QATAR UNIVERSITY

COLLEGE OF ENGINEERING

# CAPACITY ANALYSIS OF SINGLE-LANE ROUNDABOUTS IN THE STATE OF QATAR

BY

NAEEM NASSER NAIM ALBEITJALI

A Thesis Submitted to

the College of Engineering

in Partial Fulfillment of the Requirements for the Degree of

Masters of Science in Civil Engineering

June 2020

# COMMITTEE PAGE

The members of the Committee approve the Thesis of
NAEEM ALBEITJALI defended on 12/05/2020.

Dr. Wael Alhajyaseen
Thesis/Dissertation Supervisor

Approved:

Khalid Kamal Naji, Dean, College of Engineering

## ABSTRACT

ALBEITJALI, NAEEM, NASSER., Masters : June : [2020:],

Master of Science in Civil Engineering

Title: Capacity Analysis of Single-Lane Roundabouts in The State of Qatar

Supervisor of Thesis: Dr. Wael, Khalil, Alhajyaseen.

This master thesis presents capacity analysis of Single-Lane roundabouts in the State of Qatar. The aim of this paper is to update Qatar highway manual, by developing a new capacity model using empirical data collected from directly the field for a single lane roundabout, also to compare the obtained capacity model with the one provided by the Highway Capacity Manual (HCM, 2016). The operations of single-lane roundabouts should be studied to ensure a safe and smooth flow for road users. This study aims to analyze drivers' behavior and estimate the capacity of two single-lane roundabouts using critical gap, entry headway gap and circulating headway gap. Video data were collected at two roundabouts located in Doha, Qatar. The analysis estimated the critical gap $t_c$, follow up headway gap $t_f$ and circulating headway gap $\tau$ for each approach alone. Then capacity was calculated using the approach of the most critical conditions. The capacity was estimated using the Highway Capacity Manual (HCM, 2016) approach. The critical gap was different among the two sites with an average of 3.39 sec for Site 2 and 2.61 secs for Site 1. The average circulating headway gap was 2. 51 and 2.24 seconds for Site 2 and Site 1 respectively. The average follow-up headway gap was between 2.61 and 2.67 seconds for Site 2 and Site 1 respectively. The results signify that the HCM 2016 fails at higher circulating flow rates in capacity estimation in Qatar. Further, the importance of roundabouts geometry and drivers'

behavior on impacting the capacity estimation of single-lane roundabouts was reflected on the critical gap parameters.

# DEDICATION

*It is my genuine gratefulness and warmest regard that I dedicate my thesis to my beloved family who have meant and continue to mean so much to me. I also dedicate this work to my supervisor DR. Wael Alhajyaseen, and who supported me throughout the process. I will always appreciate his hard working with me, and I will always remember his valuable tips.*

# ACKNOWLEDGMENTS

This study was supported by Qatar University, Qatar transportation and traffic safety center. I am especially grateful to DR. Wael Alhajyaseen, who has been supportive to my career objectives and who spent a massive amount of time to pursue those targets.

# TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

| | |
|---|---|
| **HCM** | Highway capacity manual |
| **JRM** | Japan Roundabout Manual |
| **HBS** | Germany Highway Capacity Manual |
| **PCE** | Passenger Car Equivalent |

# CHAPTER 1: INTRODUCTION:

## 1.1 Overview

The continuous increase in population in residential areas is becoming increasingly challenging for traffic engineers. As existing infrastructure such as roads and roundabouts is facing higher demands with more conflicts arising between commuters of these transit networks, leading to congestions and accidents (Dahl & Lee, 2012). The objective of traffic engineers is to ensure safety of commuters by reducing accidents in roads and roundabouts. Roundabouts are considered as at grade intersections usually built in suburban areas where the traffic volumes don't reach saturation (Muley & Al-Mandhari, 2014). The function of roundabouts is to ensure smooth flow of traffic in all directions, by forcing road traffic to slow down when approaching the roundabout circulate around the central island to their respective exits. Reduced delays, enhanced traffic flow and safety are the main advantages of using roundabouts. However, in situations where traffic volumes exceed capacity, accident rates increase, and traffic conditions reache congestion. Therefore, estimation of the capacity in roundabouts is needed to ensure smooth traffic flow in all approaches of the roundabout (Guo, Liu, & Wang, 2019). There are many models that have been established to estimate the capacity of roundabouts. One of the most common approaches of estimating the entry capacity of roundabouts is the one proposed by the highway capacity manual (HCM, 2010). The theory is based on the gap acceptance theory, which is based on entry vehicle headway and circulating vehicle headway. The HCM provides an empirical equation that assumes constant gap parameters to estimate the entry capacity. The German Highway Capacity Manual proposes estimation of the entry capacity based on different gap parameters (Wu, 2015). These parameters are the critical gap, follow up headway and circulating vehicle headway. Further, the impact of the geometric information on these parameters of roundabouts is not well investigated in the recent literature (Guo et al., 2019), (Johnson & Lin, 2018) and (Flannery, 2001). Some of the recent developments in estimating the capacity are defined by the HCM as it defines capacity as the greatest sustainable flow rate per hour at which vehicles or persons can reasonably be expected to pass through a point or a section of a lane or roadway during a given period. The capacity of the roundabout depends on the weaving section and its geometry (Wang & Yang, 2012). Moreover, the circulating flow on the roundabout conflicting with the entry flow also determines the entry capacity of the roundabout (Robinson et al., 2000) in addition to the pedestrian flow(Kang & Nakamura, 2014). This study investigates the performance of HCM 2016 single lane roundabout equation applying it in Qatar. This is done by comparing the capacity values with the actual capacity estimated using critical gap, follow up headway and circulating headway. In addition, roundabouts geometry will be investigated to assess whether the geometry of roundabouts affects capacity estimation of single-lane roundabouts.

Roundabouts are the most widely used intersection worldwide for which safety is the main constituents. In addition, regarding their operational effectiveness, they are typically beneficial at medium level of vehicular traffic with balanced flows at the minor and major approaches. When choosing a specific intersection to be constructed in a specific area, it is important to know its capacity to evaluate its performance. Hence, it is crucial to understand the entry capacity for roundabouts because it is one of the most significant indices to predict their operational performance by examining whether it can handle the expected demand of traffic or not.

The regular approach to estimate the entry capacity of a given roundabout is provided by the Highway Capacity Manual (HCM, 2016), this approach is basically based on the theory of gap acceptance by defining some gap parameters in entry and circulating flows. This methodology is simplified by HCM (2016) by assuming constant gap parameters to deliver empirically calibrated equations to predict entry capacity of a given roundabout by using only the circulating flow as an input variable without taking into consideration the geometric impact of that roundabout. On the other hand, the Germany Highway Capacity Manual HBS (Handbuch für die Bemessung von Straßenverkehrsanlagen, 2005) in addition to Japan Roundabout Manual (JRM, 2016) propose the original equation that comprises various gap parameters in order to estimate the entry capacity of a given roundabout. These parameters include the critical gap $(t_c)$, minimum headway of circulating flow $(\tau)$ and the follow-up time $(t_f)$. However, a few numbers of studies investigated the influence of vehicle type and roundabout geometry on the gap parameters and on the entry capacity (Kang & Nakamura, 2014) and (Kanbe et al., 2016). Though, rational quantification of these relations is still absent, and this is the reason why the present manuals suggest a fixed gap values that does not depend on the roundabout geometry nor the vehicle type. The existence of heavy vehicles at the entry approach or on the circulatory roadway will differently and significantly impact the roundabout entry capacity. (HBS, 2005) and (JRM, 2016) suggest a factor which is called Passenger Car Equivalent (PCE). This factor is presented based on the entry capacity reduction due to heavy vehicles, this can be used to convert the demand of the heavy vehicles into the corresponding number of passenger cars without considering their effect on the gap parameters. HBS and JRM proposed a constant value of 2.0 to be used to convert to PCE, while the recent studies show that PCE value can change based on heavy vehicles percentage.

Notwithstanding, roundabouts in Qatar are being built with different dimensions because of the area limitation. Driver behavior as well as entry capacity are significantly affected by the different layouts of roundabouts. Hence, the aim of this master thesis is to investigate the impact of different roundabout geometry on the gap parameters and on the corresponding entry capacity using real empirical values from the field.

