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Analysis of gap parameters for the estimation of single lane roundabouts' capacity in the State of Qatar

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Abstract

Entry capacity is an important parameter for evaluating the roundabout performance. In general, entry capacity is influenced by three gap parameters: critical gap, follow-up time and minimum headway of circulating vehicles. These gap parameters certainly are correlated with the driving behavior as well as the roundabout characteristics. In this paper, video records of two single roundabouts in the state of Qatar were used to estimate the gap parameters. In addition, the entry capacity of both roundabouts was estimated and compared through different methodologies. Results showed that the entry capacity is directly related with the inscribed circle diameter (ICD) until 400 vph of circulating flow. However, it is inversely related with ICD if the circulating flow exceeds 400 vph. Moreover, we found that the entry capacity has a negative relation with the gap parameters. Estimated entry capacities with the calibrated Highway Capacity Manual 6th Edition model (HCM, 2016) were significantly higher than estimated ones through the proposed approach by Qatar Highway Design Manual (QHDM, 2015). Interestingly, the entry capacity was underestimated in both approaches if default gap parameter values are used compared to the calibrated models using the observed gap parameters (36.7% less for HCM, and 19.4% less for QHDM). Thus, the utilization of realistic gap parameter values representing local traffic condition is essential for traffic planners to accurately estimate the entry capacity and accordingly ensure feasible design of different types of roundabouts.

Keywords: critical gap; follow-up time; minimum circulatory headway; single-lane roundabout; entry capacity

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1. Introduction

Roundabouts are at-grade circular intersections that permits the rotational movement of traffic in one direction (i.e., clockwise or anticlockwise) around the central island with the priority for circulating traffic over the entering traffic. The main advantages of roundabouts over other types of intersections are that they aid in minimizing conflicts, lowering delays, and reducing drivers' travel speed [1, 2]. Among the uncontrolled intersections, roundabouts are considered very effective in ensuring smooth traffic movement [3].

Qatar Highway Design Manual (QHDM) 2015 [2] defines the roundabout entry capacity as the maximum rate at which vehicles can enter the circulatory roadway during a given period under prevailing traffic conditions. Roundabout capacity is an important parameter since it significantly affects the level of service (LOS) of the facility estimated through the queue lengths and delays. Several models have been established to estimate the entry capacity of roundabouts, e.g., interweave theory model, regression model and gap acceptance theory [4]. Particularly, gap acceptance theory uses gap parameters to estimate the entry capacity such as critical gap (t_c), follow-up time (t_f) and minimum headway of circulating vehicles (τ) [5]. Critical gap is defined as the minimum time interval between two consecutive vehicles in the circulating stream that allows a safe merging of an entry vehicle from a respective approach in the roundabout. Meanwhile, the follow-up time is calculated as the time interval between the departure of two consecutive queued vehicles from one approach in the roundabout to the circulatory stream. The minimum headway of circulating vehicles is defined as the minimum time headway between two consecutive vehicles in the circulatory stream.

