Roundabout Entry Capacity Estimation Under Heterogeneous Traffic Conditions

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Abstract: Traffic in developing countries are characterized by the presence of vehicles of different categories with widely varying physical and operational characteristics. Under moderate traffic conditions, a roundabout may reduce delay and enable safer movement in comparison with un-signalized intersections. The capacity of a roundabout is defined as the maximum number of vehicles that can enter the roundabout in a unit time at a given entry leg for the flow in a circulating roadway. PCU is an important element of traffic studies. Present study focuses on determining PCU values at different roundabouts and also determining the entry capacity of roundabouts with different diameters. The results of the present study are expected to compare the field capacity values with capacity values suggested by US-HCM and recently launched Indo-HCM. These findings may be used for planning and designing of roundabouts under heterogeneous traffic flow conditions.

*Keywords***:** Passenger Car Units; Roundabout; Occupancy Time; Entry Capacity

1. INTRODUCTION

Traffic intersections are complex locations on any road. This is because vehicles moving in different directions want to occupy same space at the same time. In addition, the pedestrians also seek same space for crossing. Drivers have to make split second decision at an intersection by considering his route, intersection geometry, speed and direction of other vehicles etc.

The capacity of a roundabout with heterogeneous traffic flow with vehicles of widely varying static and dynamic characteristics is best expressed in terms of PCU/h. This dictates an accurate estimation of PCU, which varies dynamically with various traffic flow parameters such as stream speed, vehicle composition and traffic volume. The PCU values of different types of vehicle are determined by keeping the small car as a standard vehicle. In the past, various researchers have adopted different approaches for the estimation of Passenger Car Unit (PCU) or Passenger Car Equivalent (PCE) values of vehicles. The bases used for the estimation process are: (i) delay (ii) speed (iii) density (1999), (iv) headway and (v) queue discharge. All these studies

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and their results, however, not always applicable to Indian conditions as these have been carried out under fairly homogeneous traffic conditions.

Major research on the capacity of roundabouts has been carried out in several countries including the United Kingdom, Australia, United States, Germany, and France and various models have been developed in past for analyzing the traffic flow on these intersections. These methods can be broadly classified in two groups. The first group consists of methods which are purely empirical and are based on geometry of intersections including entry width, entry angle, no of lanes in entry and circulation etc. The second group consists of methods which are based on Gap acceptance process.

The U.K. method is based on the formula proposed by Transport and Road Research Laboratory (TRRL). Geometric parameters like entry width, flare length, sharpness of the flare, entry bend radius, entry angle, inscribed circle diameter, etc. are mainly considered in UK method (Kimber 1980). The Swiss method is similar to the U.K. method but considers the effect of exiting traffic in the direction opposite to the entering traffic (Bovy et al. 1991)

In US HCM, the capacity of a roundabout entry (Q_e) was found to be the function of the one flow variable; circulating flow (Q_c), in a negative exponential regression equation while the HCM proposes an analytical approach based on critical gap and follow-up time to determine the entry capacity of a roundabout.

Chandra (2012) carried out a comparative assessment of various methods of capacity estimation and observed large variation in the results. UK model gave maximum and US model gave minimum capacity on approach. Present study is carried out to determine entry capacity of various roundabouts by field observations. Also, efforts have been put up to compare the entry capacity values using US-HCM and Indo-HCM.

2. STUDY AREA

Aim of the present study is macroscopic analysis of traffic flow characteristics at four legged roundabout. It is extremely important to study different traffic movements in all possible directions at entry and exit points of approaches in roundabout along with its circulatory traffic movement. For this purpose,5 four-legged roundabouts having diameter in the range of 23 to 49 m have been considered One located in Jaipur (Western part of India), Trivandrum (Southern Part of India) and three located at Chandigarh (Northern part of India). The approach roads are four-lane divided in all the directions for all the selected roundabouts. The geometric details are tabulated as below.