## 1.2 Scope of the study:

Evaluation of roundabout capacity is very crucial since it is directly related to level of service, delay, operation, accident, environmental issue, and operation cost. Hence, it is important to conduct a comprehensive capacity analysis. The capacity of the roundabout is defined as the maximum number of vehicles that can pass to the island (Cheng, Zhu, & Song, 2016). It is commonly determined by using the gap acceptance theory. In order to determine the roundabout level of service, it is important to determine its capacity. For this reason, a single-lane roundabout was selected to analyze its capacity and level of service. The objective of this research is to investigate the effect of geometric design of roundabout on three gap parameters which are critical gap $(t_c)$, minimum headway of circulating flow $(\tau)$ and the follow-up time $(t_f)$ for evaluating entry capacity for a given roundabout.

## 1.2 Research layout:

The research flow is shown in Figure.1 The main aim of this research is to investigate by what means entry capacity affected by roundabout geometric elements which can be represented by the three important parameters as mentioned before. In order to have an adequate estimation for the relationship between the three gap parameters and the geometric elements, it is necessary to collect empirical data from roundabouts in Qatar to get the gap parameters. Hence, the collection of data and the analysis is shown later in the analysis. After that, we can conclude the effect of the geometric elements on the geometric parameters in the state of Qatar and provide an equation to estimate the entry capacity for a roundabout.

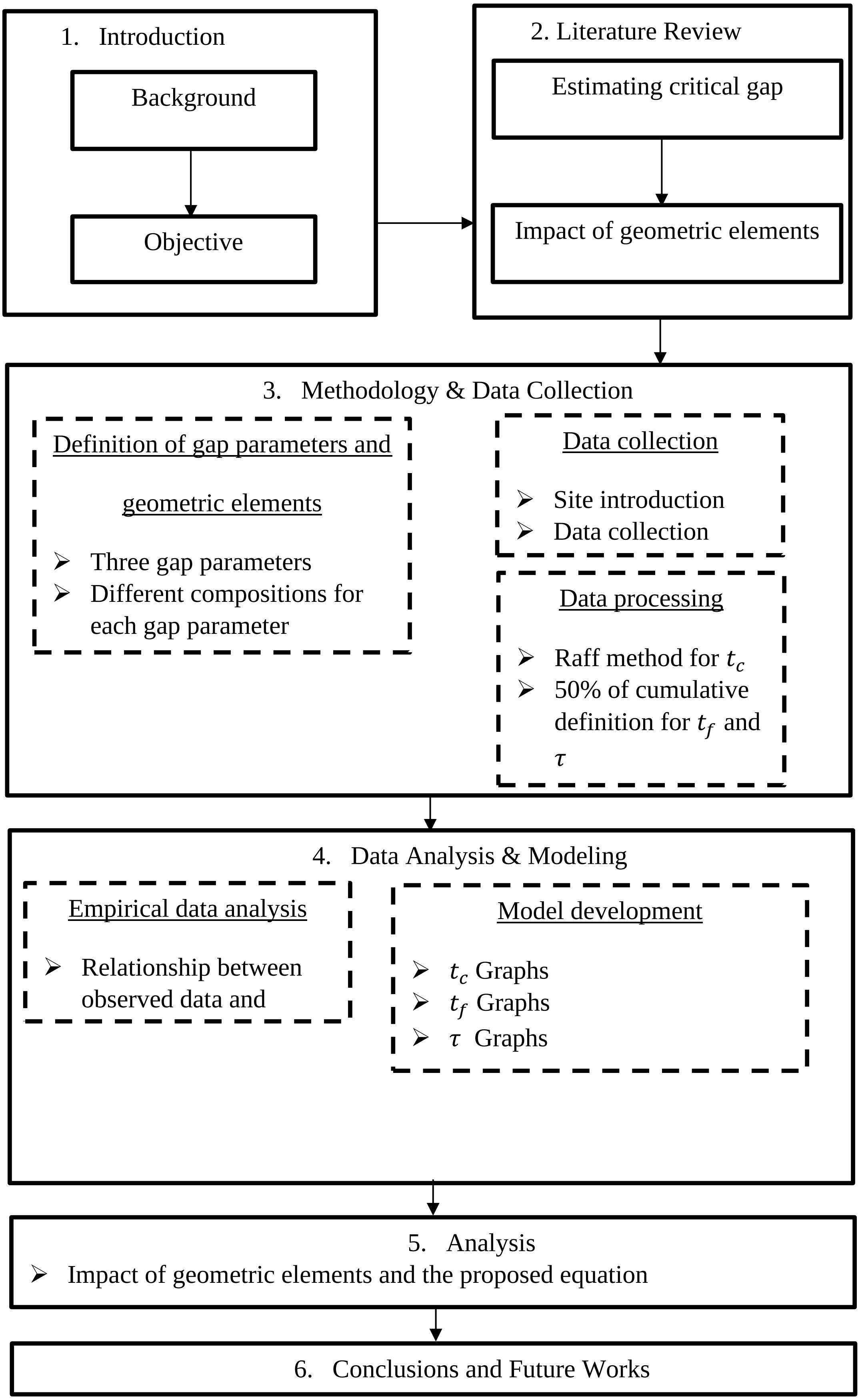


Figure 1 Procedure of this research

# CHAPTER 2: LITERATURE REVIEW

## 2.1 Capacity Concepts:

The definition of roundabout entry capacity is the maximum number of vehicles that enters the roundabout from one approach during a specific period. During the planning phase, one of the most important inputs is entry capacity, which is essential to evaluate the roundabout ability for accommodating the demand of traffic.

(HBS, 2005) estimates the entry capacity based on equation (2.1) which is similar to the equation that proposed by (JRM, 2016). This equation depends on circulating headway, follow up headway and critical gap. According to Highway Capacity Manual, the capacity of single lane roundabout can be estimated using equation (2.3). This equation is generated using the original form equation (2.2), while neglecting circulating headway and assuming fixed values for critical gap and follow up headway. The HCM assumes that the critical gap and follow up headway are constant, although in reality, it varies based on factors such as study location, time of day (peak or slack times), manoeuvre being made, queue waiting time, driver waiting time at the yield line (time spent waiting for an acceptable gap or number of gaps rejected), vehicle classification, point of departure in the circulating lanes, driver demographics, and presence of a passenger next to the driver.

$$c_{pce} = \frac{3600}{t_f}\left(1 - \tau\frac{q_r}{3600}\right) exp\left[-\frac{q_r}{3600}\left(t_c - \frac{t_f}{2} - \tau\right)\right] \tag{2.1}$$

$$C_{pce} = \frac{3,600}{t_f} e^{-\frac{(t_c - 0.5t_f)}{3,600}q_r} \tag{2.2}$$

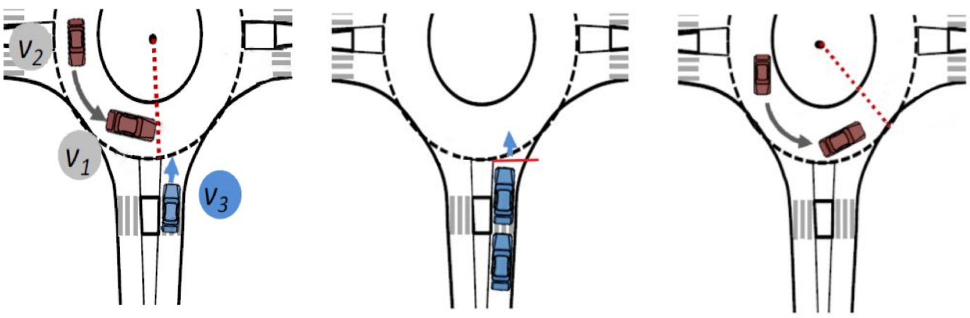
$$C_{pce} = 1380e^{-(1.02x10^{-3})q_r} \tag{2.3}$$

**where:**

$c_{pce}$: entry capacity of entry e in the unit of pcu/h if there are no heavy vehicles otherwise the unit will be veh/h,

$q_r$: circulating flow at the entry e in the unit of pcu/h if there are no heavy vehicles otherwise the unit will be veh/h,

$t_c$: critical gap (sec), $t_f$: follow-up time of entry vehicle (sec), $\tau$: minimum headway of circulating flow (sec). The circulating flow is defined by the circulating flow that passes in front of the subject entry. The headway is defined by the time interval between two successive vehicles as they pass a point in a road (s) (i.e. front bumper). The critical headway is defined as the minimum time interval within the circulating flow when an entering vehicle can safely move into a roundabout (Xu & Tian, 2008). Lastly, Follow-up time is the time between the departure of one vehicle from the minor street and the departure of the next vehicle using the same gap under a condition of continuous queuing, they were measured by observing traffic flow. The most important variables that give a representation of driver's gap acceptance behavior are known as the gap parameters, which are $t_c$, $t_f$, and $\tau$ as shown in Figure 2.




