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REDUCTION IN ENTRY CAPACITY OF ROUNDABOUT UNDER THE INFLUENCE OF PEDESTRIANS IN MIXED TRAFFIC CONDITIONS

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Resume

Models developed in Highway Capacity Manual (HCM) are not suitable to cater to the effects of mixed traffic conditions and hence, its use is unjustifiable. This research investigates such a challenging problem as the effect of undesignated pedestrian crossings on the entry capacity of roundabouts. For the present study, field survey data were collected using video cameras from three roundabouts such that the base section (roundabout without pedestrian influence) and non-base sections (with pedestrian influence), both scenarios, were captured. A modified HCM equation was developed to estimate entry capacity and further, the reduction in capacity with respect to pedestrian volume is determined. Lastly, a relationship was developed to check the effect of pedestrian crossflow on the entry capacity. The relation shows that capacity reduced to 1841 Passenger Car Unit (PCU/h) when the pedestrian flow increased to 288 pedestrians/hour.

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1 Introduction

Nowadays, the safety of pedestrians has become a part of public apprehension. Pedestrian crossing, especially at undesignated places, causes two-fold effects. One, the crossing pedestrians forced the vehicles to reduce their speed to find sufficient gaps to cross the road and consequently reduced the capacity of the section [1]. Two, the pedestrians put themselves at risk in the collision with running vehicles [2]. A way to ensure the right level of the road traffic safety is designing a safe road infrastructure. Roundabout intersections are a good example of a point road infrastructure that increases the road safety [3-4]. A circular intersection with the central island in which continuous traffic movement is observed (clockwise direction in the left-hand drive) is called a roundabout. The roundabouts necessitate the entering traffic to give way to traffic already in the circle and observe various design rules to increase safety. At roundabouts, the pedestrian visual advances in a single direction rather than in multiple directions. Further, it improves the understanding of the drivers' movements compared to the perpendicular junctions. Additionally, it lowers the queueing condition

due to the absence of traffic lights. Moreover, the traffic conflict points and thus the damages due to crashes reduce due to the installation of the roundabouts instead of the conventional intersections [5-6]. In addition, the lower conflict points are observed as compared to other point facilities [4]. It is due to the merging and diverging of vehicles at small angles at lower speeds causing less potential for accidents [7]. Further, speed reduction when crossing the intersection, low loss of time for drivers at inlets, etc., contribute significantly to ensuring the appropriate level of road safety at a given point of the network transport [8].

Hence, they are mostly accepted worldwide as a replacement to the conventional intersection for every traffic scenario, i.e. homogeneous and mixed traffic. A decrease in idling time is observed at roundabouts compared to signalized intersections as the vehicles are continuously in motion for crossing the roundabout.

Pedestrians interact with vehicles at the roundabout while crossing in places where there is no provision for pedestrian crossings. In the absence of traffic signals and markings, the complexity and flexibility of pedestrian behaviour is observed more than that of vehicles at roundabouts. Therefore, this study aims to determine the effect of the pedestrian crossing on

a roundabout capacity where the pedestrian has not provided any entry facility such as marking or foot over bridge at roundabouts. Under such conditions, pedestrians force the vehicle to make sufficient gaps and reduce entry capacity. The well-recognized manual for traffic operations and planning, i.e. the United States Highway Capacity Manual (US HCM), is widely followed in India, irrespective of its transferability for mixed traffic conditions, [9-10]. The objectives of the present study are twofold, one is to determine the approach leg entry capacity at a roundabout operating under highly heterogeneous and quasi-lane discipline scenarios and the second is to determine the effect of the undesignated pedestrian crossing on the roundabout's entry capacity. The outcome of the present study can be useful for providing some insights for the revision of the Indian Highway Capacity Manual [11].

The remainder of the study is as follows. Section 2 describes the detailed literature review of the studies carried out at roundabouts in developed and developing countries. Next, Section 3 describes the detailed objectives and methodology of the present study. Section 4 describes the data collection and the preliminary data analysis, including traffic composition, traffic and pedestrian volume. Section 5 focused on determining Passenger Car Units (PCU), which are further used for estimating entry capacity, as discussed in Section 6. After that, Section 7 describes the critical gap analysis, which is finally used to derive the capacity of the non-base section, discussed in Section 8. Lastly, Conclusions are given in Section 9.

2 Literature review

Various researchers worldwide focused on roundabout entry capacity research, including the US, Germany, United Kingdom (UK), etc. The researchers have given various models for evaluating the traffic operations at the roundabout, which can be broadly categorized into two groups. Out of two, one deals with the empirical methodology based on the intersection geometry and the other depends purely on the gap acceptance process. Many researchers used a simulation approach to study the roundabout capacity [12-16]. The Indian standard document, referred to as Indian Roads Congress (IRC) [17], gives the formula for estimation of the entry capacity of the roundabout. The method is purely based on empirical approach and uses the principles of Wardrop. According to the US HCM [9], roundabouts' entry capacity (Q_e) equation is given based on the circulating flow (Q_c). On the other hand, the HCM [10], proposed the formulas for determining the entry capacity of a roundabout based on the critical gap and follow-up time. Schroeder and Rouphail [18] developed the pedestrian delay model based on the probability of crossing for the single-lane roundabout. Meneguzzo and Rossia [19] studied the effect of a pedestrian on

the entry capacity of roundabouts in Italy. Firstly, a nonlinear relationship was developed between the percent occupancy and pedestrian volume, which is further used to develop the equation for entry capacity. A simulation approach using SIDRA INTERSECTION software was applied by [20] to assess the roundabout capacity given HCM. Al-Ghandour et al. [21] analyzed the single-lane roundabout with slip lanes with pedestrian volumes using microsimulation. The results showed that there is an increase of 28.1s/veh of delay if the vehicles yield 100 pedestrians per hour in high traffic conditions. A comparative evaluation of roundabout capacity by UK method, US method, Swiss method, IRC method and German method was carried out by Chandra and Rastogi [22]. They concluded that the IRC method estimated a higher capacity value when compared to the other methods. Various shortcomings of the HCM [9] roundabout capacity model listed in HCM [10] and some related model extensions provided by the SIDRA INTERSECTION software are discussed regarding the future development of the HCM roundabout capacity model. Kang et al. [23] used the microsimulation approach to evaluate the effect of a pedestrian on the entry capacity of the roundabout. It was found that the installation of a splitter island at entry enhances pedestrian safety and the entry capacity roundabout. Ahmad and Rastogi [24] developed the static Passenger Car Units (PCUs) for roundabouts under mixed traffic conditions. They developed the heterogeneity equivalency factor (H-Factor) for converting flow from vehicles per hour to PCUs/h. Osei et al. [25] studied the effect of roundabout signalization on the capacity of roundabout using microsimulation. The results showed that the capacity enhanced by 50% due to signalization at the roundabouts.