Table 1. Geometric details of selected roundabouts

	S. No.	Diameter	Circulating roadway width	Entry width	Exit width	Approac h width	Departure width	Weaving Length
R1	Chandigarh	25	8	7	7	6.7	6.7	28
R2	Chandigarh	37	7	8.5	8.5	7.5	7.5	33
R3	Jaipur	25	11.75	10	10.5	8	7.5	28.75
R4	Trivandrum	23.5	9.5	8.5	10	7	7.5	19.9
R5	Chandigarh	49.0	10.0	14.7	15.5	11.0	7.5	43.0

Data was collected on a typical weekday covering off-peak as well as peak hours. During morning and evening peak hours, substantial queue formation was observed due to which there was a considerable delay to traffic streams in both roundabouts. This aspect was focused to get data on traffic operation at roundabouts over varying traffic conditions.

3. TRAFFIC COMPOSITION

Vehicles are classified comprising of smaller vehicles: motorized two-wheeler (2W) , motorized three- wheeler (3W), Small Car (SC), Big Car (BC) and heavy vehicles: Light Commercial Vehicle (LCV), Bus and Truck. Vehicular composition for the selected roundabouts are shown in Table 1. It is observed that the proportion of smaller vehicles in traffic composition has a maximum share of around 95% at all the roundabouts and since located at urban areas, the composition of heavy vehicles is found to be less than 5 %. The proportion of vehicles at study locations is graphically represented in figure 1 below.

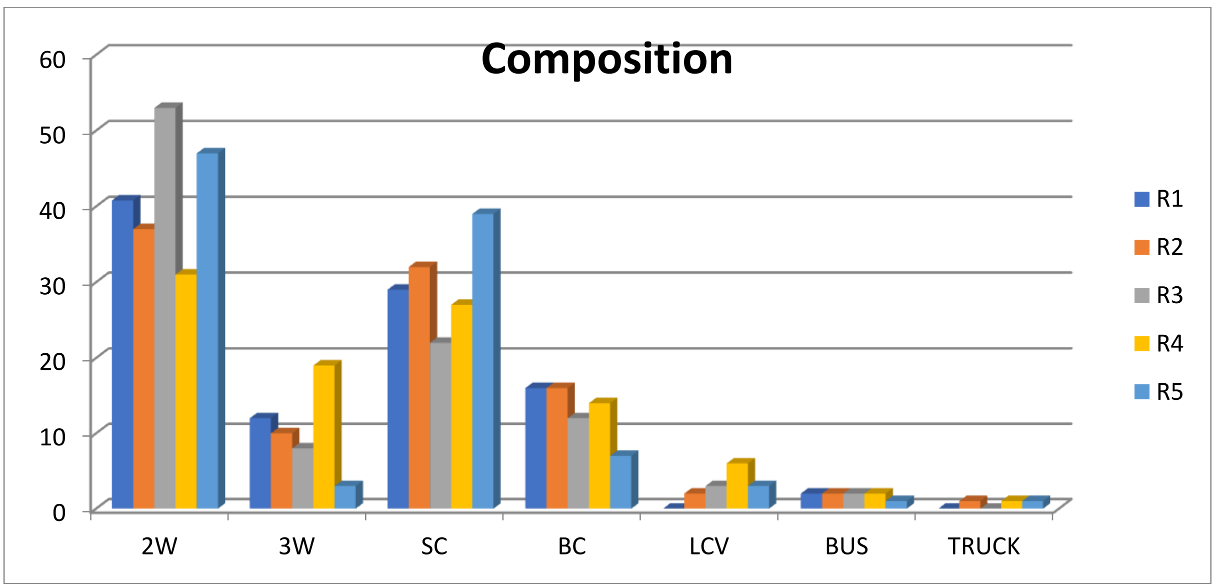

Figure 1. Bar Chart for Proportion of Vehicles

The heterogenous traffic condition in India is observed in figure 1 comparing the compositions of the roundabouts studied. The composition of various vehicle category at the different intersection was tested for paired t-test using intersection R1 ideal intersection by geometry. The results of Paired t-test was observed from 0.974 to 0.990 for each pair suggesting that composition doesn't have a significant difference between them and can be considered to be similar.