Critical Gap ($t_c$) Follow-Up Time ($t_f$) Circulating Headway (τ)

Figure 2 Gap parameters

## 2.2 Methodology of estimating critical gap ($t_c$)

The critical gap $t_c$ is defined as the minimum time interval in the circulating roadway stream (major street stream in roundabout), that will allow one minor-street vehicle to enter and merge into the circulating roadway. Hence, the critical headway of the driver is the minimum headway that would be adequate, and the value of $t_c$, is always changing depending on the driver behavior and judgment. Direct estimation of the critical gap is difficult, therefore there are several methods to estimate it. Moreover, the critical gap most likely reflects the driver behavior.

There are several methods to estimate the critical gap ($t_c$), such as:

1- Maximum likelihood method
2- Median method
3- Raff's method

In this paper, Raff's method was used for estimating the critical headway since it is widely used and a practical and simple method.

Raff's Method is a graphical method, defines that the critical lag L as the size of which lag has the property that the number of accepted lags shorter than L is the same as the number of rejected lags longer than L (Raff & Hart, 1950). A cumulative graph for observed drivers accepted gaps is drawn, and another cumulative graph for the rejected gaps is drawn, the intersection point between these two graphs is the critical gap. Equation (2.4) express this method:

$$1 - F_r(t) = F_a(t) \tag{2.4}$$

Where $t$ is headway of major stream.

$F_a(t)$ is defined as the accepted gap cumulative probability.

$F_r(t)$ is defined as the rejected gap cumulative probability.

Raff's method is used widely because of its practicality and simplicity and it can be used to estimate $t_c$ with a small sample size, and it is named as the threshold method.

Additionally, the critical gap $t_c$ can be estimated using Logit model, in combination with a utility function that can estimate the probability of accepting a specific gap (Alhajyaseen, Asano, & Nakamura, 2012) and (Cassidy, Madanat, Wang, & Yang, 1995)

Where accepted it can be set as 1, rejected it can be set as 0, and the probability of accepted gap *pa(t)* can be expressed as equation (2.4).

$$F_c(t) = p_a(t) = \frac{1}{1+\exp(-V_a)} \tag{2.5}$$

Where $v_a$ is defined as the utility function of the accepted. For example, $v_a$ can be expressed as the linear function as shown in equation 2.6 below.

$$V_a = \alpha + \beta t \tag{2.6}$$

α and β can be estimated to know the critical gap distribution.

On the other hand, for the case of small sample size, using the Logit model is not useful. In other research, (Wu, 2012) estimated the critical gap using the accepted and the rejected gaps cumulative probability distribution as in equation (2.7), By using this method there is no requirement to assume exact function for the probability distribution.

$$F_C(t) = \frac{F_a(t)}{F_a(t)+1-F_r(t)} \tag{2.7}$$

Among these various methods, (Goto & Nakamura, 2017) determined that the Raff method (1950) is similar to the 50-percentile distribution of Wu method. Therefore, Raff Method was used in this master thesis for the estimation of the critical gap *tc*.

## 2.3 Impact of heavy vehicles on entry capacity:

There are primarily two approaches to take into account the effect of heavy vehicles on the roundabout entry capacity. The first approach is to use the passenger car equivalent

(PCE) for heavy vehicles to adjust the traffic flow. And the other approach is to adjust the three gap parameters based on the heavy vehicles. HBS (2005) and JRM (2016) suggested a constant of 2 PCE of heavy vehicles at the same time HBS (2005) recommended PCE value of 1.5 to be used for buses. Nevertheless, many studies observed that PCE is not a constant value, but it changes based on the percentage of heavy vehicles and based on the circulating flow.(Brown, 1995) and (Tanyel, Çalişkanelli, Aydin, & Utku, 2013) observed that PCEs of heavy vehicles on circulating and entry roadway are different.

Table 1 Passenger car equivalent for heavy vehicles

<table>
<tr><th>Guideline</th><th>Trucks</th><th>Buses</th></tr>
<tr><td>HBS</td><td>2.0</td><td>1.5</td></tr>
<tr><td>HCM 2000</td><td>2.0</td><td>1.5</td></tr>
<tr><td>HCM 2010</td><td colspan="2">2.0</td></tr>
<tr><td>ARR 123</td><td colspan="2">2.0</td></tr>
<tr><td rowspan="3">Regular road capacity (1984) (in Japanese)</td><td colspan="2">Road types</td></tr>
<tr><td>Urban / Plain</td><td>Mountainous</td></tr>
<tr><td>2.0</td><td>3.5</td></tr>
<tr><td>Japanese Roundabout Manual (2016)</td><td colspan="2">2.0</td></tr>
</table>

The next method is to model gap parameters as function of heavy vehicle percentage in the entering and circulating flows. (Dahl & Lee, 2012) adjusted the gap parameters by taking into consideration the percentage of heavy vehicles for a study that was done in Canada using empirical data, hence trying to estimate the capacity using the new modified gap parameters. But, in this study the effect of roundabout geometry was not considered. In another study conducted in the US using empirical data, (Lee, 2014) modeled and evaluated the impact of heavy vehicles on the critical gap and on the follow up time. They proposed PCE for various heavy vehicle percentages and concluded that the estimation of roundabout capacity can be improved using the PCE. Nevertheless, they declared that the PCE is influenced by the characteristics of heavy vehicles at the subject roundabout such as the weight and the size.

(Kang & Nakamura, 2016) and (Goto et al., 2016) also evaluated the passenger car equivalent for heavy vehicles based on realistic and simulated data in Japan. They assessed the effect of heavy vehicles on the gap parameters by separating the heavy vehicles into several categories based on the existence of heavy vehicles as shown in Table 2, the letter P stand for passenger cars and H stand for Heavy vehicle. The different categories were used to model a roundabout with a diameter of 27 m using VISSIM software to estimate the entry capacity for different heavy vehicles percentages. They came up with a conclusion that the values of PCE range between 1.3 – 1.5 on the circulating roadway and 1.4 to 3 on entry approach, but the effect of roundabout geometry was not considered in this paper.

Table 2 Normalized values of different gap parameters under various vehicle compositions (Goto et al., 2016)

| Gap parameter | $t_c$ | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Vehicle composition | PP-P | HP-P | PH-P | PP-H | HH-P | HP-H | PH-H | HH-H |
| Normalized value | 1 | 1.2 | 1.1 | 1.3 | 1.3 | 1.6 | 1.4 | 1.7 |
| Gap parameter | $t_f$ | | | | $\tau$ | | | |
| Vehicle composition | PP | PH | HP | HH | PP | PH | HP | HH |
| Normalized value | 1 | 1.2 | 1.4 | 1.4 | 1 | 1.1 | 1.4 | 1.9 |

Where PP-P means the two circulating vehicles are passenger cars while the vehicle entering to the roundabout is a passenger car.

Where HP-P means the first circulating vehicle is heavy vehicle and the second circulating vehicle is passenger car while the vehicle entering to the roundabout is a passenger car.

Where PH-P means the first circulating vehicle is passenger car and the second circulating vehicle is heavy vehicle while the vehicle entering to the roundabout is a passenger car.

Where HH-H means the two circulating vehicles are heavy vehicles while the vehicle entering to the roundabout is a heavy vehicle.

