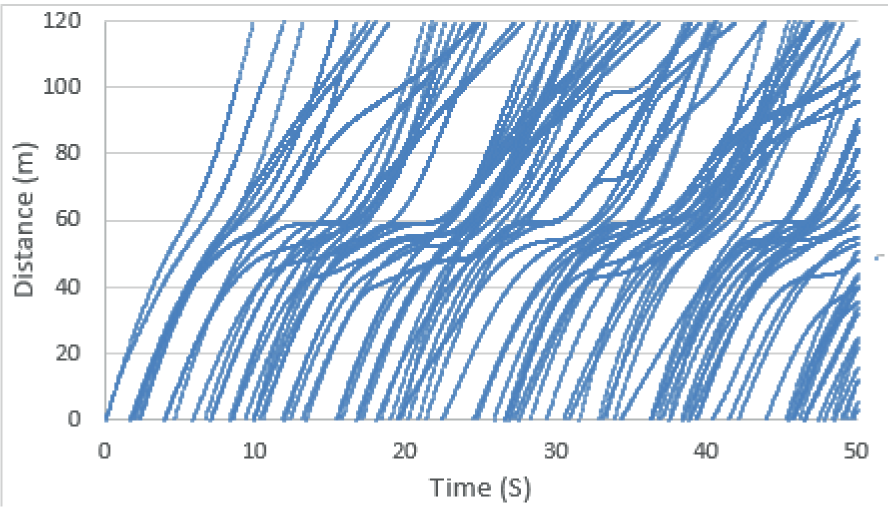
Delay is the major performance measure for the level of service of a roundabout. Average delay can be defined as the delay per vehicle expressed in seconds. The average delay for any minor road vehicle is a function of the capacity of the approach and the degree of saturation (HCM 2000). HCM 2010 has suggested the following equation for estimating delay at a roundabout:

$$d=\frac{3600}{c}+900T\times\left(x-1+\sqrt{(x-1)^2+\frac{\left(\frac{3600}{c}\right)x}{450T}}\right)+5*\min(x,1), \tag{1}$$

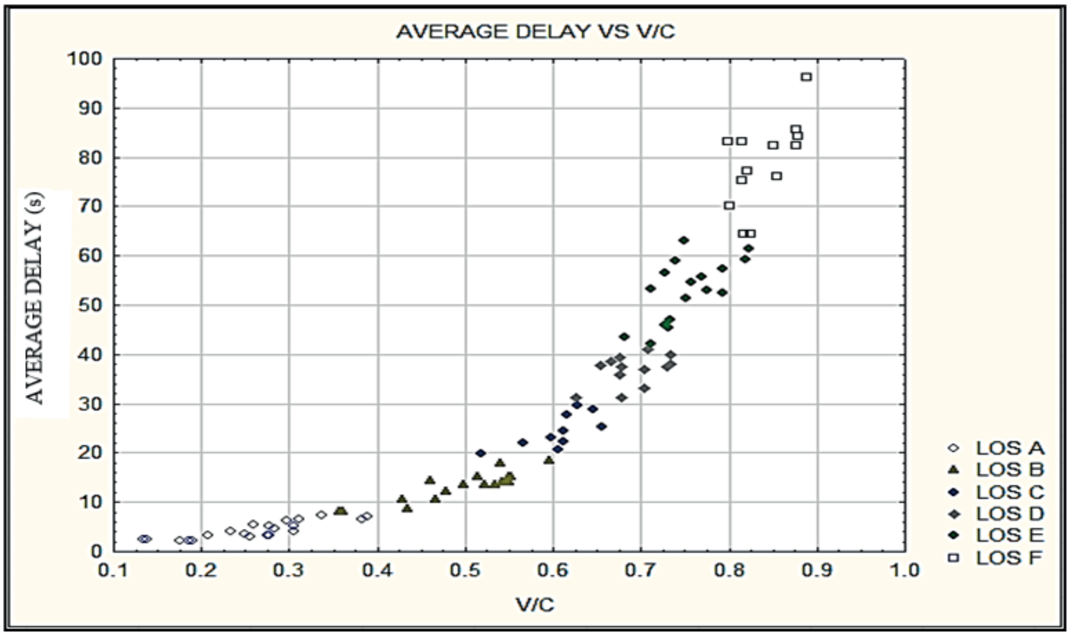
where:
d = average control delay (s/veh),
x = volume to capacity ratio,
c = capacity of subject lane (veh/hour),
T = time period (T = 0.25 h for a 15-min analysis).

In the present study, the average delay was calculated from the VISSIM model generated trajectory data of entry vehicles. A sample plot of the trajectories generated from the simulation model is shown in Figure 5. Some vehicles can enter the roundabout without stop delay and some vehicles may have to stop and go at the intersection. All these conditions can be observed in Figure 6(a).