In Nagano city, Japan, the critical gap and follow-up time for single-lane roundabouts were found to be varying between 3.0-3.8 s and 3.26-4.9 s, respectively [6]. While in Tokyo city, Japan, the gaps were ranging between 3.1-6.6 s for critical gap and 2.7-3.1 s for follow-up time [7]. Mathew et al. [8] estimated the critical gap and follow-up time under Indian traffic condition to estimate the entry capacity of roundabouts. The critical gap and follow-up time were found to be 1.6 s and 1.24 s, respectively. Although the observed critical gap and follow-up time values were smaller compared to the ones obtained in other countries, it was reported that the proportion of motorized two-wheelers was predominant at the study sites (53% and 31% for both sites, respectively), which could have resulted in smaller gap values. In addition to the critical gap and follow up time, the obtained entry capacity from calibrated Highway Capacity Manual (HCM) 2010 and original HCM 2010 were compared. It was found that the original HCM 2010 model underestimates the entry capacity by 11.8% [8]. Wei & Grenard [9] found that the uncalibrated HCM 2010 model underestimates the entry capacity of single-lane roundabouts in Indiana compared to the calibrated model. The study emphasized the importance of calibrating the HCM 2010 model for the planning of new roundabouts or even for the modification of existing ones. Another study which was carried out in Australia compared the entry capacity obtained from the field with five different models (i.e. HCM 2000, HCM 2010, signalized and unsignalized intersection design and research aid (SIDRA), German Highway Capacity Manual (GHCM) and new roundabout capacity (NRC)) [10]. The results showed that all the models underestimated the capacity of the single-lane roundabouts. When it comes to the state of Qatar, a study conducted by Shaaban & Hamad [11] have reported a critical gap of 2.24 s for a single lane roundabouts. However, the study was limited to the analysis of the critical gap only without addressing other gap parameters or the entry capacity. Zacharia et al. [12] used a non-linear regression model to investigate the effect of geometric features of six different roundabouts on the entry capacity. Nevertheless, the gap parameters of those roundabouts were not presented or discussed in the study. The main conclusion of the study was that the entry capacity increases with the increased inscribed circle diameter (ICD).

Although many multi-lane roundabouts are being converted to signalized or grade-separated intersections due to the large increase in traffic demand, there are still many existing and new built roundabouts which are mainly single lane and located in local roads, including residential areas, where the traffic volume is low. The QHDM 2015 adopts SIDRA model with the default gap parameters values (t_c = 4.98 s and t_f = 2.61 s) as the main procedure to estimate entry capacity of single lane roundabouts in the state of Qatar [3]. However, research indicates that the gap parameters can be strongly influenced by driving behavior, which could be different from one region to another [5, 11]. This could directly affect the entry capacity of roundabouts [9]. In this regard, previous studies revealed that drivers in the state of Qatar have aggressive driving behavior [13, 14] which is reflected in shorter commonly accepted gap parameters. Therefore, it is important to empirically estimate the gap parameters (i.e., critical gap, follow-up time and minimum headway of circulating vehicles) considering the multi-cultural driving backgrounds in the state of Qatar [15-17].

The main objective of this study is to measure the three gap parameters (i.e. critical gap, follow-up time and minimum headway of circulating vehicles) for single lane roundabouts in the state of Qatar using empirical field data. In addition, this study aims at estimating entry capacity of a single-lane roundabout using observed gap parameters and compare it with the estimated capacities using currently adopted procedures with default gap values in Qatar.

2. Methods

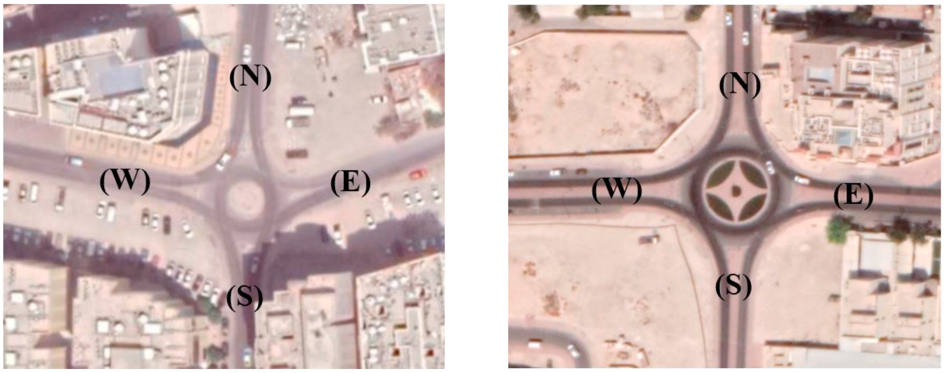
2.1. Site characteristics

Two single-lane roundabouts located at two different sites in the city of Doha were selected in this study. The first roundabout (site 1) was a four-leg intersection of Al Quds street with Abdullah Bin Masoud street, located in an urban area (Fig. 1a). The second roundabout (site 2) was also a four-leg intersection of Oqba Bin Nafie street with Jaber Bin Hayyan street and was located in sub-urban area (Fig. 1b). The ICD for site 1 and site 2 were 24 m and 41 m, respectively. The characteristics of both sites including entry width, approach half width, ICD, entry radius, effective flare length, entry angle and merging angle are reported in Table 1.