4. ESTIMATION OF PCU VALUE BASED ON TIME OCCUPANCY

The capacity of a roundabout with heterogeneous traffic flow with vehicles of widely varying static and dynamic characteristics is best expressed in terms of PCU/h. This dictates an accurate estimation of PCU, which varies dynamically with various traffic flow parameters such as stream speed, vehicle composition and traffic volume. The PCU values of different types of vehicle are determined by keeping the small car as a standard vehicle. Chandra and Kumar developed the concept of dynamic PCU considering the various traffic interactions and flow characteristics. The PCU for a vehicle can be calculated using equation (1)

$$PCU_i = \frac{V_c / V_i}{A_c / A_i} \tag{1}$$

Where, PCU_i is the PCU of the subject vehicle i; Vc =Average speed of cars in the traffic stream, Vi= Average speed of subject vehicles i; Ac= Projected rectangular area of a car as reference vehicle and Ai= Projected rectangular area of the vehicle type i.

4.1 PCU Value from Field Observation

In a roundabout area, it is difficult to measure the running speed of a vehicle as there are subsequent delays while the vehicle meets the entry flow from different legs. Further, the merging and diverging operation will lead to cover the various longitudinal path of a vehicle in the roundabout area. Hence, occupancy time was used to estimate the PCU values for different roundabouts. Time occupancy in a given direction of movement is defined as the time taken by the subject vehicle to clear the roundabout separately, for left-turn movement, straight movement or right-turn movement. Therefore, the time difference between the two timestamps (entry time stamp at which the front bumper of the subject vehicle enters into the roundabout at a particular entry point and the time stamp at which the back bumper of the same vehicle exits out of the roundabout), is considered as the time occupied by each of the vehicle categories in the extraction process. By employing this movement based time occupancy approach, it may be noted that an important parameter, that is, delay in weaving zone (measure of performance for assessing level of service) for a particular movement under consideration, is also incorporated in the occupancy time for PCU estimation.hence, it is logical to consider the total occupancy time of a vehicle in the roundabout area. A vehicle which occupies lesser time in the roundabout area will create less impedance to the circulating flow. Therefore, the PCU will be different for each vehicle category on the basis of time taken to clear the roundabout. It may be noted that by using this approach, the critical parameter for performance evaluation at intersections, delay, is also incorporated in the clearing time. Considering the above concept, the dynamic PCU equation proposed by Chandra and Kumar (2003) is modified and the total occupancy time of a vehicle type is compared with the occupancy time of standard car for estimation of dynamic PCU. The modified equation is given as Equation 2.

$$\textbf{PCU} = \frac{\textit{Clearing time(occupancy)ratio of } i^{th} \textit{vehicle to standard car}}{\textit{Space ratio of standard car to the i th vehicle}} \quad (2)$$

$$\boldsymbol{PCUi} = \frac{T_i/T_c}{A_c/A_i} \quad (3)$$

Where, PCUi is the PCU of the subject vehicle i; Tc = Average time occupancy of standard car in seconds; Ti= Average time occupancy of subject vehicle in seconds; Ac= Projected rectangular area of a car as reference vehicle in m^2 and Ai= Projected rectangular area of the vehicle type 'i' in m^2.

It may be considered as a real representation of the overall interaction of a given vehicle type (for which PCU is to be estimated) in reference to standard vehicle category as cars in the presence of other vehicle types. Hence, the clearing time variable represents the roundabout occupancy in comparison to a conventional car.

The PCU values for different categories of vehicles were computed for all three possible movements considering entry from all four legs and the values are given in Table 2.

Table 2 PCU Using Occupancy Time Method

R1	**Left**	**Straight**	**Right**	**R2**	**Left**	**Straight**	**Right**
2W	0.20	0.20	0.20	**2W**	0.20	0.19	0.18
3W	0.73	0.70	0.63	**3W**	0.64	0.67	0.54
S CAR	1	1	1	**S CAR**	1	1	1
B CAR	1.60	1.74	1.76	**B CAR**	1.27	1.59	1.40
LCV	2.20	1.90	2.59	**LCV**	1.60	1.96	1.16
BUS	6.10	5.98	5.79	**BUS**	4.60	4.70	4.67
R3	**Left**	**Straight**	**Right**	**R4**	**Left**	**Straight**	**Right**
2W	0.22	0.22	0.22	**2W**	0.21	0.23	0.23
3W	0.67	0.70	0.71	**3W**	0.63	0.63	0.69
S CAR	1	1	1	**S CAR**	1	1	1
B CAR	1.50	1.58	1.70	**B CAR**	1.54	1.59	1.61
LCV	1.83	1.92	2.10	**LCV**	1.67	1.71	1.77
BUS	4.02	4.37	4.41	**BUS**	4.06	4.50	4.87

From Table2, it is observed that PCU values for each vehicle categories in different directions are nearly same for four roundabouts. Due to non-availability of proper data at R5, it was not possible to determine occupancy time since the complete roundabout was not visible in videography. Hence analysis were carried out for the PCU values found at R1, R2, R3 and R4.