From the aforementioned literature, it can be seen that a lot of work is carried out in developed countries where the traffic has lesser heterogeneity and with lane discipline. Further, the countries where the study was done had well-planned pedestrian crossing facilities. However, the conditions in developing countries differ from those of developed nations with a highly heterogeneous nature of traffic with quasi-lane discipline nature. Further, well-designated pedestrian facilities are not provided at intersections in developing countries and hence, the models developed in developed nations cannot justify the true nature of the traffic in developing countries. Thus, there is indeed a need to study the effect occurring on the traffic operations at roundabouts due to the undesignated pedestrian crosswalks under the mixed traffic scenario.

3 Objectives and the methodology of the present study

As the literature review implies, the studies related to developing countries are scarce where the pedestrian

himself forces the vehicle to find the sufficient gap under mixed traffic conditions. The activity of pedestrian crossing on the road is purely a gap acceptance phenomenon. Here, the pedestrian will estimate the available gap on all the lanes for crossing the road. Then, the pedestrian will accept or reject the gap depending on the lane traffic volume and perception. As the number of pedestrian's increases, there ought to be a reduction in the capacity and a reduction in the entry speed of the vehicles approaching the roundabout, thus increasing delays. This must be analyzed because a significant increase in delay would be detrimental to the idea of using roundabouts. Thus, the objectives of the present study are two-fold (a) to estimate the entry capacity of the roundabout under mixed traffic conditions and (b) to determine the effect of crossing pedestrians on the entry capacity of the roundabout. However, it has been assumed that drivers' behavior is consistent throughout the observation period at all the study roundabouts.

Initially, roundabout sections were selected on arterial/sub-arterial roads without gradient and curvature to determine the capacity loss. The basic consideration in selecting a section will be that it should be free from the bus stop, parked vehicles, curvature, gradient, pedestrian movement and any other side friction. Further, roundabouts with significant pedestrian crossings are considered for the study to determine the effect of the pedestrian crossing on the capacity of the roundabout, as well. Finally, the reduction factor due to crossing pedestrians is calculated.

4 Data collection

Field studies are carried out to study the prevailing traffic characteristics and operation at roundabouts.

For the present study, three roundabouts with four legs and diameters ranging from 20 to 25m were selected from the different regions of the country. Two of the three roundabouts are considered the base roundabouts, located in Jaipur (Northern region) and Trivandrum (Southern region). The third one is having a significant number of crossing pedestrians, located in Surat (Western region), which is considered for the comparative study. All the candidate roundabouts have a four-lane divided carriageway in all directions. Field data has been collected using high resolution video cameras keeping cameras at a high vantage point in order to capture the whole roundabout area. The data related to entry, exit flows from each lane, circulatory flow and the crossings pedestrians were captured in the video camera. Field data was collected on a typical weekday in normal weather conditions for more than twelve hours, covering both off-peak and peak hours for each roundabout.

Along with the videographic survey, details of the geometry of all the candidate roundabouts were collected, as shown in Table 1.

The whole survey data was compiled to get the traffic data in the desired format. Then, the data extraction was done in the laboratory by replaying the recorded traffic video on a large screen and the data related to traffic volume and composition, accepted gap, rejected gap and follow-up time were extracted manually using AVIDEMUX software and recorded for further analysis.

4.1 Traffic composition

The traffic was divided into seven vehicle classes for dealing with mixed traffic scenarios for the present

Table 1 Inventory details of the candidate roundabouts

Inventory details	Chomu House Circle (Jaipur)				Chakka roundabout (Trivandrum)				Keval Chowk			
	Leg 1	Leg 2	Leg 3	Leg 4	Leg 1	Leg 2	Leg 3	Leg 4	Leg 1	Leg 2	Leg 3	Leg 4
Entry Width (m)	8.5	11.2	9.4	11.6	8.5	8.5	8.5	8.5	9.4	8.5	10.7	7
Exit Width (m)	8.5	14	10.3	9.6	9.0	10.5	10	10.5	10.9	8.5	8.9	7
Approach Width (m)	6.25	10.5	5.3	10	6.5	7.0	6.5	7	9.4	8.5	10.7	7
Departure Width (m)	6.25	10.5	5.3	8.2	7.0	7.5	7.0	9.0	12.4	15.6	12.2	14.2
Circulating Roadway width (m)	14	10.5	10.2	12.3	9.5	9	10.2	9.5	14	10.5	14	12
Weaving Length (m)	34.8	24.8	24.8	30.6	17.5	21.9	18.2	22.1	9.4	8.5	10.7	7
Central Island Diameter (m)		24.9				23.4				24.8		
Central Island Perimeter (m)		78.5				73.5				77.87		