2.2. Data collection

Data was collected using a high-quality camera installed with appropriate height to record the four approaches of each site at different times. In total, 10 hours of video footages were recorded for each site in a normal weekday in daytime. Since both sites were located in urban and sub-urban areas, heavy vehicles were not encountered. Therefore, this study did not consider heavy vehicles.

For the analyses, the data was extracted using the Forevid Video analysis software, through which the accepted and rejected gaps, follow-up time and minimum headway of circulating vehicles were estimated. For each approach, all the accepted and rejected gaps were extracted for the estimation of the critical gap. An accepted gap for a driver



(a) Site 1 (ICD=24 m) (b) Site 2 (ICD=41 m)

Fig. 1. Aerial views of the roundabouts

Table 1. Characteristics of site 1 and site 2

Roundabout	Approach	Geometric elements						
		Entry width (m)	Approach half width (m)	ICD (m)	Entry radius (m)	Effective flare length (m)	Entry angle (deg)	Merging angle (deg)
Site 1	N	4	3.75	24	10	3.875	47	57
	S	4	3.75		10	3.875	36	67
	E	4	3.75		10	3.875	45	50
	W	4	3.75		10	3.875	43	59
Site 2	N	5	3.75	41	25	4.375	49	55
	S	5	3.75		25	4.375	42	48
	E	5	3.75		25	4.375	44	46
	W	5	3.75		25	4.375	48	59

was considered when the driver came to a complete stop and then entered the roundabout between the two consecutive circulatory vehicles. On the other hand, a rejected gap was considered when the driver came to a complete stop and then did not enter the roundabout in a certain gap between the two consecutive circulatory vehicles. The follow-up time was considered only when two or more vehicles were queued at the entry of an approach of the roundabout. Consequently, follow-up time was recorded as the time interval between the entry of two consecutive queued vehicles to the circulatory roadway under the condition of having no circulating vehicles within one quarter upstream of the roundabout [18].

2.3. Data analysis

For each approach, critical gap, follow-up time and minimum headway of circulating vehicles were estimated. Several methods have been used to find the critical gap in including Raff, maximum likelihood, Wu, logit, etc. [19, 20]. In this study, Raff's method, which is very common procedure for the estimation of critical gap, was followed due to its simplicity [21]. The method identifies the critical gap as the intersection point between the cumulative distributions of the accepted and rejected gaps. Follow-up time and minimum headway of circulating vehicles were obtained by drawing the cumulative distribution curves and taking the 50th percentile value.

After obtaining the three gap parameters, entry capacity of roundabouts was calculated by two different models. The first model is the QHDM 2015, which adapts the SIDRA model (Equation 1), taking into consideration the observed three gap parameters [22]. The second model is based on the HCM 2016 (Equation 2) [23]. The overall value of each gap parameter was obtained by combining the observed data of the four approaches at each site.

$$C_{SIDRA} = \frac{\varphi v_c exp(-\lambda(t_c-\tau))}{1-exp(-\lambda t_f)} \quad (1) \qquad C_{HCM\,2016} = v_c \times \frac{exp\left(\frac{-v_c t_c}{3600}\right)}{1-exp\left(\frac{-v_c t_f}{3600}\right)} \quad (2)$$

Where:

C_e = entry capacity of the roundabout (v/h), v_c = circulating flow of the roundabout (v/h), t_c = critical gap (s), t_f = follow-up time (s), τ = minimum headway of the circulatory flow (s), φ = proportion of free vehicles, λ = scale parameter.