In order to understand relation between PCU values thus obtained for different directions, paired t-test was carried out between PCU values for left, right and straight movement. The t-test result concludes that PCU values obtained for each vehicle category are significantly similar

Also, analysis of variance (ANOVA test) was carried out on PCU values. F-value for all group of PCU was found as 0.070 which is less than F-critical value of 3.098 and hence the hypothesis, that there is no significant difference in PCU values and the average PCU values listed in is accepted.

Table 3. Suggested PCU values for Urban Roundabout in Heterogenous condition

	2-wheeler	3-wheeler	Small Car	Big Car	Light Commercial vehicle
Field observation	0.21	0.73	1.00	1.55	1.82
Indo-HCM 2017	0.32	0.83	1.00	1.40	1.64

The PCU values suggested above are obtained using occupancy method. It may be noted that an occupancy method, an important parameter, that is, delay in weaving zone (measure of performance for assessing level of service) for a particular movement under consideration, is also incorporated in the occupancy time for PCU estimation.hence, it is logical to consider the total occupancy time of a vehicle in the roundabout area. A vehicle which occupies lesser time in the roundabout area will create less impedance to the circulating flow. Therefore, the PCU will be different for each vehicle category on the basis of time taken to clear the roundabout. Indo-HCM recently launched has suggested values for PCU at roundabout the value suggested by Indo-HCM and IRC-65-2017 are shown in table 3. The values suggested by Indo-HCM are derived using Headway method which considers headway of particular vehicle category. Studies in recent past by Satish Chandra(2015) has concluded that headway method for mixed traffic condition is not correct since there is no lane discipline and following and hence the results are often misleading.

5. ENTRY CAPACITY MODEL FOR MIXED TRAFFIC SCENARIO

The relationship between entry capacity and circulating flow is developed for all the roundabouts since substantial queue formation. Entry capacity is considered as dependent variable whereas circulating flow is regarded as an independent variable. For this purpose, the entry flow values and circulating flow values of each observed queue formation is first converted into the equivalent entry capacity and circulating flow using the corresponding aggregated PCU values of different vehicle categories. The entry capacity is calculated based on the conflicting flow in the circulatory roadway space, comprising of the various turning movements for different vehicle categories from other approaches that pass in front of the subject approach leg, for which the entry capacity is to be estimated. The relationship between entry capacity and circulatory flow is found to be negative exponential. It implies that the entry capacity reduces exponentially with the increase in circulating flow. The proposed model validates the findings of Mahesh *et* al.,2014 on roundabout under mixed traffic in India *(10)*. The relationship obtained is supporting the general trend that when the flow on circulating space is low, more number of vehicles can enter from a given approach, but as vehicles add to the circulating flow lesser number of vehicles can enter. The model obtained for entry capacity is as follows

Observed entry capacity for R1 $Q_e \left(\frac{PCU}{h}\right) = 3098e^{0.0003Q_c}$ (4)

Observed entry capacity for R2 $Q_e \left(\frac{PCU}{h}\right) = 3056e^{0.0003Q_c}$ (5)

Observed entry capacity for R3 $Q_e \left(\frac{PCU}{h}\right) = 2965e^{0.0003Q_c}$ (6)

Observed entry capacity for R4 $Q_e \left(\frac{PCU}{h}\right) = 2880e^{0.0003Q_c}$ (7)

Observed entry capacity for R5 $Q_e \left(\frac{PCU}{h}\right) = 2621e^{0.0003Q_c}$ (8)