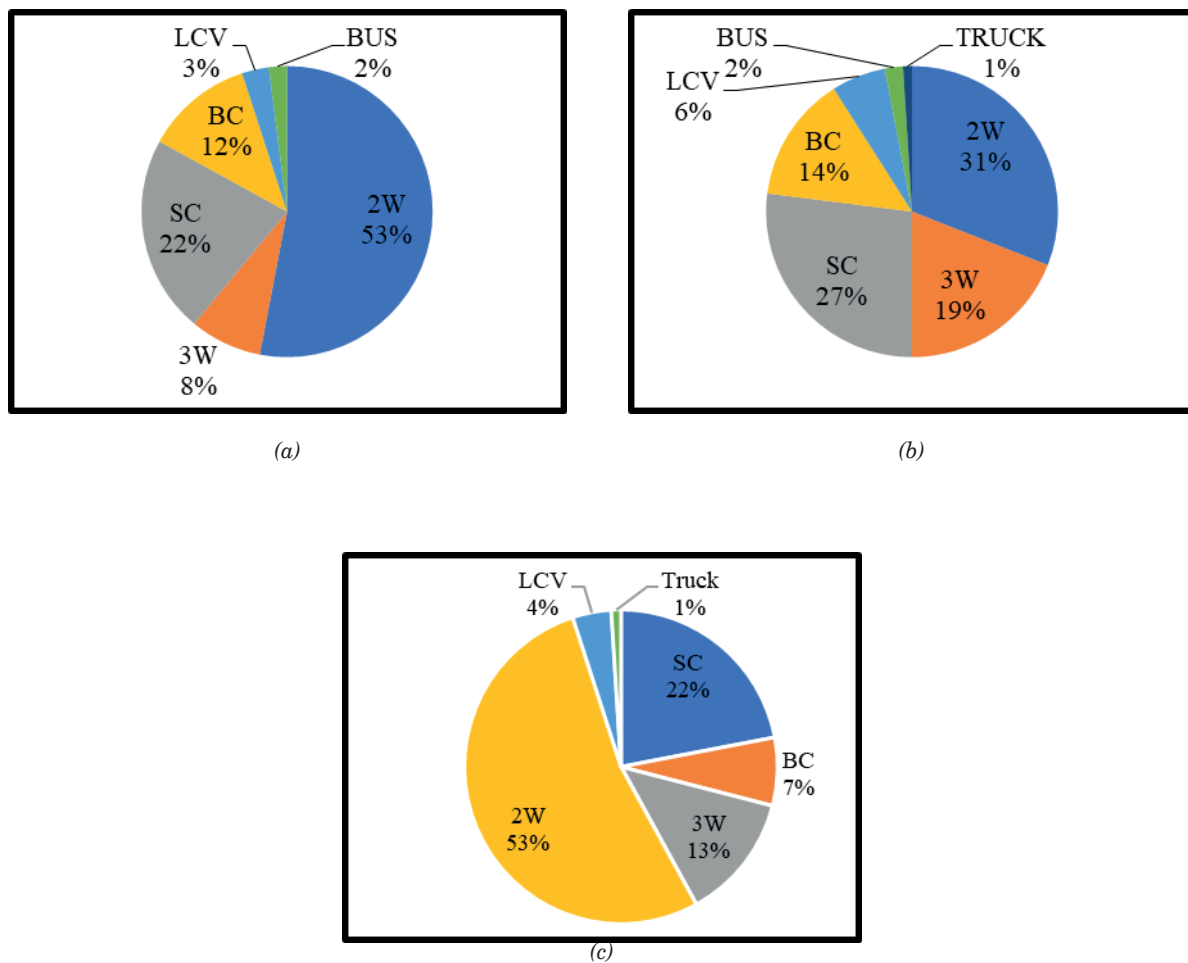


Figure 1 Traffic Composition (a) Chomu House Circle (b) Chakka Roundabout (c) Kewal Chowk

study. The classification includes motorized two-wheeler, motorized three-wheeler, Small Car, Big Car, Light Commercial Vehicle (LCV), Bus and Truck. The small car includes vehicles with a capacity of engine less than 1400 cc and the big cars include vehicles having more than an engine capacity of 1400 cc. The small cars are mostly hatchbacks and sedans, while the big cars include sports utility vehicles and cross utility vehicles. As all the candidate roundabouts were in the urban road network, a lower proportion of trucks were observed and hence, trucks were combined with vehicle class buses for the present study. After extracting filed survey data for all three locations collected using video cameras it was observed that most of the share is acquired by two-wheelers at the base section. Motorized two-wheeler share was maximum in Jaipur and Surat (53%) and minimum in Trivandrum (31 %). On the other hand, the share of small cars at all the three candidate locations is nearly the same, 22% in Jaipur and Surat and 27% in Trivandrum. Motorized three-wheelers proportion was maximum in Jaipur (19%) and minimum in Surat (13 %). The proportion of LCV is 4% in Surat and both truck and bus found less than 1% in the observed traffic mix. Figure 1 shows the traffic composition at three locations.

4.2 Pedestrian volume

To study the pedestrian flow effect on the roundabout, it is essential to study the pedestrian volume that crosses the roadway. Figure 2 illustrates the variation of pedestrian volume observed in the roundabout area during different hours of the selected time.

4.3 Traffic volume

Traffic volume is a quantitative flow measure, with vehicles per day and vehicles per hour being the most frequent units. Traffic volume observed at three different roundabouts is analyzed per approach lane.

5 Determination of passenger car units (PCU)

For highly heterogeneous and quasi-lane discipline traffic, the estimation of capacity in vehicles per hour (vph) is not justifiable and hence, there is a need to develop the equivalency factors for different vehicle classes to represent capacity in equivalent terms. Passenger Car Unit (PCU) is the multiplying factor

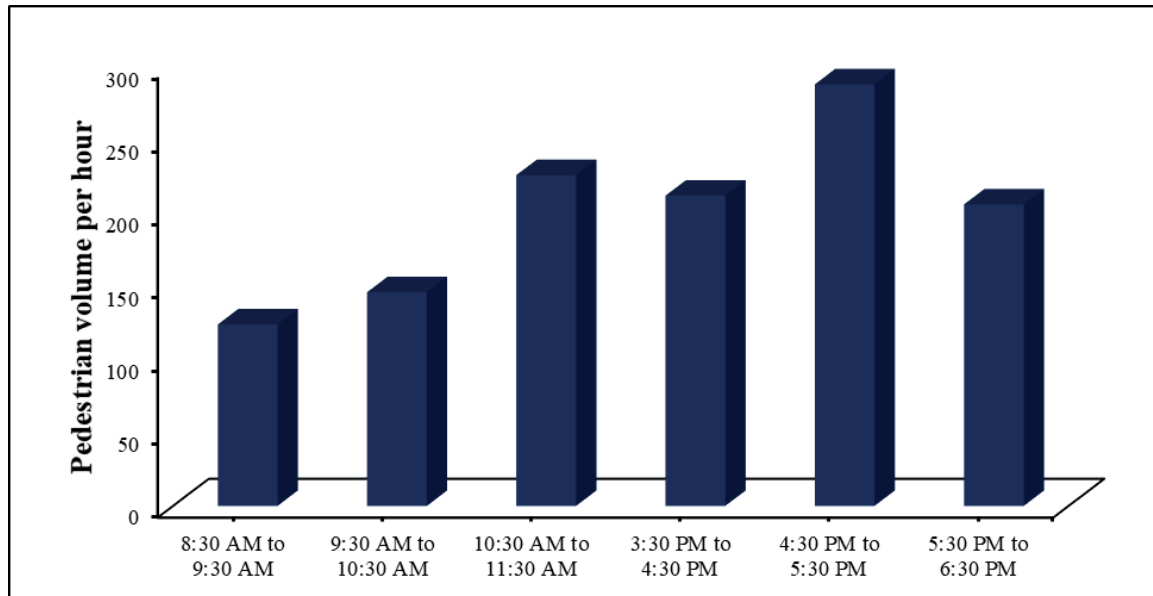


Figure 2 Number of pedestrians crossings at different time intervals

that differs for each vehicle class, which gives the traffic in equivalent terms, i.e. PCU/h. For the present study, the time occupancy method developed by Sonu et al. [26] is used to determine the PCU for each vehicle class at roundabouts. In the time occupancy method, the ratio of time required to pass from one arm to another arm for the i -th vehicle to the time required for the same car movement is considered. The occupancy time is considered here as it is a representative factor that takes into the effect caused due to variation in roadway geometry and the traffic characteristics of a vehicle during a particular movement in a roundabout. Additionally, it can clearly represent the interaction between the considered vehicle class and the standard vehicle class (here, small car) for determining the PCU.