In this study, the Monte-Carlo simulation technique was employed for generating data with a known cluster structure. The resulting graph shows a rising exponential curve, as shown in Figure 6(b), which is the expected trend of delay. The delay experienced up to a certain degree of saturation will be almost the same and as the degree of saturation reaches a value close to the capacity, the delay will rise rapidly. The LOS is an indication of the suitability of delay to the drivers. For developing the LOS thresholds for roundabouts in Indian conditions, k-means clustering was performed on the delay plot. The clustering results are shown in Figure 6(b). Existing guidelines offered by HCM 2010



a) Trajectory data of entry vehicles



b) LOS thresholds for the roundabout

***Figure 6** Plots for trajectory data and the LOS threshold for the entry flow*

***Table 8** Comparison of existing level of service guidelines to the present study*

LOS	Average Delay		
	Present Study	AUSTROADS	HCM 2010
A	<10	<10	<10
B	10-20	10-20	10-15
C	20-30	20-35	15-25
D	30-40	30-50	25-35
E	40-65	50-70	35-50
F	>65	>70	>50

and AUSTROADS for LOS for roundabouts are based on a delay. It can be seen that the HCM has lower levels of a delay for each level of service and the results from the present research are found much deviating from the HCM 2010. However, AUSTROADS guidelines are almost comparable to the current study. A comparison of existing practices of the LOS given by HCM 2010 and AUSTROADS to the current study findings is shown in Table 8.

10 Modification of the HCM 2010 delay model

Due to the heterogeneous traffic conditions in India, there is a mix of vehicle categories with different static and dynamic characteristics. Driver's behavior in developing countries like India is additionally a point of concern. It is a usual observation in Indian traffic conditions that priority rules are not observed by the minor traffic and lane discipline is absent. It contributes towards increased delay to entry vehicles at roundabouts. However, the delay model suggested by the HCM is developed considering the traffic conditions in developed countries where the lane discipline and priority rules are strictly adhered to. This necessitates modifying the delay equation suggested by the HCM 2010 to be applied in heterogeneous traffic conditions in India. To understand the variation in delay in Indian traffic conditions, a plot for a delay, obtained in the present study (vehicles based and PCU based) observations and the delay values predicted by the HCM 2010 model for different entry flows is plotted in Figure 7.

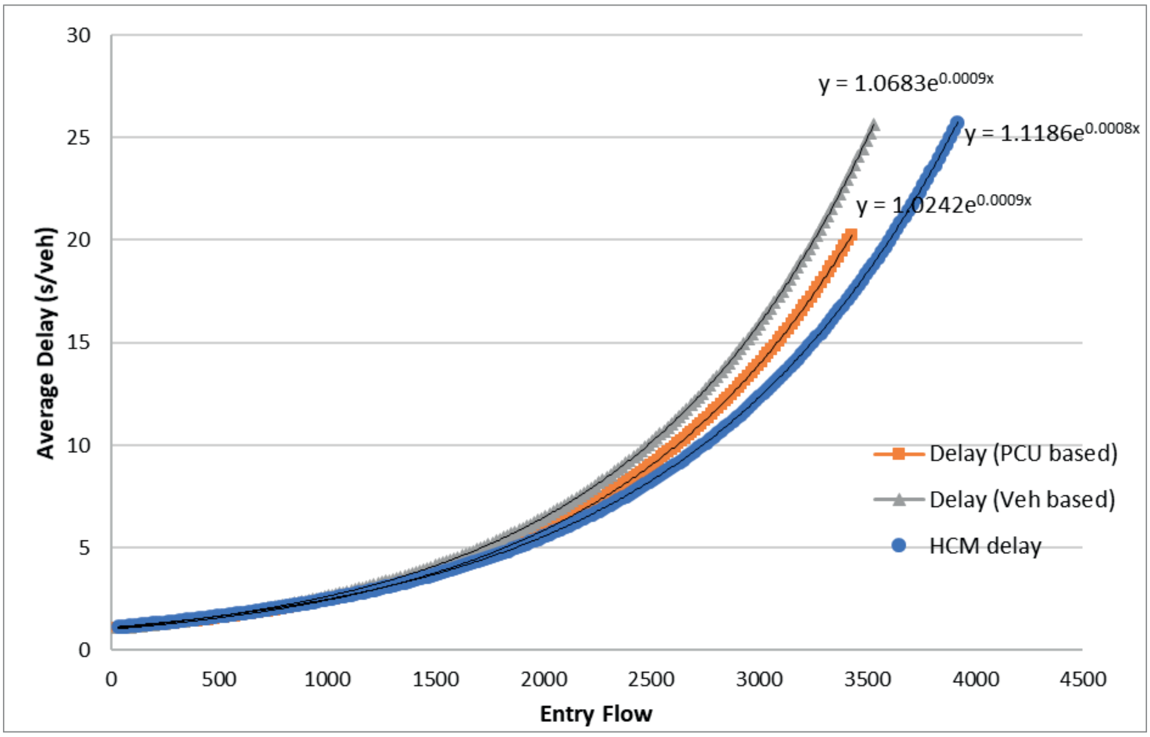


***Figure 7** Delay and entry flow plot at the roundabout*

***Table 9** Comparison of the estimated delay values*

	Minimum Delay (s)	Maximum Delay (s)	Average Delay (s)
Present Study	1.11	29.52	8.72
HCM 2010	1.01	47.89	6.94