The proportion of free vehicles (φ) and the scale parameter (λ) can be calculated based on the following equations (3 and 4, respectively):

$$\varphi = 0.75\left(1-\frac{\tau v_c}{3600}\right) \quad (3) \qquad \lambda = \frac{\varphi v_c}{3600\left(1-\frac{\tau v_c}{3600}\right)} \quad (4)$$

3. Results

3.1. Analysis of critical gap (t_c)

By following Raff's method, the intersection points between the cumulative distributions of the accepted and rejected gaps of site 1 and site 2, were 2.52 s and 3.30 s, respectively, as shown in Fig. 2. To understand if there was a significant difference between the accepted gaps for site 1 and site 2, an unpaired t-test was conducted considering the overall accepted gaps for each site. The results showed that the accepted gaps of the roundabout with larger diameter (Mean: 4.64, SD: 2.3) was significantly higher than the accepted gaps of the roundabout with smaller diameter (Mean: 3.58, SD: 1.0) (two-tailed/unpaired: $t_{(185)} = -6.007$, $p < .001$). The same method of Raff was applied for each approach and each site to estimate critical gaps. The results of the estimated critical gaps together with the follow-up time and minimum headway of circulating vehicles of each approach per site are reported in Table 2. The critical gap values for the north, south, east, and west approaches were 2.66 s, 2.28 s, 2.61 s, and 2.35 s for site 1 and 3.04 s, 3.64 s, 3.42 s, and 2.97 s for site 2, respectively. It can be identified from Table 2 that the overall critical gap value as well as the critical gap values of each approach separately were higher for site 2 compared to site 1. In addition, the average of the overall critical gaps combining both sites (i.e., site 1 and site 2) was found to be 2.91 s. It is important

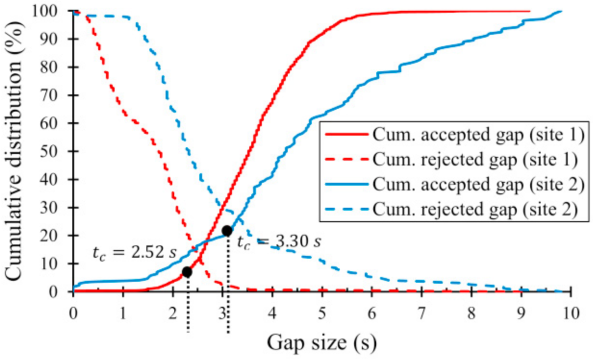


Fig. 2. Overall critical gap for each site

Table 2 Gap parameters summary of site 1 and site 2

Site	Gap parameter	Average gap (Sample size)					Average of both sites		
		North	South	East	West	Overall	t_c (s)	t_f (s)	τ (s)
Site 1	t_c (s)	2.66 (461)	2.28 (432)	2.61 (288)	2.35 (273)	2.52 (1454)	2.91	2.69	2.41
	t_f (s)	2.77 (265)	2.93 (251)	2.82 (255)	2.55 (249)	2.79 (1020)			
	τ (s)	2.46 (322)	2.25 (328)	2.16 (314)	2.35 (339)	2.35 (1303)			
Site 2	t_c (s)	3.04 (127)	3.64 (118)	3.42 (121)	2.97 (104)	3.30 (470)			
	t_f (s)	2.45 (71)	2.69 (89)	2.57 (92)	2.63 (84)	2.59 (336)			
	τ (s)	2.41 (214)	2.40 (157)	2.59 (123)	2.47 (158)	2.46 (652)			