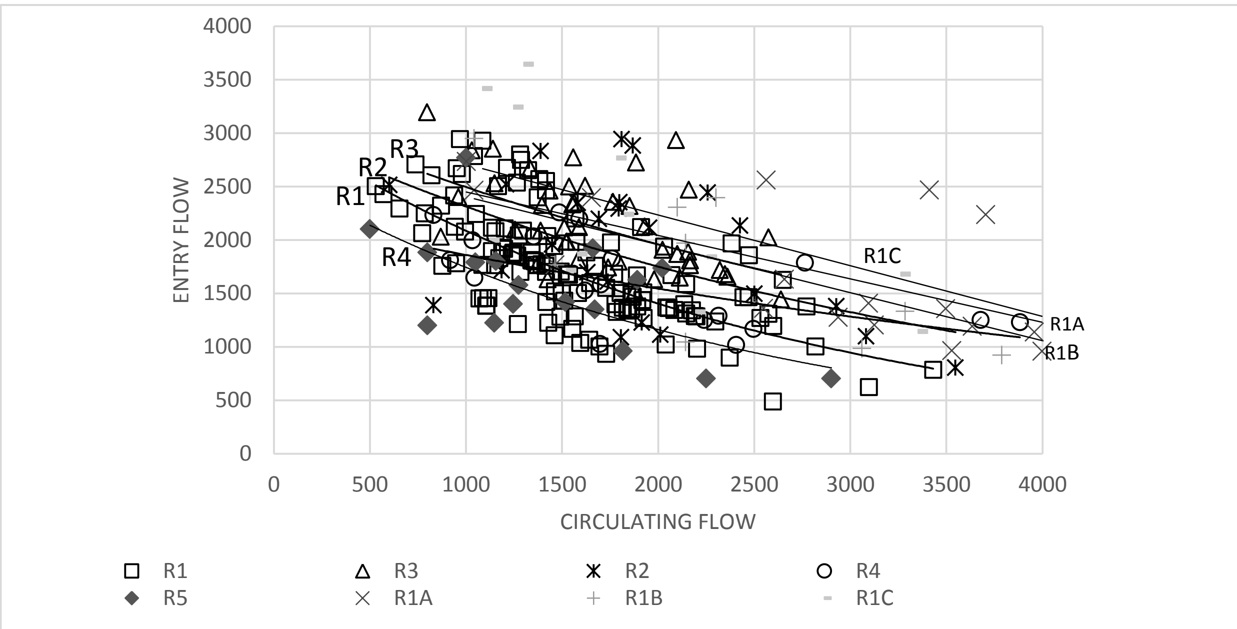

Figure 2. Combined Plots for Circulatory Flow and Entry Capacity

The above plot shows the Entry capacity value for different roundabouts. The values for R1 to R5 are observed from the videography. Methodology used by US-HCM and Indo-HCM are same except that PCU, critical gap and follow up time values are to be derived from field observation in US-HCM but Indo-HCM has clearly suggested these values which are to be adopted during analysis. Further to understand the procedure by HCM, entry flow is calculated by equation 9.

$$Qe = f_{HVe} * f_P * f_A * A * e^{-\left(\frac{B}{f_B}\right)Qc} \quad (9)$$

Whereas the parameters A and B related to the follow-up time and critical gap and simply we can write it as shown in equation 9.

$$Q_e = \mathrm{A} * \mathrm{e}^{-\mathrm{B}Q_c} \quad (10)$$

Where $A = \frac{3600}{t_f}$ $B = \frac{tc - 0.5t_f}{3600}$

Q_e-Entry capacity, Q_c-circulatory flow, t_f-follow up time, t_c-critical gap

For understanding the method, it is needed to first understand the variables utilised. Two factors contributing for entry capacity through the said method are critical gap and follow up time. The critical gap can be defined as the least possible time interval which can be taken up by an entering vehicle so that it can safely merge into the circulating stream. Explicitly, a driver with a specific critical gap value will never accept a gap less than and will accept each major stream gap larger than. Estimation of the critical gap has been carried out by adopting maximum likelihood method for the roundabouts R1, R2, R3 and R4. For R5, due to constraints in extraction of data, Raffs Method was used to determine Critical Gap for various vehicle categories.