## 2.4 Capacity and Impact of geometric elements on entry capacity

In a study that was done in Britain using empirical data by Kimber (1980), he examined the effect of the geometry of the roundabout on the entry capacity. He investigated the impact of six different independent parameters as shown in table 3 that are related to the roundabout geometry and model it as a function of these parameters to estimate the capacity of the roundabout. These equations are listed below:

$$C_e = k(F - f_c \times q_c)$$

$$k = 1 - 0.00347(\varphi - 30) - 0.978\left(\frac{1}{r} - 0.05\right)$$

$$F = 303 \times x_2\left(\frac{veh}{h}\right)$$

$$f_c = 0.21 \times T_D(1 + 0.2 \times x_2)$$

$$x_2 = v + \frac{e - v}{1 + 2S}$$

$$T_D = 1 + \frac{0.5}{\left(1 + e^{\left(\frac{D-60}{10}\right)}\right)}$$

$$S = \frac{e - v}{l'}$$

Where $C_e$ is the entry capacity (pcu/h)

*Qc* is the circulating flow(pcu/h)

*F* is the capacity at *qc* is 0 (pcu/h)

*e* is the width(m)

*v* is the approach half width(m)

*l'* is the effective flare length(m)

$r$ is the is entry radius(m)

$\varphi$ is the entry angle(deg)

$S$ is the sharpness of the flare

$D$ is the inscribed circle diameter(m)

Table 3 Scope of use of geometric elements

| Geometric Elements | Applicable Range |
|---|---|
| 1. Entry Width e(m) | *3.6(m) ~ 16.5(m)* |
| 2. Approach Half Width *v*(m) | *1.9(m) ~ 12.5(m)* |
| 3. Effective Flare Length *l'*(m) | *1.0(m) ~ ∞* |
| 4. Entry Radius *r*(m) | *3.4(m) ~ ∞* |
| 5. Inscribed Circle Diameter *D*(m) | *13.5(m) ~ 71.6(m)* |
| 6. Entry Angle $\varphi$(deg) | *0(deg) ~ 77(deg)* |

He investigated the geometry of the roundabout and revealed that the entry capacity is significantly affected by the geometry of the roundabout. This method, however, is missing the theoretical background. Therefore, generalizing this method has a major concern among researchers to be utilized at other locations in different environments. According to FHWA (2000), the roundabout capacity would decrease as the widths and radii decrease.

The influence of roundabout geometry on the three gap parameters $t_c, t_f$ and $\tau$ is infrequently investigated in the literature. (Kanbe et al., 2016) conducted a study on 4 roundabouts in Japan using limited data to investigate the effect of geometric elements on the gap parameters. Moreover, he created empirical models to approximate gap parameters as a function of roundabout geometry by assuming the percentages of heavy vehicles is 0% in circulating and entry flows. He concluded that the critical gap time is significantly affected by the effective flare length and entry width, because these parameters make it simpler for the vehicles entering the roundabout to merge with the circulating flow. Additionally, the Minimum headway of circulating roadway $\tau$ is clearly affected by the merging angle and the inscribed circle diameter. Though, the main constraint of their research is the restricted sample size and neglecting the impact of heavy vehicles. To sum up, as shown in the previous literature, there is a need to investigate the impact of geometric elements on the entry capacity.

# CHAPTER 3: METHODOLOGY AND DATA COLLECTION

## 3.1 Definition of Gap Parameters:

The entry capacity $c_{pce}$ is evaluated equation (2.1) suggested by (JRM, 2016). Critical gap *tc*, follow-up time *tf*, and minimum headway of circulating roadway $\tau$ are defined as "gap parameters" and identified as the most important variable that correspond to driver's gap acceptance behavior. In this study, tc is defined as the minimum acceptable gap between two circulating vehicles for an entry vehicle. tf and τ are minimum headway between entry and circulating vehicles, respectively.

For the estimation of tc, only observed gaps less than 10 sec were considered since all gaps over 10 sec can be considered as accepted gap. Raff Method is applied to estimate the value of tc for each approach. In the estimation of tf and τ, only gaps below 5 sec were considered. The values of tf and τ are defined as the 50 percentile of the cumulative distribution of the observed follow up headways at the entry approach and headways between vehicles in the circulatory roadway.

## 3.2 Definition of geometric elements:

Commonly roundabout geometric layout is defined based on several parameters as shown in Figure 3. These parameters are: Entry width *We* (m), which is the width of the entry approach which is the vertical to the splitter island; Approach half width *W* (m), the width of lane of entry approach; Inscribed circle diameter *D* (m), Entry radius *R* (m), which is the radius of entry trajectory; Effective flare length *l* (m), which is the length from entry width to the half of entry width plus approach half width; Merging angle *φm* (deg), which is the angle between vertical to the entry width of entry approach and the tangent line of the center circle of the circulating roadway; and Entry angle *φe* (deg), which is the angle between vertical to the entry width of entry approach and the tangent line of the center circle of the circulating roadway. The impact of these parameters will be investigated in this study using empirical data.

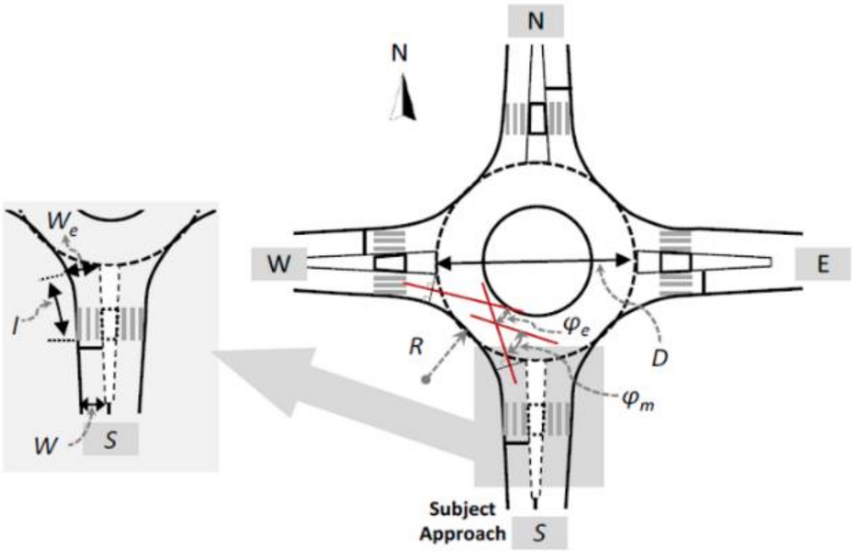



Figure 3 Geometric elements layout

3.3 Description of the selected sites

Two sites with a single lane roundabout located in Bin Mahmoud area and Old Airport area Doha, Qatar. The roundabout is located in residential area with geometric illustrations shown and geometric details of the roundabout are specified in Table. 4 below. Heavy vehicle percentages and pedestrian volumes were neglected in capacity analysis, because there were no heavy vehicles observed in both site locations.

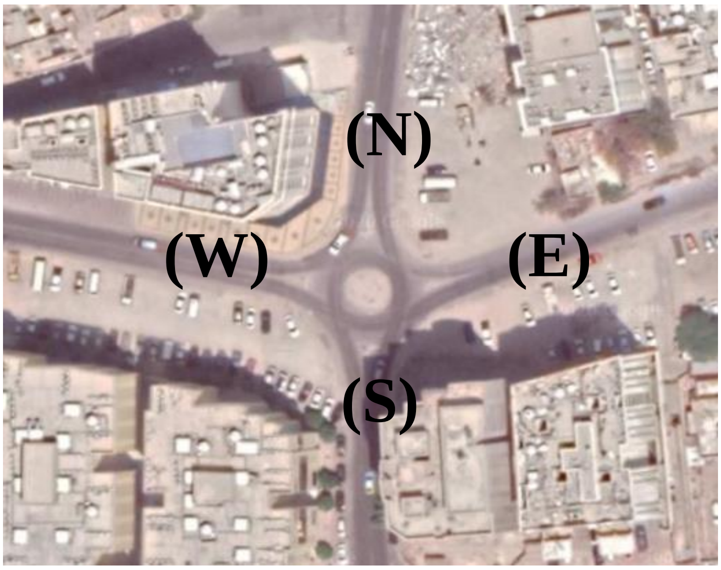



Figure 4 Satellite image for AL Quds st intersection with Abdullah Bin Masoud St roundabout

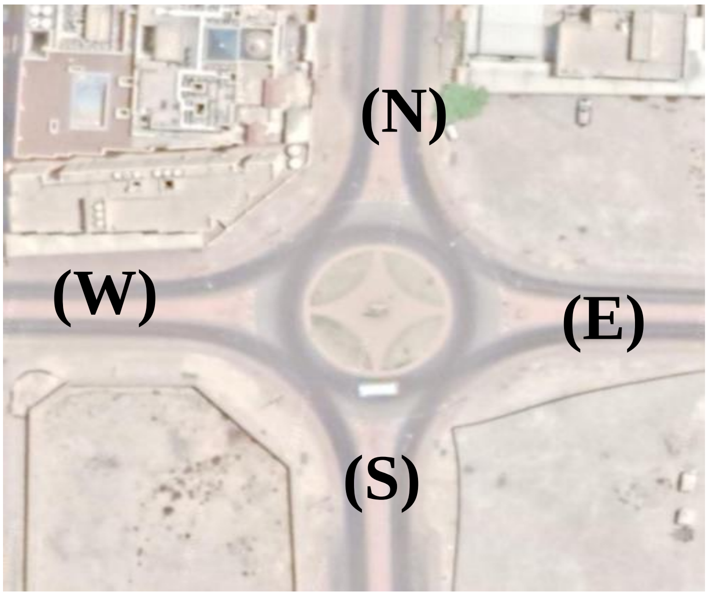



Figure 5 Satellite image for Oqba Bin Nafie st intersection with Jaber Bin Hayyan St roundabout