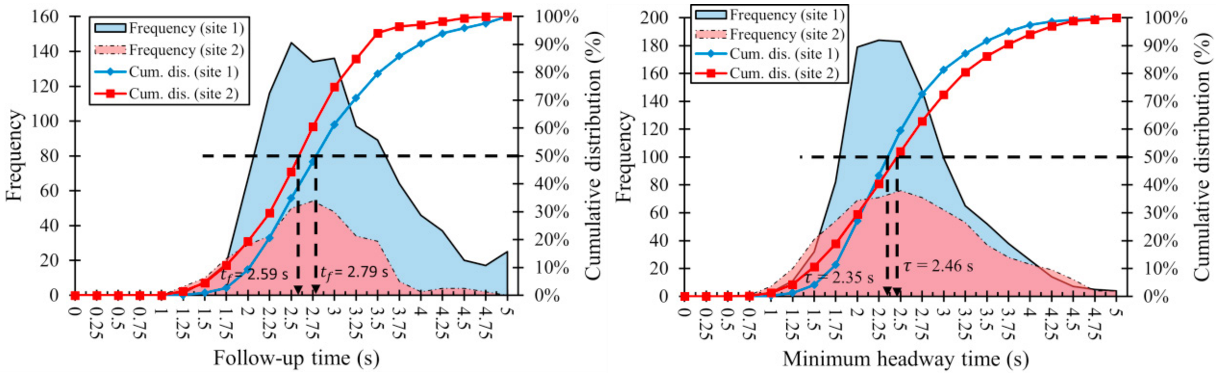
to mention, that the average values of the parameters (see Table 2) were used in the models to estimate the entry capacity.

3.2. Follow-up time (t_f)

The overall follow-up time of each site was obtained by taking the 50th percentile of the cumulative distribution curve of the follow-up time as shown in Fig. 3a. The y-axis on the left represents frequencies of each follow-up time, while the right y-axis represents the cumulative distributions. The follow-up time was found to be 2.79 s and 2.59 s for site 1 and site 2, respectively. The same procedure was followed to calculate the follow-up time of each approach per site and the results are provided in Table 2. After conducting a T-test, it was concluded that the mean follow-up time for site 1 (Mean: 2.92, SD: 0.78) is significantly higher than that of site 2 (Mean: 2.63, SD: 1.2) (two-tailed/unpaired: $t_{(259)} = 3.459$, $p < .001$). The average of the overall follow-up time combining both sites (i.e., site 1 and site 2) was found to be 2.69 s.

3.3. Minimum headway of circulating vehicles (τ)

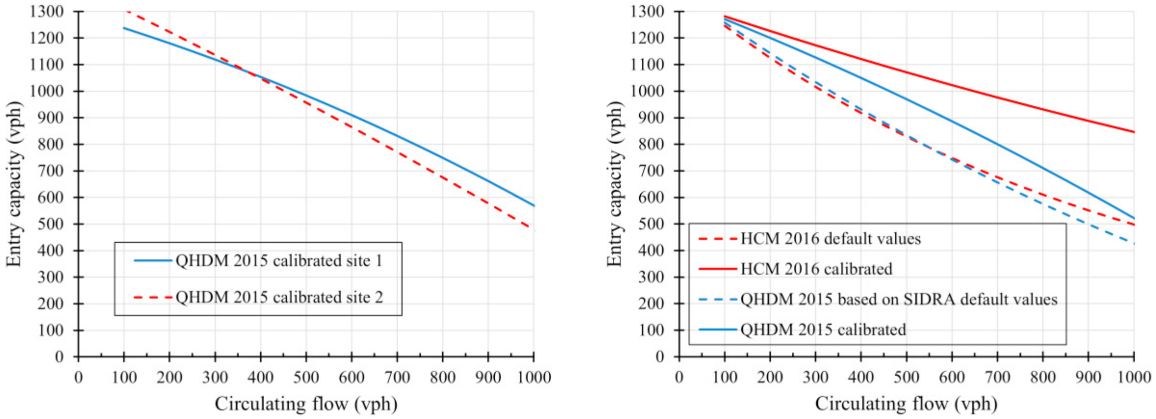
The procedure that was used to obtain the follow-up time was also used for the minimum headway of circulating vehicles. As shown in Fig. 3b, the 50th percentile of the cumulative distribution of the minimum circulatory time for site 1 and site 2 were 2.35 s and 2.46 s, respectively. The same procedure was followed to calculate the minimum headway of circulating vehicles for each approach in each site and the results are summarized in Table 2. After comparing the two distributions in Fig. 3b through a T-test, it was found that the mean minimum headway of circulating vehicles for site 1 (Mean: 2.39, SD: 0.62) was significantly lower than that of site 2 (Mean: 2.50, SD: 0.99) (two-tailed/unpaired: $t_{(457)} = -1.968$, $p = .0497$). The average minimum headway of circulating vehicles combining both sites (i.e., site 1 and site 2) was found to be 2.41 s.