The values of critical gap are observed to increase with the increase in road space occupied by the type of vehicle as given in Table 4. This is a general observation on all the roundabouts studied. The composition of LCV, Bus and Truck was less than 5% and hence the samples of accepted and rejected gap simultaneously for the same vehicle was not available. As a result, the plotting of critical gap values for these three categories of vehicle was not possible. The stream equivalent critical gap has been estimated by multiplying critical gap value with the corresponding composition of vehicle category in the study location shown in equation 11.

$$tc_{mix} = t_{c,2W} * P_{2W} + t_{c,3W} * P_{3W} + t_{c,SC} * P_{SC} + t_{c,BC} * P_{BC} + t_{c,HV} * P_{HV} \quad (11)$$

Where $t_{c,2W}$ = Critical gap of two-wheeler, P_{2W} = Percentage composition of two-wheeler; $t_{c,3W}$ = Critical gap of three wheeler, P_{3W} = Percentage composition of three wheeler; $t_{c,SC}$ = Critical gap of small car, = Percentage composition of small car; $t_{c,BC}$ Critical gap of Big car, P_{BC}= Percentage composition of big car; $t_{c,HV}$ = Critical gap of HV and P_{HV}= Percentage composition of heavy vehicle. Similarly, stream equivalent critical gap for the selected roundabouts are presented in Table 4.

The critical gap in combination with follow-up time gives a reliable and realistic estimate of capacity at roundabout entry. The study was further extended by developing a stream equivalent value for follow-up time under queuing conditions since it becomes a logical necessity to evaluate the follow-up time for saturated conditions.

Table 4. Critical Gap Values for Different Vehicle Categories

Roundabout No.	2W	3W	SC	BC	Stream Equivalent Critical Gap values from field observation	Critical gap values from Indo-HCM
R1	0.88	1.30	1.57	1.71	1.24	2.01
R2	1.90	1.57	2.14	2.59	1.96	1.87
R3	1.21	1.50	1.94	1.70	1.46	2.01
R4	1.40	1.74	1.78	1.89	1.64	2.01
R5	1.34	1.63	1.54	1.89	1.40	1.61

The value of critical gap thus obtained is utilized by the HCM method. It is noteworthy that Indo-HCM has provided values of critical gap and these suggested values are to be utilized for determining entry capacity. The comparison of observed critical gap value and values suggested by Indo-HCM is compared in the following Table

To understand the difference more clearly, following plot is shown for critical gap values obtained in field and that obtained from Indo-HCM.

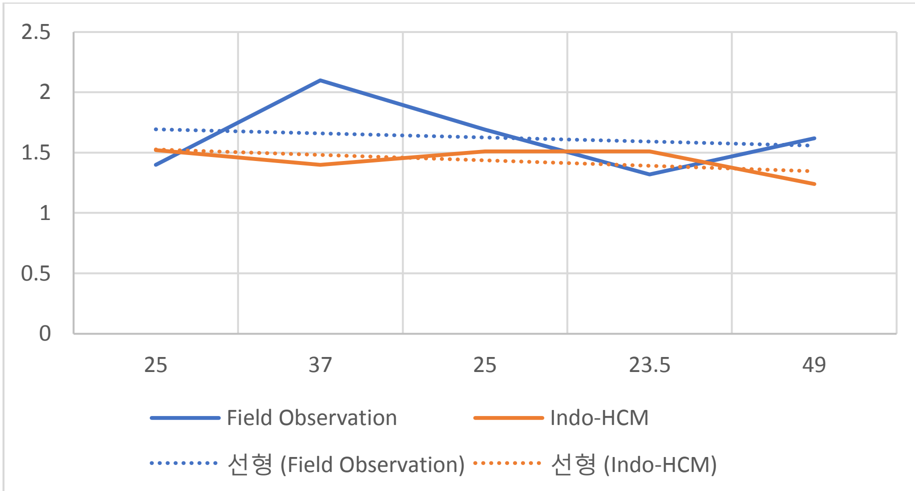

Figure 3. Comparison of critical gap values

From the plot it can be observed that there is difference in the critical gap values from field observation and values suggested in Indo-HCM. Values suggested in Indo-HCM is higher than field observed values. The difference may be due to the methodology used in both ways are different. In present study, critical gap is derived using MLM method and values of Indo-HCM are derived using Root mean Square method. It is also clear that the values for critical gap provided by Indo-HCM decreases with increase in diameter and is constant for all the locations. However, it may not be the case as critical gap is a factor of driving behavior and studies have concluded that there is high variation in the driving behavior from location to location. Also, since India has heterogenous traffic condition, the driver's behavior changes from vehicle to vehicle and hence it is not logical that a static value of critical shall be used. Another parameter required for determining entry capacity is Follow-Up time.