Table 4 Geometry of the roundabouts

| **Roundabout Name** (Control Type) | | **Geometric elements** | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | ***We (m)*** | ***W* (m)** | ***D* (m)** | ***R* (m)** | ***L* (m)** | ***φe* (deg)** | ***φm* (deg)** |
| **AL Quds** | N | 4 | 3.75 | 24 | 10 | 3.875 | 47 | 57 |
| (Yield) | S | 4 | 3.75 | | 10 | 3.875 | 36 | 67 |
| (Site 1) | E | 4 | 3.75 | | 10 | 3.875 | 45 | 50 |
| | W | 4 | 3.75 | | 10 | 3.875 | 43 | 59 |
| **Oqba Bin Nafie** | N | 5 | 3.75 | 41 | 25 | 4.375 | 49 | 55 |
| (Yield) | S | 5 | 3.75 | | 25 | 4.375 | 42 | 48 |
| (Site 2) | E | 5 | 3.75 | | 25 | 4.375 | 44 | 46 |
| | W | 5 | 3.75 | | 25 | 4.375 | 48 | 59 |

48 hours of video footage for the roundabout was collected and analyzed to calculate the critical headway, follow up headway and circulating headway. These parameters are used to calculate the capacity of the two roundabouts according to the procedure mentioned in the capacity concepts section. The geometry of the roundabout was assessed based on the existing conditions comparing it to some recent studies.

CHAPTER 4: DATA COLLECTION:

4.1 The critical gap *tc* for (site 1)

For the case of tc, only the gaps below 10 seconds was collected, if it's more than 10 seconds it can be considered as an accepted gap. The method used in this paper to estimate the critical gap is Raff's Method for each approach, based on this method the critical gap is defined as the intersection point between the cumulative distribution of rejected gaps and accepted gaps, as shown in Figures.6,7,8,9 for North, South, East, West Approaches respectively. The results of the critical gap for site 1 is summarized in Table.5.

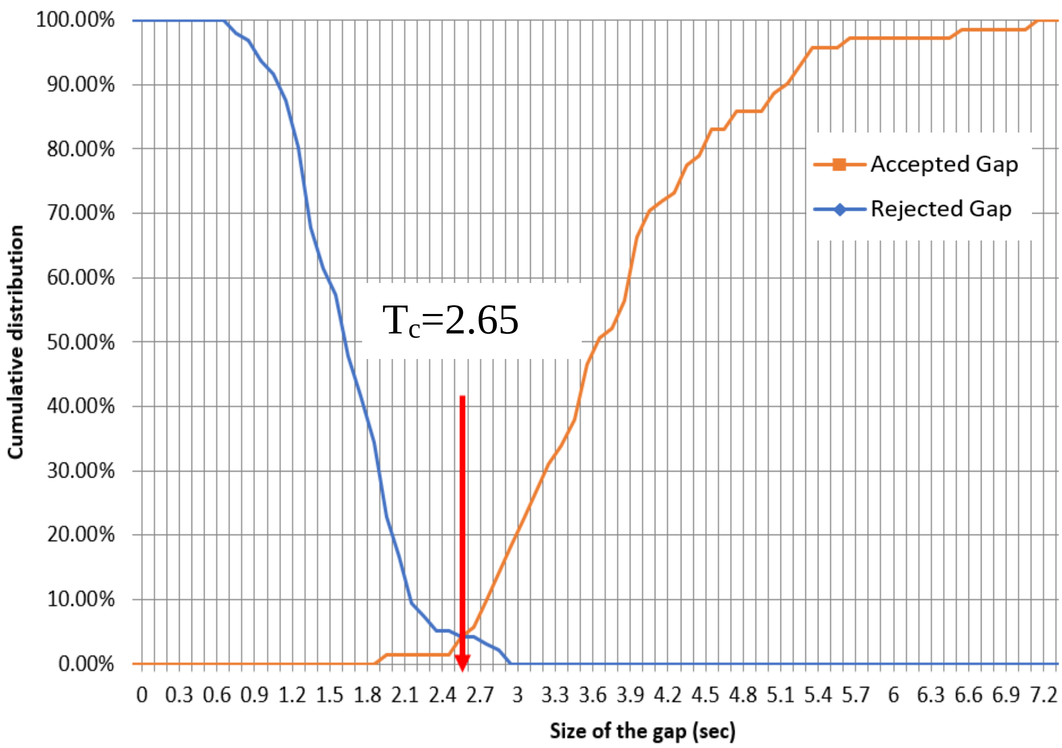



Figure 6 Site 1 North approach critical gap

Figure 6. illustrates the cumulative distribution of critical rejected and accepted gaps versus the size of the gap for the North approach for site number 1, Raff Method is used to estimate the value of $t_c$, the intersection point of the cumulative distribution of the accepted gaps and the rejected gaps is defined to be the critical gap for this approach

which is equal to 2.65 seconds.

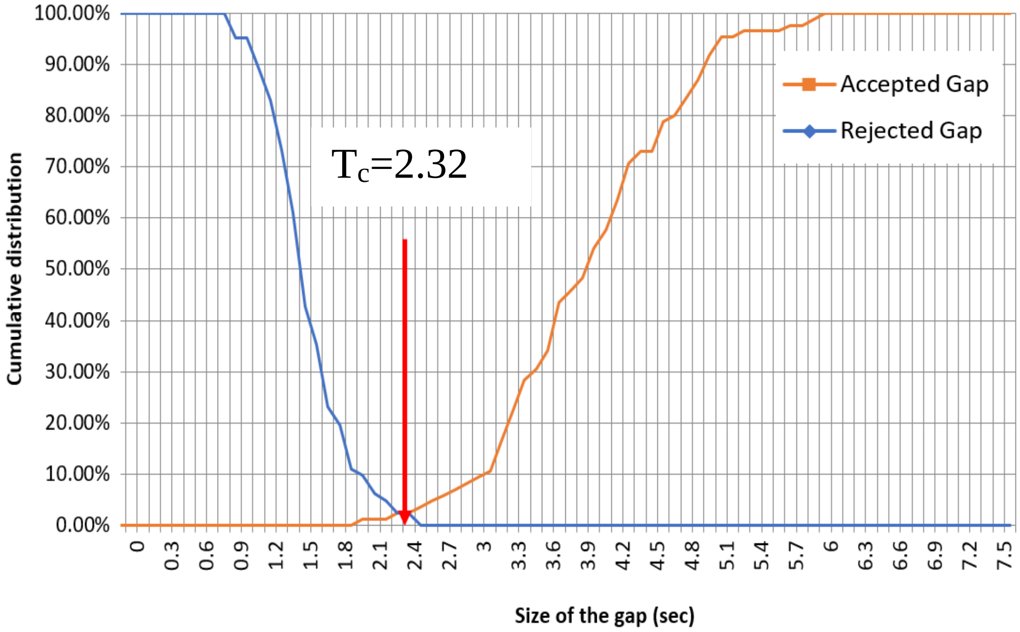



Figure 7 Site 1 South approach critical gap

Figure 7. demonstrates the cumulative distribution of critical rejected and accepted gaps versus the size of the gap for the North approach for site number 1, Raff Method is used to estimate the value of $t_c$, the intersection point of the cumulative distribution of the accepted gaps and the rejected gaps is defined to be the critical gap for this approach which is equal to 2.32 seconds.