PCU values for the present study are used for each movement separately, i.e. the left turn, straight and right-turn movement. Interestingly, no significant difference was found in the PCU values for all the movements of motorized two-wheelers and three-wheelers; thus, the constant values are adopted as 0.22 and 0.67, respectively. As a small car was taken as the base category, the PCU value was obtained as 1.00 for it. On the other hand, for big cars, the PCU value varies from 1.52 to 1.65 for the left-turn and right-turn movement, with 1.58 for the straight movement. Similarly, for LCV and bus, the PCU values are 1.75 and 4.04 for the left-turn, 1.81 and 4.43 for the straight movement and 1.93 and 4.64 for the right-turn, respectively. These values are used for capacity estimation and to determine the reduction in entry capacity at the non-base location.

6 Estimation of entry capacity

In the present study, the entry capacity is found using the relationship between the entry flow and the

circulatory/conflicting flow. For the requirement of the circulatory flow, the data from the candidate roundabout located in Jaipur (base section) is considered since the significant delay and queue formation was captured during the data collection. First, the entry flow and circulatory flows are converted in equivalent terms, i.e. PCU/h using the vehicle class-wise PCU values mentioned in the previous section. Separate values for the right, left and straight turning vehicles are used for the present study to convert the traffic flow into equivalent PCU flow. Entry capacity for the roundabout is the maximum equivalent flow in PCU/h when the conflicting flow exists in the roundabout area. Here, the conflicting flow consists of all the other turning movements in front of the leg for which entry capacity is to be found. For this, the relationship is developed between the entry flow and conflicting flow, which was further compared to the relationship given in HCM [10]. For the present study, a negative polynomial relationship is found to exist between the entry flow and the circulatory flow. Moreover, the same reference value can be employed to compare capacity values at the non-base locations (locations with a significant pedestrian crosswalk) as well. The HCM [10] model for entry capacity is formulated as given in:

$$Q_e = f_{HVe} * f_p * f_A * A * e^{\left(\frac{B}{f_B}\right)Q_c} \quad (1)$$

whereas parameters A and B are related to the follow-up time and critical gap, it can be expressed as:

$$Q_e = A * e^{BQ_c}, \quad (2)$$

$$\text{where } A = \frac{3600}{t_f} \quad B = \frac{tc - 0.5t_f}{3600}$$

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

From Equation (2), it is evident that the entry capacity of a roundabout is conspicuously influenced by the value of critical gap and follow-up time. So, a profound analysis of the critical gap and related parameters is conducted to study the effect of the undesignated pedestrian crosswalk on roundabout capacity needs.

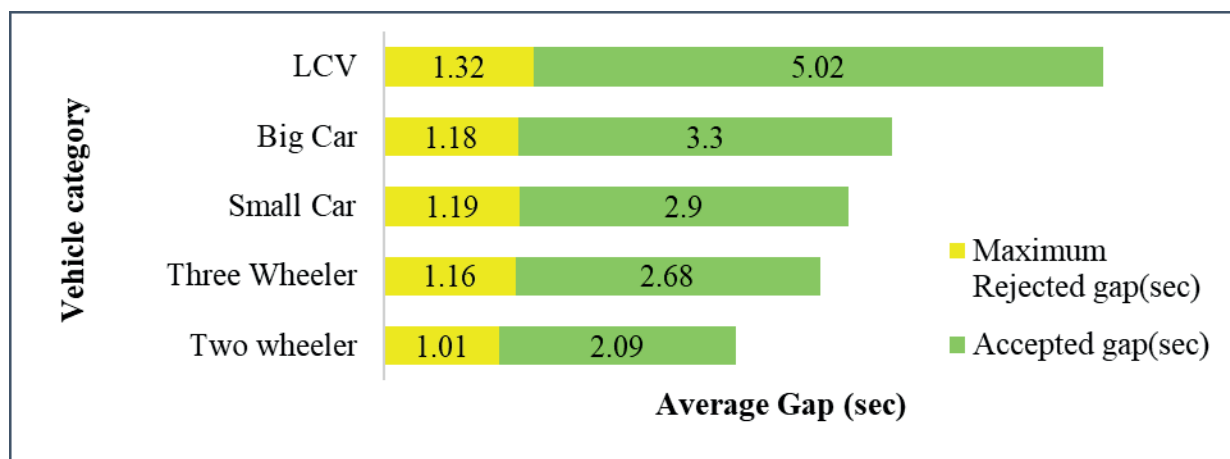
7 The Gap Analysis for the base and non-base section

The estimation of critical gaps from observed traffic flow patterns is one of the most challenging tasks in the case of roundabouts. Concerning the traffic rules, there is no minimum delays to major stream vehicle at the roundabout. However, for the minor stream vehicle, the delay may occur, as the minor stream vehicle can only enter the conflict area at the roundabout if the safe passage zone through the complete conflict area is available to the driver in the aspect of the major stream vehicle. Here, the critical gap plays an important role, which can be defined as the least possible time interval

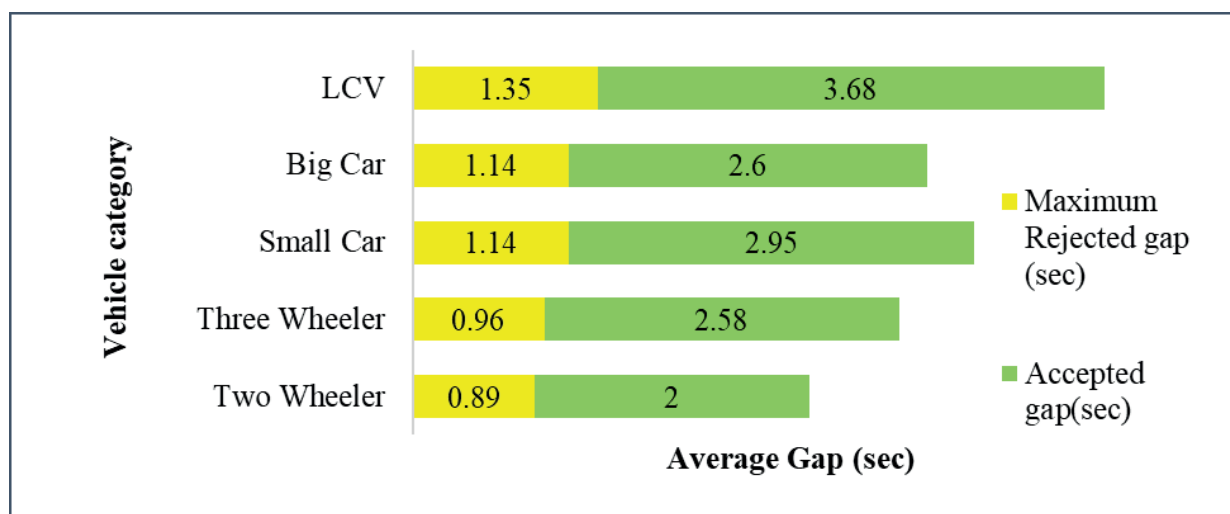
that an entering vehicle can take to merge into the circulating stream safely. It can be said that the driver cannot make the gap less than the critical gap for maneuvering, but he can take the gap more than that for the safe maneuver. The probability Equilibrium Method (PEM) is used in the present study to estimate the critical gap for each vehicle class. After that, the equivalent stream critical gap was derived to deal with the highly heterogeneous traffic conditions observed in the field.