From the plot, it is observed that both the delay values (observed from field data and predicted by the HCM 2010 delay model) increase exponentially with an increase in entry flow. It is also observed that in the free-flow condition (up to entry flow of 1500 vehicles per hour), in Indian traffic conditions, entering vehicles do not interfere with circulating vehicles which depicts that priority rules are observed and hence the delay plot follows the same trend as predicted by the HCM. Trends are similar for observations in terms of vehicles and that in terms of PCU. Further increase in entry flow reduces the headway, which increases interaction between entering and circulating vehicles. This results in vehicles stopping at the entry for the preferred gap before entering the circulatory flow. Hence, from the plot, it can be observed that a lack of the lane discipline and the absence of priority rule increase the waiting time for the entry vehicles. It can be observed from the plots that delay, when measured in terms of PCU, gives a slightly lower values.

Further, as the entry flow increases beyond the free-flow conditions, traffic in developed countries are observed to continue following lane discipline and priority rules. This observation can be validated through the above plot as the delay time in the study area is higher than the values predicted by the HCM model after the free-flow condition. Additionally, when priority rules are followed during the occurrence of saturated flow, vehicles have to wait for a longer period for the acceptable gap, which increases the delay time considerably. However, in the absence of priority rules, the entering vehicles create a forced gap and hence the there is no change in the trend of increase in delay values with an increase in entry flow. When the saturated flow condition exists, the delay predicted by the HCM model increases rapidly as compared to the field observation. The minimum, maximum and average delay values obtained from the present study and HCM 2010 model are presented in Table 9.

From Table 9, it is observed that the minimum delay values, obtained from the study area during free-flow conditions, are quite close to each other. However, as discussed, in saturated flow conditions, the delay value is higher for the priority rule-based flow conditions and hence the maximum delay value is higher than that observed in non-priority rule following traffic conditions. Hence, it is concluded that the delay values predicted by the HCM model are not suitable for direct application when the priority rules are not adhered to. This causes a need for a modification factor for the HCM model to be applied in heterogeneous conditions like India. After analyzing the delay values in both conditions, the present study attempts to determine the modification factor using the data from three roundabouts as a part of a pilot study. The analysis of this pilot study suggests a multiplication factor of 1.25 to be adopted for using the HCM model in Indian traffic conditions, as shown:

$$d' = d * 1.25, \tag{2}$$

where,
d' = average control delay (s/veh) in heterogeneous traffic condition,
d = average control delay (s/veh).

Hence, the modified HCM equation is:

$$d = \left\{ \frac{3600}{c} + 900T \times \left(x - 1 + \sqrt{(x-1)^2 + \frac{\left(\frac{3600}{c}\right)x}{450T}} \right) + 5 * \min(x,1) \right\} * 1.25, \tag{3}$$

where
d' = average control delay (s/veh) in heterogeneous traffic condition,
x = volume to capacity ratio,
c = capacity of subject lane (veh/hour),
T = time period (T = 0.25 h for a 15-min analysis).

After applying the correction factor, error in delay prediction through the HCM model in India traffic condition reduces to 0.05 seconds per vehicle from an earlier value of 1.78 seconds per vehicle and hence can be acceptable. Thus, the study proposes a modification factor of 1.25 to be adopted for heterogeneous traffic conditions where the priority rules are not followed. It is to be noted that the current analysis and suggestions are based on a pilot study carried on three roundabouts, so additional data are required to be analyzed using the same methodology.

11 Conclusions

This study presented a methodology for the performance evaluation of roundabouts under the mixed traffic conditions using VISSIM. The VISSIM model was calibrated by changing various parameters like speed distribution, conflict areas, priority rules and driving behavior. Validation of the simulation model was conducted using the occupancy time and critical gap. The statistical tests substantiated the reasonably good performance of the model. The critical gap obtained from the field and simulation is 1.5 seconds and 1.7 seconds, respectively. The variation is due to the presence of two-wheelers and their gap acceptance behavior, which cannot be captured exactly using the software.

The study was extended further to estimate the performance of roundabouts and to develop the LOS thresholds for roundabouts under the heterogeneous traffic conditions. Trajectory data of vehicles from VISSIM was used for calculating the average delay and corresponding volume of the minor stream. Since the data points were normally distributed, the Monte-Carlo simulation technique was employed to generate more points. The obtained plot is a rising exponential curve, which indicates that the delay increases exponentially with the degree of saturation. The average delay is increasing rapidly after a V/C ratio of 0.6. The K-means cluster analysis was employed to obtain the LOS for each range of delay. The obtained values are seen comparatively closer towards Australian guidelines and the HCM has the lower levels of thresholds.

Analysis of delay time per vehicle is carried out using the field data and the HCM 2010 model. The average delay per vehicle is slightly higher than the average delay per PCU. In addition, the average delay per vehicle is found to be higher in the field as compared to the values predicted by the HCM 2010 model. A multiplication factor of 1.25 is estimated in the present pilot study for estimating delay in heterogeneous traffic conditions using the HCM delay model. The methodology and results described in this pilot study may help transportation planners and engineers for suggesting a methodology to examine the performance of roundabouts in a heterogeneous traffic condition.

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