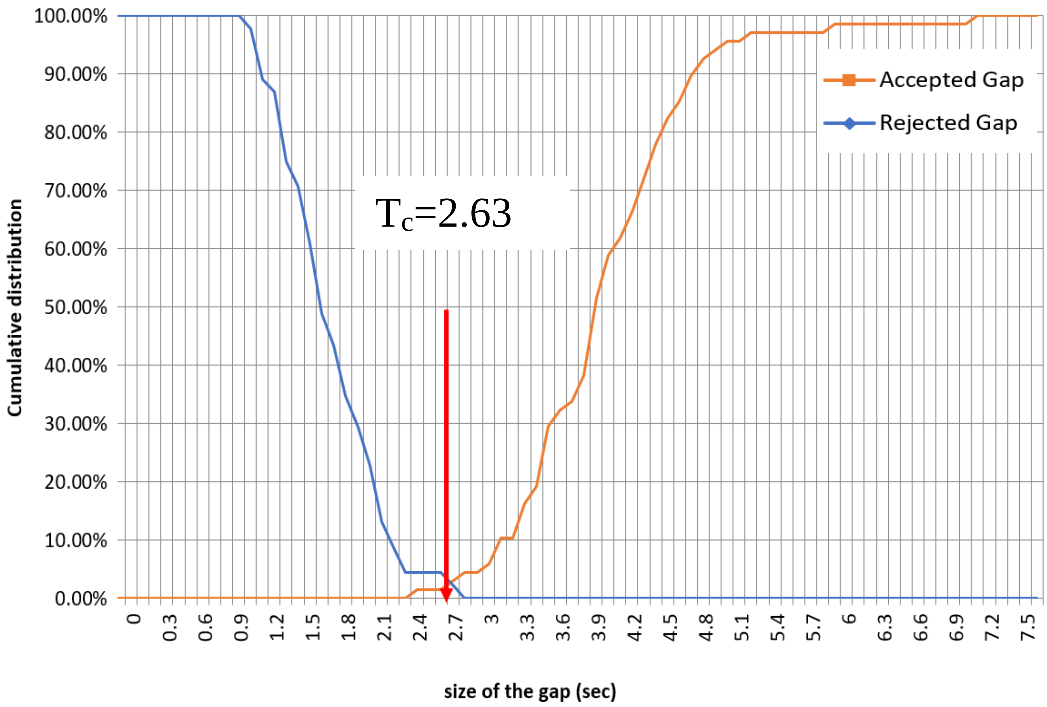



Figure 8 Site 1 East approach critical gap

As shown in Figure 8, the intersection point of the cumulative distribution of the accepted gaps and the rejected gaps is defined to be the critical gap for this approach which is equal to 2.63 seconds.

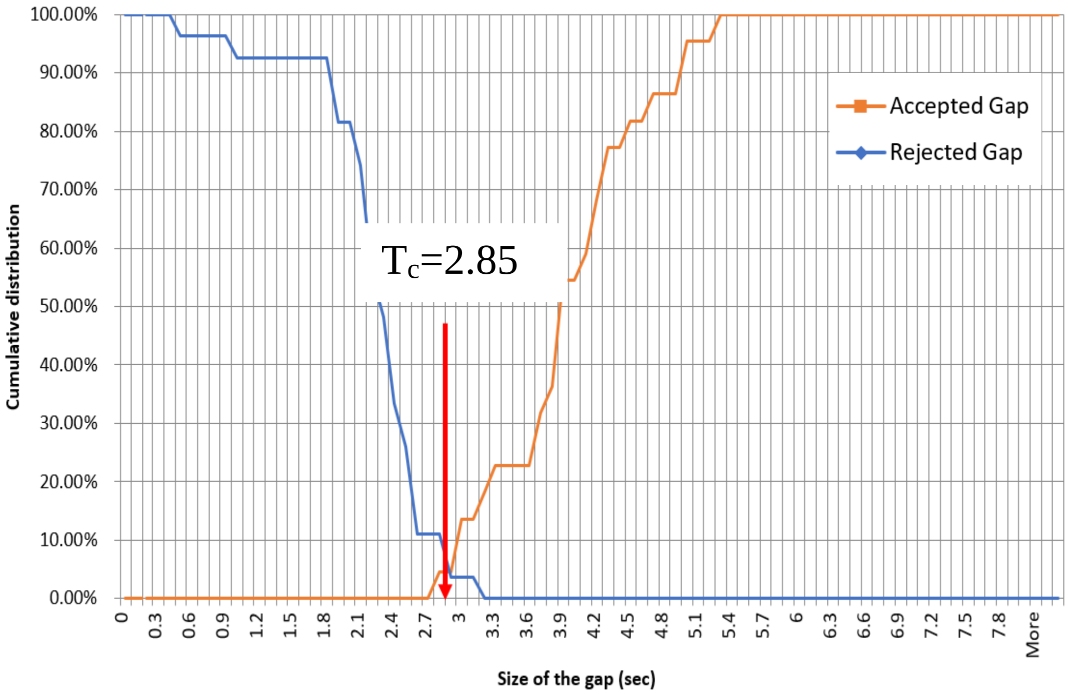



Figure 9 Site 1 West approach critical gap

For the West approach, the critical gap is observed to be 2.85 seconds as shown in Figure 9. Table 5 summarize the critical gap values for site 1 for each approach.

Table 5 Summary for the Critical gap tc for site 1

| Summary for the Critical gap $t_c$ for site 1 | |
|---|---|
| Approach | Critical gap $t_c$ (sec) |
| North | 2.65 |
| South | 2.32 |
| East | 2.63 |
| West | 2.85 |

### 4.2 The Follow-up time tf for (site 1)

For the case of the Follow-up time $t_c$, only the gaps under 5 seconds were collected, because if the gap is exceeded 5 seconds it considered that the two vehicles are not following each other (by observation). The methodology for calculating the Follow-up time $t_c$, is as the following steps:

1) Draw a cumulative distribution of the Follow-up time.
2) Take the 50 percentile of this cumulative distribution and this value is defined as the Follow-up time $t_f$.

Figures from 10,11,12 and 13 shows the Cumulative distribution of follow-up time for the North, South, East, West Approaches respectively.

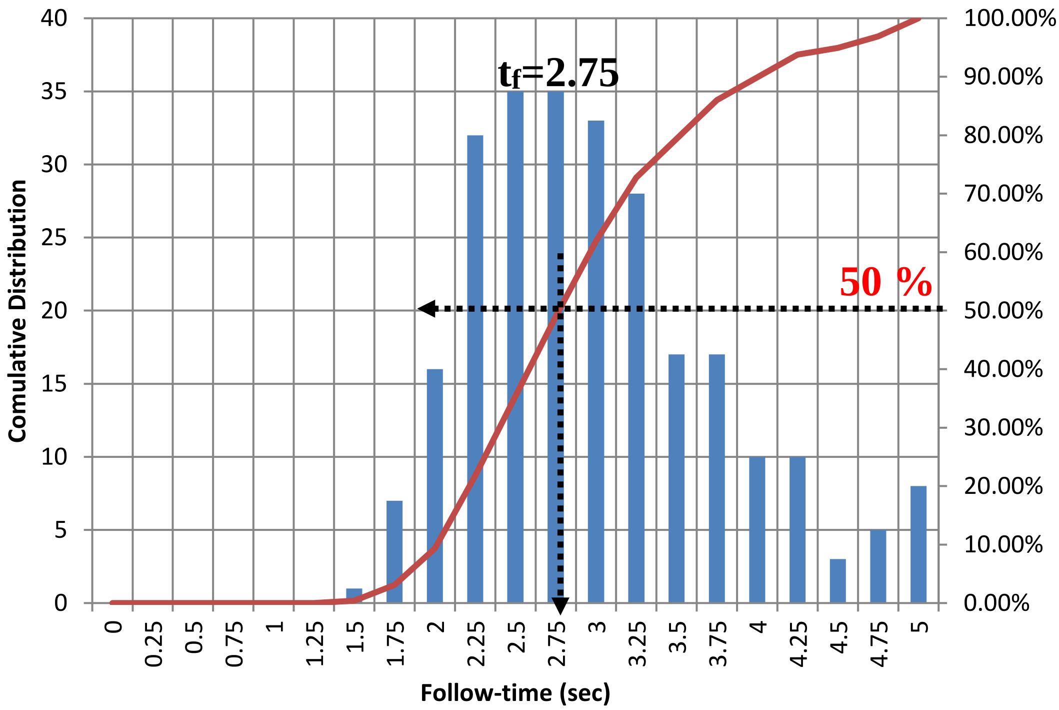



Figure 10 Cumulative distribution of follow-up time North Approach for site 1

Figure 10. shows the cumulative distribution of follow-up time for the North approach for site number 1, to get the value of the follow up time the 50 percentile of this curve

is defined to be the follow up time for the North approach which is equal to 2.75 seconds.