7.1 Accepted and rejected gaps

Data related to the classified vehicular gap was extracted purposefully considering the major stream vehicles in the weaving zone while the minor vehicle enters the major stream. The accepted and rejected gap by the drivers is observed to be influenced by the type of vehicle. This can be understood by the graph shown in Figure 3 for the average values of accepted and maximum rejected gaps at both study locations. A general trend of increase in average gap size with the increase in the size



(a) Chakka Trivandrum



(b) Chomu House Jaipur

Figure 3 Average accepted and rejected gaps at base sections

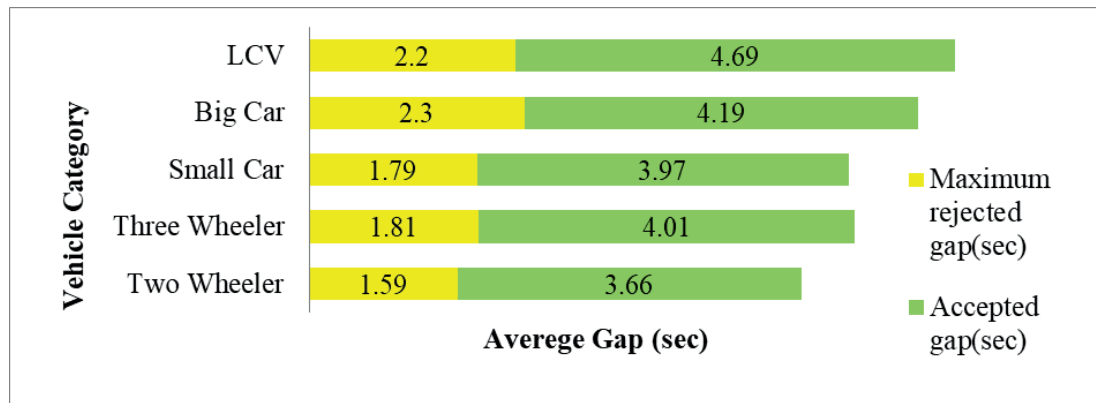


Figure 4 Average accepted and rejected gaps at the non-base section (Keval Chowk)

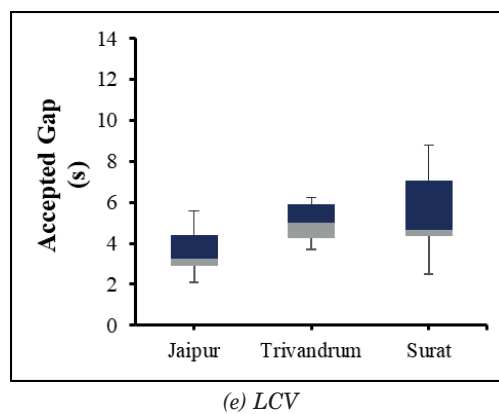
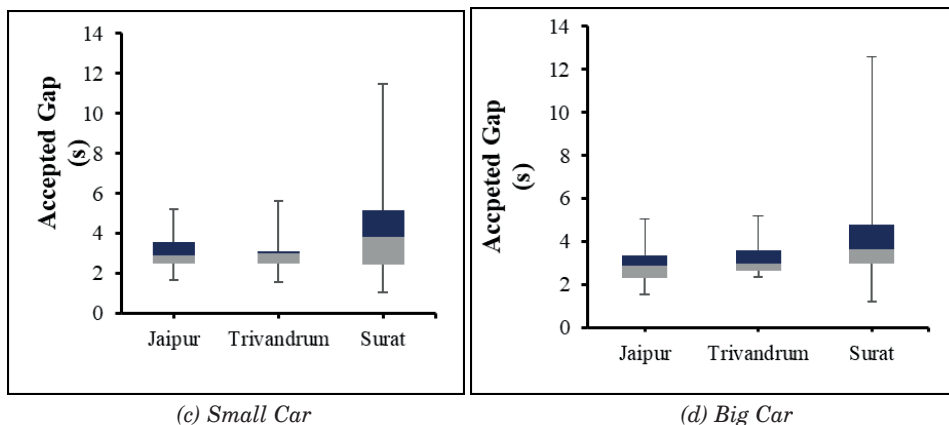
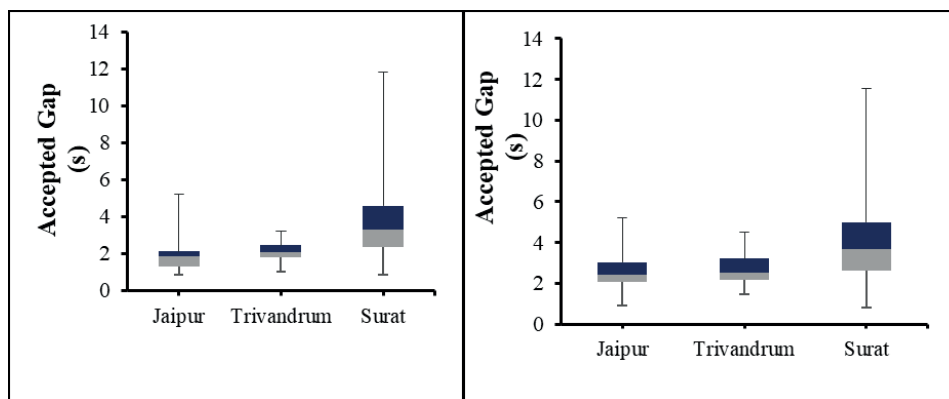


Figure 5 Accepted Gap variations for each category of vehicles

of subject vehicle type exists at selected roundabouts. As the size increases, the drivers tend to enter larger gaps. The samples available for trucks and buses at the selected roundabout are relatively low; hence, the gap analysis of such vehicles is not considered in the study.

Similar analysis has been performed in the non-base section as well, to comprehend the observed variation in accepted and maximum rejected gap values. From the analysis shown in Figure 4, it is envisaged that

there is a reasonable variation in the accepted and rejected gap at the non-base section, where pedestrian crossings are recurrent. This also focuses on pedestrians' influence (hindrance created by vehicular movement) in the selected study zone. Furthermore, the statistical analysis clearly designates the substantial variation in the accepted gap at the location with significant pedestrian movement.