Follow-up time can be defined as the minimum time interval between two successive vehicles of a minor stream which enter the roundabout using the same gap from the major stream. The factors such as vehicle type, waiting for a position in a queue, queuing vehicles behind, traffic volume and driver's gender will largely affect the follow-up time. The present study mainly focused on the estimation of follow-up time for different categories of the vehicle at the time of queue formation by considering the following vehicle as the subject vehicle. The resultant follow-up time obtained is shown in the Table 5 below.

Table 5. Follow-up Time Values

Category/Roundabout	**2W**	**3W**	**SC**	**BC**	**Average Value from field observation**	**Values suggested by Indo-HCM**
R1	0.76	1.18	1.26	1.40	1.40	1.52
R2	0.82	1.23	0.96	2.10	2.10	1.40
R3	1.04	1.50	1.74	1.69	1.69	1.51
R4	0.93	1.14	1.27	1.32	1.32	1.51
R5	1.08	1.26	1.45	1.62	1.62	1.24

The follow up time is also suggested by the Indo-HCM in similar manner as it was for critical gap. The values suggested by Indo-HCM and the values obtained from the field data are compared in the table 5. There has been significant difference in follow up time derived and suggested by Indo-HCM. To understand the trend, following graph is plotted in figure 4 below.

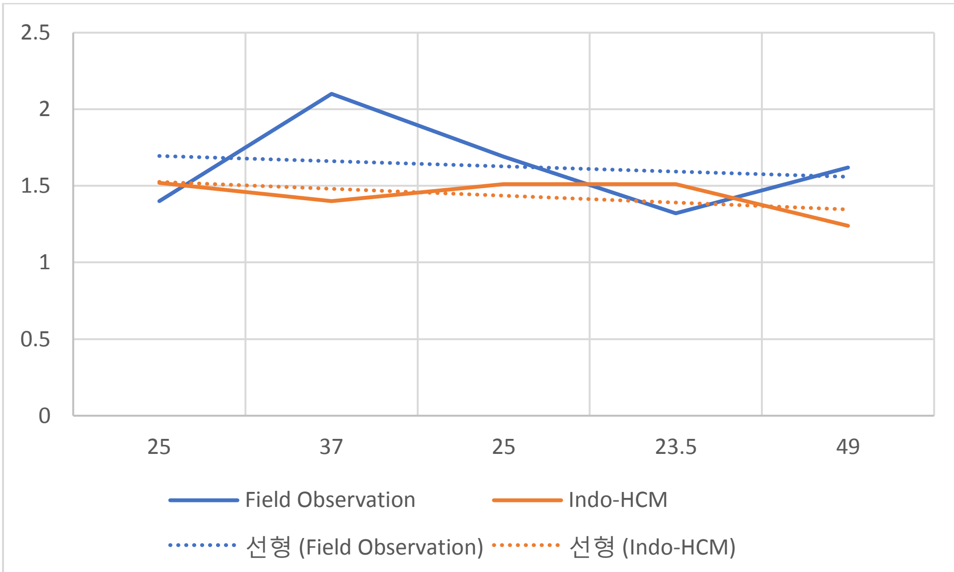

Figure 4. Comparison of Follow-up time

It is clear that in the similar way as was in critical gap, there is decrease in suggested values with increase in diameter also, it is understood that follow-up time is a parameter of driver's behavior and expected to change from location to location, driver to driver and vehicle to vehicle. Similarly, here also, it's suggested to avoid static follow up time values and instead efforts be made to determine the follow up time from the field observation.

Further efforts have been taken to compare the entry capacity values obtained by using PCU values of field observation, US HCM method and Indo-HCM method along with PCU values suggested by Indo-HCM. The results are tabulated as under.