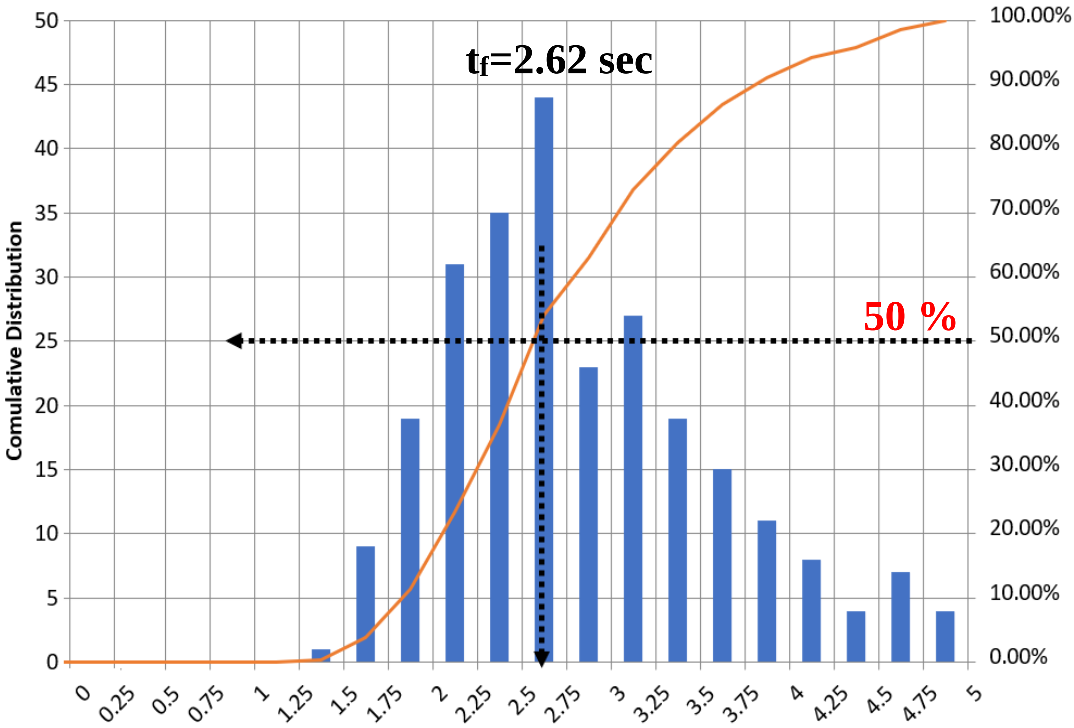



Figure 11 Cumulative distribution of follow-up time South Approach for site 1

Figure 11. demonstrates the cumulative distribution of follow-up time for the South approach for site number 1, to get the value of the follow up time the 50 percentile of this curve is defined to be the follow up time for the South approach which is equal to 2.62 seconds. Moreover, the gaps above 5 seconds was not taken into consideration because it is considered that these two vehicles are not following vehicle.

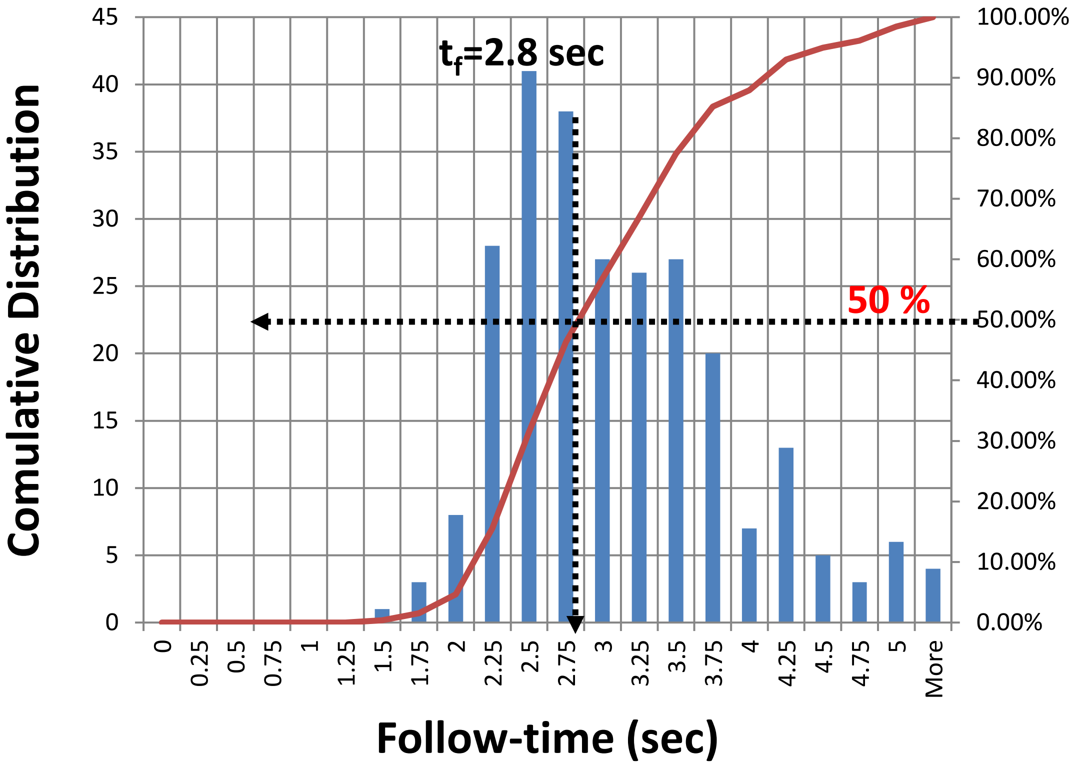



Figure 12 Cumulative distribution of follow-up time East Approach for site 1

As shown in Figure 12, the 50 percentile of this curve is defined to be the follow up time for the East approach which is equal to 2.8 seconds.

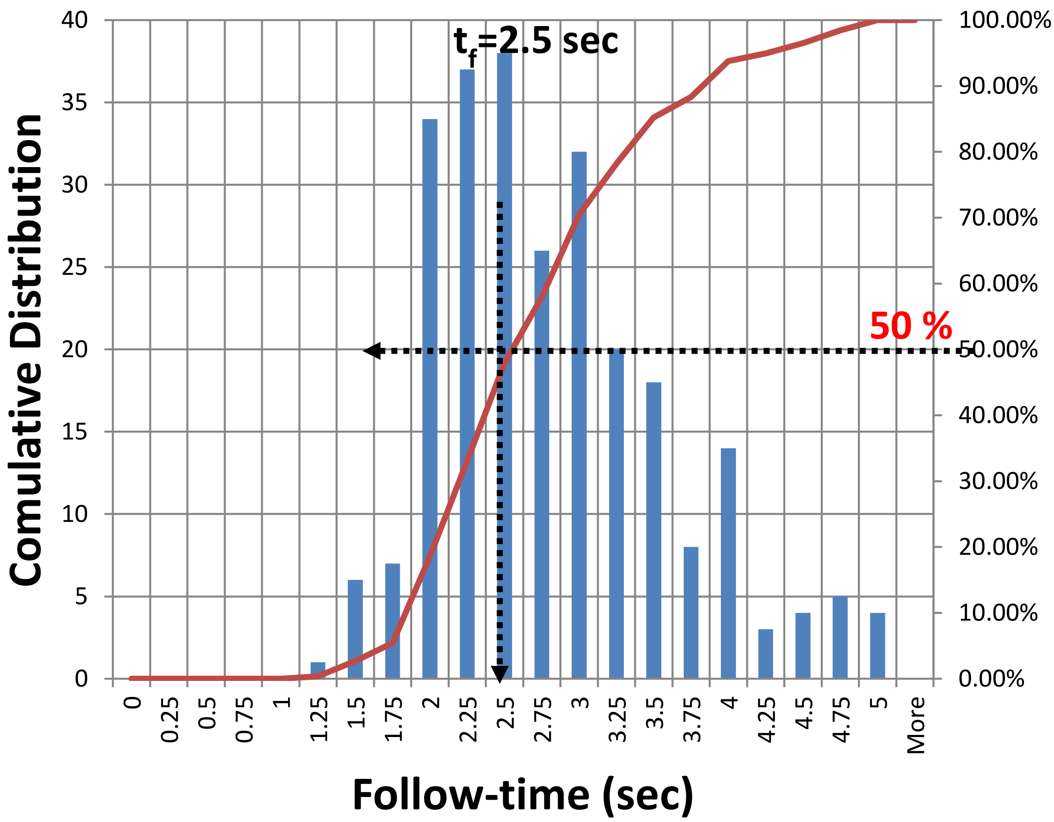



Figure 13 Cumulative distribution of follow-up time West Approach for site 1

For the West approach, the follow up time for this approach is be 2.5 seconds as shown in Figure 13. Table 6 summarize the Follow-time tf values for site 1 for each approach.