When discussing the pedestrian-vehicle interaction at the roundabout, it is common that some percentage

Table 2 ANOVA test statistics

Type of a vehicle	Base Section Vs. Base section			Base section Vs. Non-base section		
	F- statistical	F-critical	p- value	F-statistical	F-critical	p- value
Two-wheeler	1.010	3.920	0.320	74.000	3.860	0.000
Three-wheeler	0.170	3.980	0.680	22.761	3.954	0.000
Small Car	0.620	3.980	0.430	10.336	3.882	0.001
Big Car	1.810	4.050	0.180	9.817	3.990	0.003
LCV	0.840	4.300	0.370	8.926	4.210	0.006



Figure 6 Pedestrian crossing movement at the roundabout area

of drivers is expected to yield to a waiting pedestrian, which depends on vehicle speed and driving behavioral attributes. To understand this possible extent of variation in behavioural attributes of pedestrian and driver at selected locations, a broad analysis has been performed to analyze the variation of the accepted gap for each individual category of vehicles. The results of the analysis are illustrated as a box-whisker diagrams shown in Figure 5.

From the above analysis, it is observed that the variation in the accepted gap is found to be very high in the location with significant pedestrian movement. To construe such a finding, an Analysis of Variance (ANOVA) test has been performed for accepted gap values extracted from both the base sections, such as the Chomu House roundabout (Jaipur) and Chakka roundabout (Trivandrum). The results shown in Table 2 clearly depict that there is no variation between the accepted gaps at both the study location. Similarly, the same analysis showed a significant difference between the accepted gap values between the base and non-base section, which substantiates the earlier finding that a notable influence of pedestrians exists in the roundabout.

The rigorous analysis of the collected video disclosed a steady propensity that the pedestrian movements create a larger gap in the circulating traffic stream as the pedestrian is creating a hindrance to circulatory flow. Moreover, the minor stream vehicle also follows the same course, impeding the major stream movement in a weighty manner. Figure 6 illustrates the pedestrian crossing attributes in the roundabout area. Thus, the performance of the roundabout was altered to a significant extent. To quantify the aftermaths on roundabout performance, it is necessary to analyze parameters such as circulating flow, critical gap and

follow-up time, as they are considered the influencing entry capacity parameters.

7.2 Method of the critical gap estimation

The critical gap can be eloquently defined as the least possible time interval that an entering vehicle can take to merge into the circulating stream safely. In the present study, the critical gap is estimated by the method developed by Wu [27], known as Probability Equilibrium Method (PEM). The foundation of this method is based on the probability equilibrium theory that considers both the accepted and rejected gaps. The cumulative distribution functions (CDFs) of accepted ($F_a(t)$) and rejected gaps ($F_r(t)$) is used in this method to find out the critical gap.

Now, according to PEM,

Observed probability that a gap of length t is accepted = $1 - F_a(t)$

Observed probability that a gap of length t is not accepted = $F_a(t)$

Observed probability that a gap of length t is rejected = $1 - F_r(t)$

Observed probability that a gap of length t is not rejected = $F_r(t)$

Therefore, from above equations follows:

$F_r(t) \neq 1 - F_a(t)$ and $1 - F_r(t) \neq F_a(t)$.

Thus, it can be said that the accepted gap is always greater than the actual critical gap [28].

7.3 Estimation of the critical gap

The wide variety of vehicles in a mixed traffic stream and diversity in their size and speed over a wide

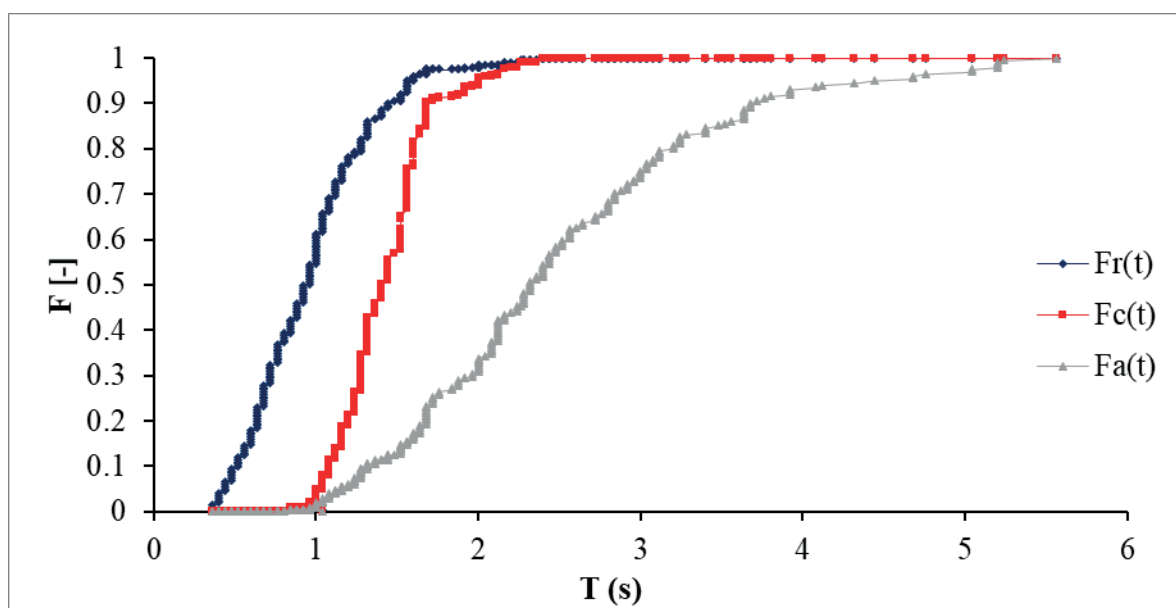


Figure 7 Schematic relationships between the PDFs for rejected gaps, accepted gaps and estimated critical gaps from PEM

range makes it extremely complex to study the driver behavior aspects, like the critical gap at intersections under prevailing traffic conditions. The critical gap is one of the major parameters for gap acceptance models. The accuracy of the critical gap mainly determines the accuracy of the capacity estimation. This study focuses on implementing the probability equilibrium method to find out the driver's critical gap in heterogeneous traffic scenarios as MLM does not efficiently produce any result as the maximized value did not converge due to the widespread between the accepted and maximum rejected gaps at the location with significant pedestrian influence. This simplified approach also shows that the probability density function (PDF) of the critical gap always lies between the functions of accepted and rejected gaps shown in Figure 7.