Table 6. Comparison of modified entry capacity values

Entry Capacity	**Field observation**	**US-HCM**	**Indo-HCM**	**Using PCU, Follow-up and critical gap suggested by Indo-HCM**
R1	3098	3372	2384	3225
R2	3056	3278	2571	3186
R3	2965	3294	2384	3142
R4	2880	3149	2384	2972
R5	2620	2854	2909	3176

It is observed from the above table that entry capacity values suggested in Indo-HCM is increasing with the increase in diameter but the same is not the case with entry capacity values found by field observation and values suggested by US-HCM. To get in depth understanding, the methodology used for all the above methods is carried out. The entry capacity values from field observations are plotted using the observations through videos during the queue formation. The count for vehicle in minor lane (entry lane) and the major lane (circulatory lane) are converted into PCU/hr. the PCU values used have been derived using occupancy method as discussed earlier. For better understanding, following plot is shown in figure 5.

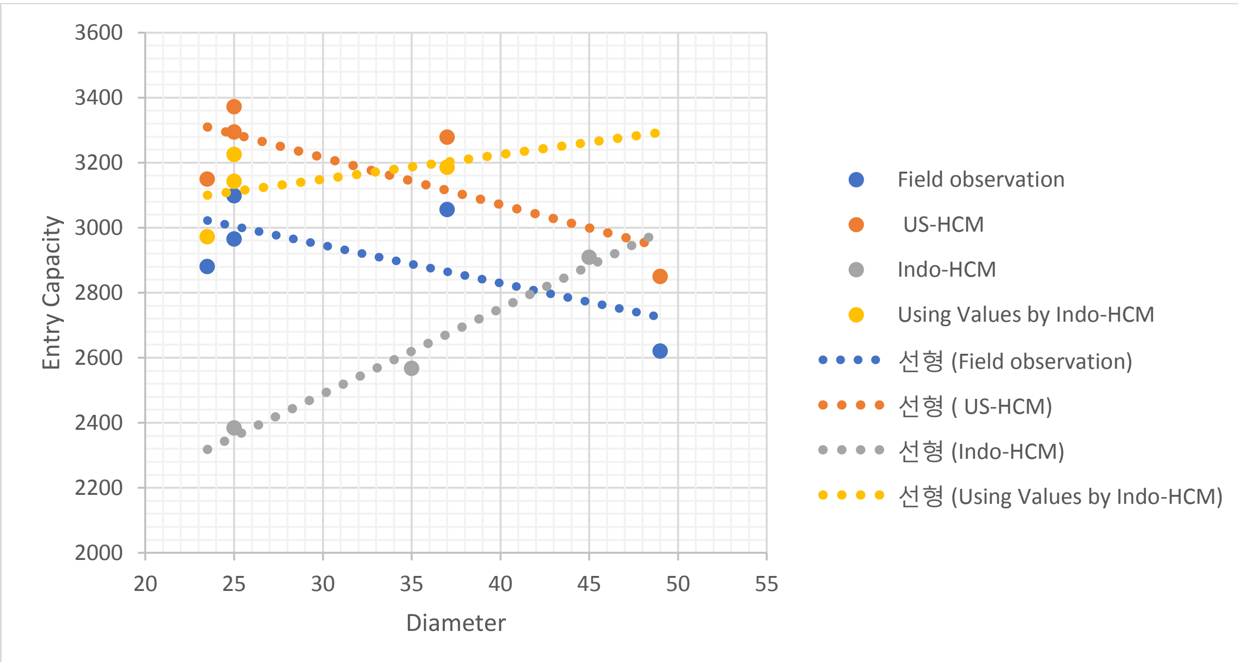

Figure 5. Comparison of Entry capacity Values

The graph plotted above shows that field observation and US-HCM capacity values follow a similar pattern of increasing with diameter and then decreasing. However, capacity values suggested by Indo-HCM is increasing with increase in diameter. Also, the capacity values obtained from using values suggested by Indo-HCM is following similar trend as that of capacity values from Indo-HCM. The difference between capacity values from field observed variable and Indo-HCM suggested variables have difference. This difference is due to the difference in PCU values, Critical gap values and the follow-up time values which has already been discussed.

CONCLUSION

Present study determines the PCU values for different vehicle categories using occupancy method. Occupancy method considers delay in weaving zone which is a measure of performance for assessing level of service hence, it is logical to consider the total occupancy time of a vehicle in the roundabout area. Also it is observed that entry capacity values suggested in Indo-HCM is increasing with the increase in diameter but the same is not the case with entry capacity values found by field observation and values suggested by US-HCM. This difference in the trend of entry capacity values is observed due to difference in methodology adopted for determining PCU values, critical gap and follow-up time.

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