a) Follow-up time t_f(s)

b) Minimum headway of circulating vehicles τ (s)

Fig. 3. Surface area and cumulative distribution diagrams for follow up time and minimum headway of circulating vehicles



a) Entry capacity based on QHDM 2015 for site 1 and site2

b) Entry capacity using QHDM 2015 and HCM 2016

Fig. 4. Entry capacity estimation using QHDM 2015 and HCM 2016

3.4. Entry capacity

The entry capacity was estimated for both sites using QHDM 2015, which adopts SIDRA model (see Fig. 4a), using the empirically observed gap parameter values. Through a T-test, it is concluded that the estimated entry capacities of site 1 (Mean: 933, SD: 193) with smaller diameter was significantly higher than those of site 2 (Mean: 905, SD: 240) which has larger diameter (two-tailed/paired: $t_{(899)} = 17.377$, $p < .001$). At the circulating flow of lower than 400 vehicles/hour (vph), the entry capacity was higher in site 2 compared to site 1. However, as the circulating flow increases over 400 vph, the entry capacity of site 1 became higher than site 2.

Fig. 4b compares the estimated entry capacities using QHDM 2015 and HCM 2016 at different circulating follows using the default gap values as well as the empirically estimated values in this study. Fig. 4b) shows that a higher entry capacity would be obtained if the three gap parameters (i.e., t_c, t_f and τ) are calibrated to match local traffic conditions. Using the default gap values in both models (HCM 2016 (dashed red line) and QHDM 2015 (dashed blue line)) resulted in comparably similar entry capacities. However, as the circulating flow exceeds 600vph, HCM 2016 model yields to higher entry capacities compared to QHDM 2015 (when both models use default gap parameters).

Furthermore, Fig. 3b) shows that the highest difference between the estimated capacities using the calibrated and the default QHDM 2015 model was 144 vph (19.4%) at 600 vph of circulating flow. While the difference between the HCM 2016 calibrated model and default model at the same circulating flow was 274 vph (36.7%). In this context, the calibrated HCM 2016 model showed higher entry capacity for all circulating flows compared to the other models (i.e., HCM 2016 default values, QHDM 2015 default values and QHDM 2015 calibrated values).

4. Discussion

In this study, we aimed to empirically investigate the values of the gap parameters for the estimation of roundabout's entry capacity, including critical gap, follow-up time and minimum headway of circulating vehicles. Raff's method was used to calculate the critical gap (t_c). Follow-up time and minimum headway of circulating vehicles were estimated as the 50th percentile of the cumulative distribution curves. The three gap parameters were obtained for the two roundabouts with different ICD. Finally, the entry capacities of both roundabouts were estimated and compared between two different models, i.e., QHDM 2015 and HCM 2016.