The reliable capacity of the roundabout can be found with help of the critical gap and follow-up time. The critical gap obtained from the PEM method is 1.58 s for the candidate roundabout in Jaipur, while it is 1.62 s for the candidate roundabout in Trivandrum. Similarly, the critical gap was also derived for the different time intervals with the varying pedestrian flow at the non-base location to assess the reduction in entry capacity due to the same. Now, the second component for the capacity estimation, i.e. follow-up time, is also evaluated at the roundabout under the queueing conditions, i.e. saturation condition. If the two consecutive vehicles from the minor stream enter the roundabout using the same gap, then the minimum time gap between the two consecutive vehicles is known as the follow-up time. Various factors affect the variation of the follow-up time, including the type of the vehicle, the number of vehicles queued behind, the traffic volume position of the vehicle in the queue and the drivers' personal parameters. In the present study, vehicle category-wise follow-up time in the queued condition is found by considering the following vehicle as to the subject vehicle. As discussed earlier, a substantial amount of delay and queue formation is observed at the candidate roundabout in Jaipur, i.e. the Chomu House roundabout; the follow-up time estimation analysis for the base section was carried out. The results showed that the weighted average follow-up time is 1.24 s. Similarly, the analysis has been extended to a non-base

location and the follow-up time is estimated for varying pedestrian flow levels. The estimated critical gap and follow-up time values at the non-base location are shown in Table 3.

8 Estimation of reduction in entry capacity due to pedestrian cross flow

As mentioned in Equation (1), the entry capacity by the HCM method depends upon the critical gap (t_c) and follow-up time (t_f) values. The HCM has given values for t_c and t_f as 4.5 s and 2.7 s, respectively. In a comparison of these values to values obtained in the present study for candidate roundabouts (Table 3), the values are found to be lower. This can be attributed to the maximum share of Motorized two-wheelers in the traffic stream and the absence of heavy vehicle traffic at the candidate roundabouts. From the previous section, the values of t_c and t_f are obtained as 1.58 s and 1.24 s, respectively. These values are obtained by the weighted average depending upon the present traffic composition. With the use of these values and the field circulatory flow values, the entry capacity of the roundabout is estimated using the HCM equation. The results showed that the entry capacity value by using the present study values and the HCM method is lower than the field capacity value observed in the equivalent units, i.e. PCU/h. The mean absolute percentage error (MAPE) is found to be 11.80%. Hence, it can be concluded that the HCM cannot be used directly for Indian conditions and there is a need to develop an adjustment factor for estimation of capacity for Indian conditions. The ratio of the entry flow value to the value given by HCM is taken as the adjustment factor [29]. A range of the adjustment factors is obtained that varies between 0.98 and 1.25. Hence, the average value of all the adjustment factors is suggested for evaluating capacity in mixed traffic conditions. The adjustment factor of 1.10 for HCM equation gives the same value of entry capacity observed in the field. This adjustment factor is used with field data and a modified plot for entry capacity is shown as illustrated in Figure 8. Thus, Equation (3) portrays the entry capacity estimation equation for roundabouts operating under a mixed traffic environment.

Table 3 Estimated entry capacity values at the base and non-base locations

Sr. No.	Pedestrian volume (peds/h)	Critical gap (s)	Follow up time (s)	Entry Capacity (PCU/h)	Reduction in entry capacity
Base Section - Chomu House Roundabout	Nil	1.58	1.24	3223	Base
1	124	2.07	1.17	2715	15.76%
2	146	2.46	1.1	2740	14.98%
3	206	1.80	1.29	2355	26.93%
4	212	3.35	1.18	2200	31.74%
5	288	1.78	1.65	1841	42.87%

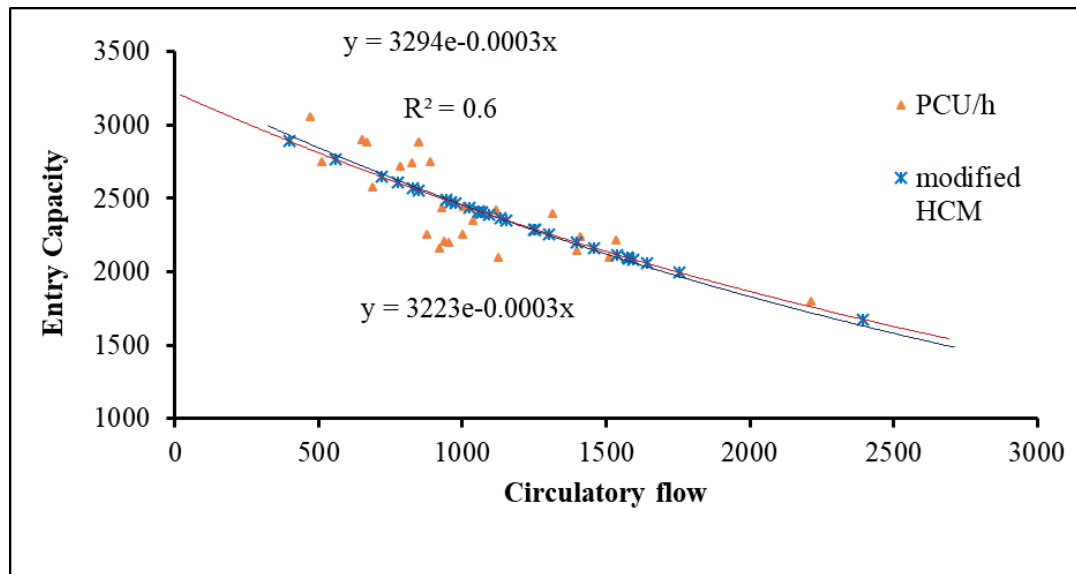


Figure 8 Modified HCM model for heterogeneous traffic condition

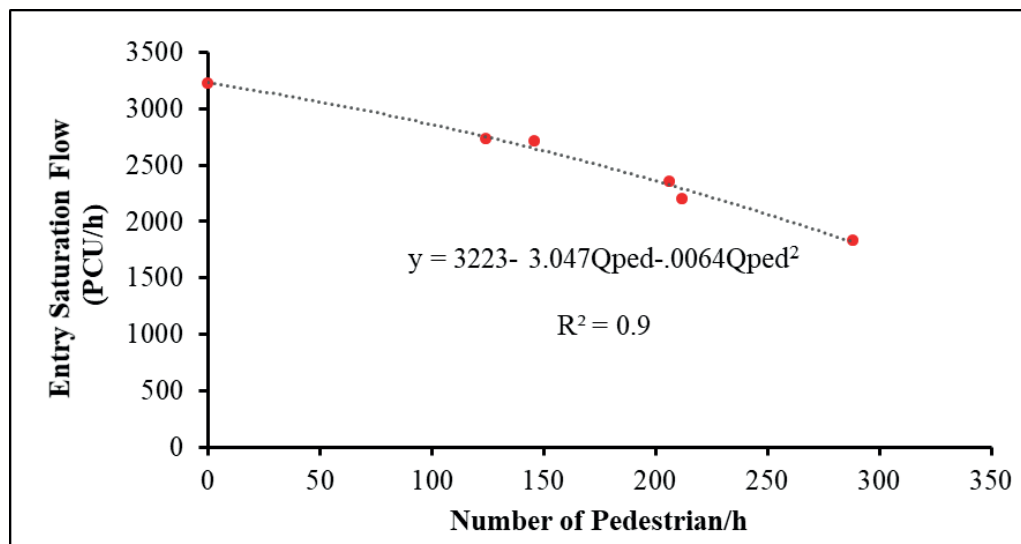


Figure 9 Reduction in entry capacity of the roundabout with respect to pedestrian volume