The geometric characteristics of both sites were comparable except the ICD, which was almost doubled for site 2. Therefore, the changes in the observed parameters between the two sites in this study might be attributed to the ICD. The critical gap of site 1 was found to be 31.07% lower than the one estimated for site 2. Similarly, the minimum time headway of circulating vehicles for site 1 was 4.42% lower compared to site 2. Different from that, an opposite relationship was observed in case of follow-up time, i.e., site 1 had higher follow-up time by 7.77% than site 2. The results indicate that ICD could have influenced the increase in critical gap of site 2. This might be due to the fact that drivers travel faster in larger roundabout compared to the smaller one and therefore, this could increase the headway between the circulating vehicles [24]. In addition, drivers need higher acceptable gaps to merge safely to the circulatory stream [8]. The main reason for the high follow-up time in site 1 compared to site 2 could be due to the lower ICD that forces the entering vehicles to reduce their speed resulting in higher follow-up time [25]. Gap parameters are estimated differently from one region to another due to the difference in driving behavior [6-8]. In this regard, aggressive driving behavior could lead to lowering the gap parameters (i.e., lower critical gap, shorter follow-up time and/or minimum headway of circulating vehicles), and hence higher entry capacity [13, 14].

Following the procedure of QHDM 2015, an inverse relation between (t_c, t_f and τ) and the roundabout entry capacity was observed. In site 1, both critical gap and minimum headway of circulating vehicles were lower than site 2 resulting in higher entry capacity. However, at low circulating flow (i.e., <400 vph) roundabout 2 had more entry capacity than roundabout 1 due to its lower follow-up time value.

The proposed procedure for the estimation of the capacity of single lane roundabouts in QHDM 2015 recommends to use the default gap values from SIDRA model (i.e., the critical gap is 4.98 s). Meanwhile, the HCM 2016 assumes a critical gap value between 4.1 s to 4.6 s. Due to the large difference between the observed critical gap and the assumed default value, the calibrated model showed higher entry capacity which was also reported in the literature [8, 9]. Therefore, the current procedure in QHDM 2015 underestimates the entry capacity of single-lane roundabouts. The main difference between HCM 2016 and QHDM 2015 models is that the HCM 2016 excludes the minimum headway of circulating vehicles [8, 26].

One of the limitations in this study is the limited observation sites. Due to the complex and time-consuming tasks of the data collection and data extraction, only two different ICDs were investigated and compared. Future studies could focus on including multiple roundabouts with different characteristics (e.g., ICD and number of lanes etc.) to investigate more accurately relationships between the gap parameters and roundabout characteristics.

5. Conclusion

In this study, gap parameters (i.e., critical time t_c, follow-up time t_f and minimum headway of circulating vehicles τ) were empirically estimated for two single-lane roundabouts in the state of Qatar. Furthermore, the effect of the ICD on the obtained parameters was discussed. The three gap parameters were obtained from a 48 h video footage that was recorded at the two sites (i.e. site 1 and site 2). As per Raff's method, the overall critical gaps of site 1 and site 2 were 2.52 s and 3.3 s, respectively. Using the 50th percentile approach, the overall follow-up times of site 1 and site 2 were 2.79 s and 2.59 s, respectively. Moreover, the minimum headways of circulating vehicles of site 1 and site 2 were 2.35s and 2.46 s, respectively.

Two different models (i.e., QHDM 2015 and HCM2016) for the estimation of the entry capacity of a roundabout were compared. Results showed that the entry capacity might be significantly affected by the ICD. Moreover, a negative relationship between the entry capacity and the gap parameters was found in this study. The comparison between QHDM 2015 and HCM 2016 using the empirically estimated gap parameters revealed that the calibrated models have resulted in significantly higher entry capacities compared to the estimated capacities using the default gap parameters. The results of this study would help transport planners and traffic engineers in estimating realistic entry capacities of single lane roundabouts in countries with similar traffic conditions and driving behaviour, such as the Gulf Cooperation Council countries. This would also assist in the design of new roundabouts or the modification of existing ones. Moreover, the obtained gap parameters can also be used for the calibration of traffic simulation models to simulate realistic entry capacities of single lane roundabouts, and therefore have reliable simulation results.

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