$$Q_e = 3223e^{-0.0003Q_c} \quad (3)$$

The number of pedestrians crossing that particular leg can affect the entry capacity. As the number of pedestrians increases, the entry capacity might probably reduce. In the present study, entry saturation flow was found and compared to the pedestrian volume at the roundabout with significant pedestrian movement (Surat Location) shown in Table 3. Further, the entry capacity value has been compared to the base value generated by the modified HCM Method.

To find out the trend in reduction of entry saturation flow due to the undesignated crosswalk of pedestrians, a plot has been generated between the pedestrian volume and entry capacity, shown in Figure 9. The relationship between entry saturation flow and pedestrian volume is found to be negative second-degree polynomial relation, indicating that with an increase in pedestrian flow rate, the entry capacity of the roundabout decreases

at a second-degree polynomial rate. The R^2 value of Equation (4) is strong enough to capture the variation.

$$\text{Entry capacity} = 3223 - 3.047(Q_{ped}) - 0.0064(Q_{ped})^2 \quad (4)$$

The entry capacity taking account of pedestrians, is then

$$Q_{e,ped} = \left(3223 - 3.047(Q_{ped}) - 0.0064(Q_{ped})^2 \right) e^{-0.0003Q_c} \quad (5)$$

It is better to use a reduction factor like

$$Q_{e,ped} = \left(3223 - 3.047(Q_{ped}) - 0.0064(Q_{ped})^2 \right) e^{-0.0003Q_c} \quad (6)$$

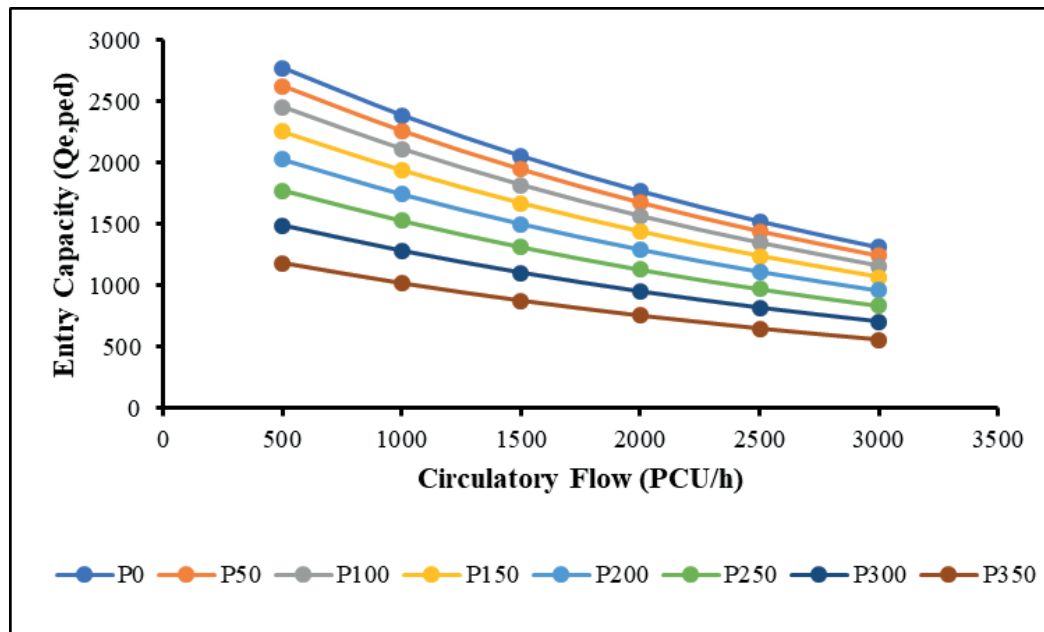


Figure 10 Entry capacity of the roundabout with respect to pedestrian volume

This reduction factor can be applied to all the possible capacity values.

The entry capacity taking account of pedestrians is then

$$Q_{e,ped} = Q_e * f_{ped} \quad (7)$$

Figure 10 shows the effect of pedestrian flow on the roundabout entry capacity.

9 Conclusions

The present study has been taken up with the prime objective to determine reduction in the entry capacity of a roundabout due to influence of the crossing pedestrians in the roundabout area. Selected roundabouts are operating under mixed traffic conditions as prevails in India and pedestrian are crossing at grade in the roundabout area without any marked crosswalk in order to access their point of interest. Such conditions are not uncommon in developing countries like India. Three roundabouts in different regions of the country have been selected for the study to quantify the influence of pedestrian flow on roundabout capacity. Two of the selected roundabouts have no pedestrian cross flow and hence are termed as the base sections, whereas the third roundabout has the significant number of crossing pedestrians during the observation time and is termed as the non-base section. The entry capacity of a roundabout for the base sections has been determined using the HCM equation. The HCM equation takes into account two parameters i.e. the critical gap and follow up time. The accepted and rejected gaps have been

determined from field collected data and the critical gap has been estimated using the PEM method. The follow up time is also determined from the field data. It is observed that the critical gap is 1.58 s, whereas the follow up time is 1.24 s for the base section. Values of the critical gap and follow up time are quite lower than the values suggested by the HCM [10]. The lower values of critical gap and follow up time are attributed to the high proportion of the two wheelers and very low proportion of the heavy vehicles in the traffic stream. The two wheelers accepted a very lower gap for merging in the circulatory stream what ultimately brings down the low values of critical gap. These low values of the critical gap and follow up time lead to the higher capacity values, as compared to those determined from the HCM equation and therefore a correcting factor of 1.10 is presented in this study. Further, it is observed that with the pedestrian cross flow the accepted gap and follow up time values are increasing due to the fact that presence of pedestrians yields the entry vehicle and the accepted gap size (value in time) higher than those of the base conditions. The higher values of the critical gap and follow up time ultimately result in the lower capacity values. It is observed that the entry capacity reduces with increase in pedestrians' cross flow. A negative second-degree polynomial equation has been proposed to determine the entry capacity relation to number of crossing pedestrians. It is observed that initially the reduction is low at smaller number of crossing pedestrians and the reduction in capacity increases with the increase in pedestrians' cross flow. This is attributed to the fact that more pedestrians are causing more hindrance to the entry vehicle.

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