Table 6 Summary for Follow-time tf for site 1

| Summary for the Follow-time tf for site 1 | |
|---|---|
| Approach | **Follow-time tf (sec)** |
| North | **2.75** |
| South | **2.62** |
| East | **2.80** |
| West | **2.50** |

## 4.3 Minimum headway of circulating roadway τ for (site 1)

For the case for determining the Minimum headway of circulating roadway only the gaps below 5 sec were collected, because if the gap exceeded 5 sec, the two vehicles are not considered following each other.

The methodology for calculating the Minimum headway of circulating roadway τ, is as the following steps:

1) Draw a cumulative distribution of the headway of circulating roadway.
2) Take the 50 percentile of this cumulative distribution of headway of circulating roadway and this value is defined as the minimum headway τ.

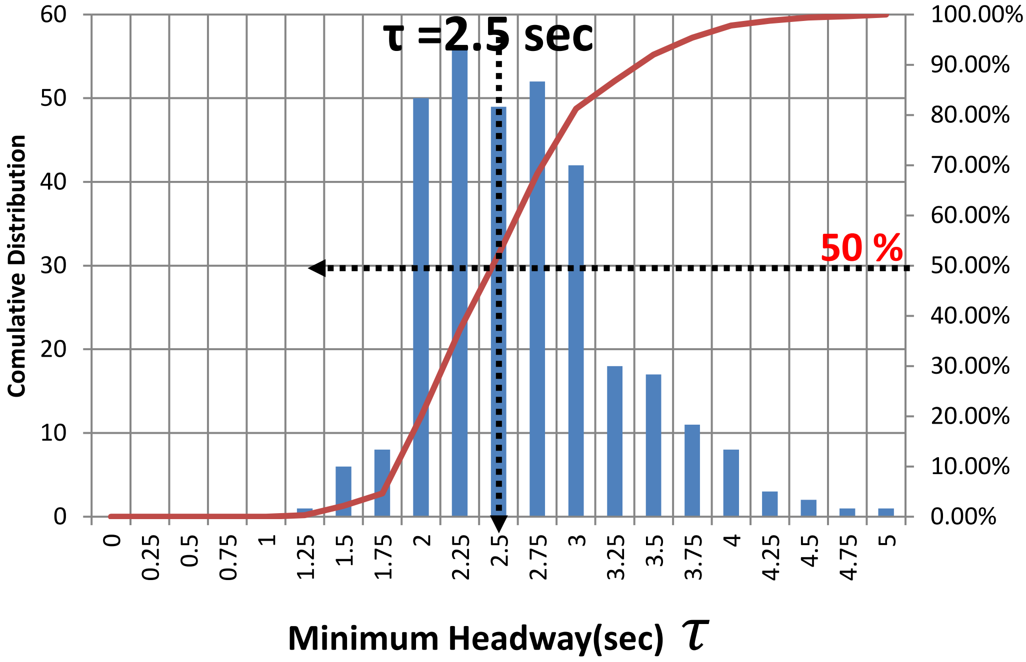



Figure 14 Cumulative distribution of minimum headway τ North Approach for site 1

Figure 14 shows the cumulative distribution of headway of circulating roadway for the North approach for site number 1, to get the value of the Minimum headway of circulating roadway of this curve is defined to be the as the minimum headway for the North approach which is equal to 2.5 seconds.

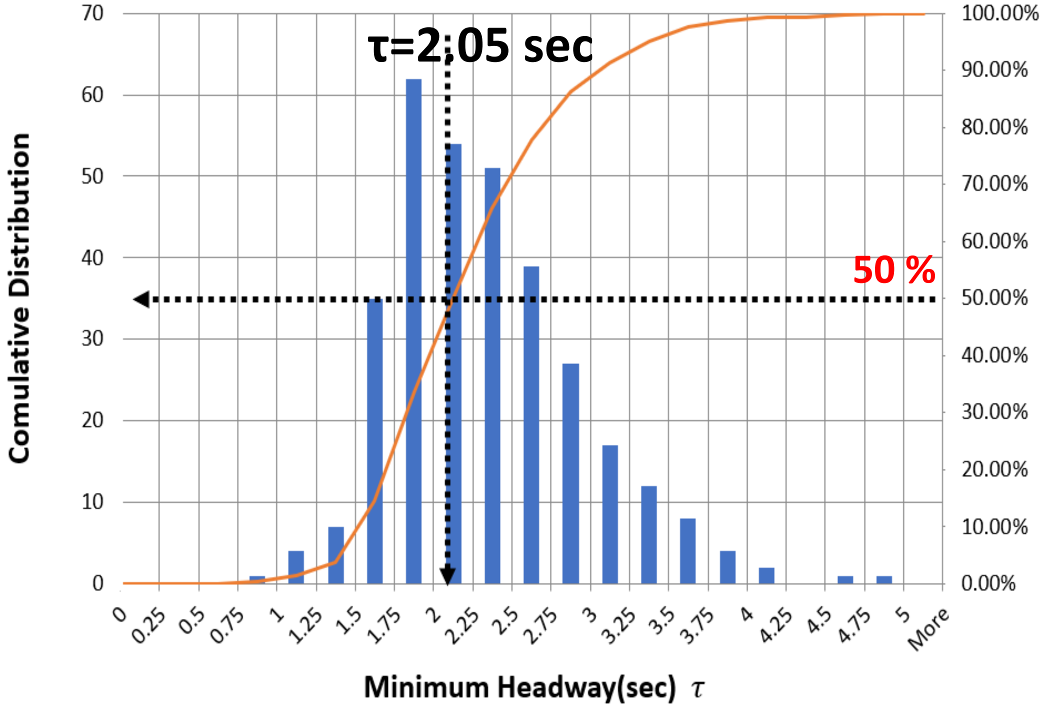



Figure 15 Cumulative distribution of minimum headway τ South Approach for site

Figure 15 demonstrates the cumulative distribution of headway of circulating roadway for the South approach for site number 1, the methodology of calculating minimum headway is the same as $t_f$, which is considered 50 percentile of the cumulative distribution of headway of circulating roadway as the minimum headway which is equal to 2.05 seconds.

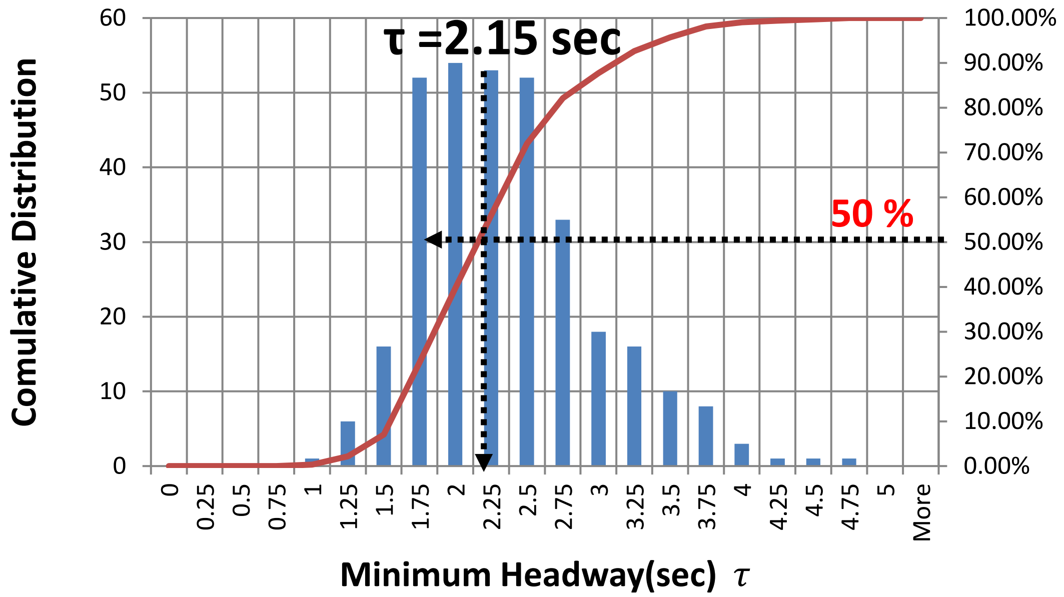



Figure 16 Cumulative distribution of minimum headway τ East Approach for site 1

As shown in Figure 16, the 50 percentile of this graph is defined to be the of minimum headway τ East Approach which is equal to 2.15 seconds.

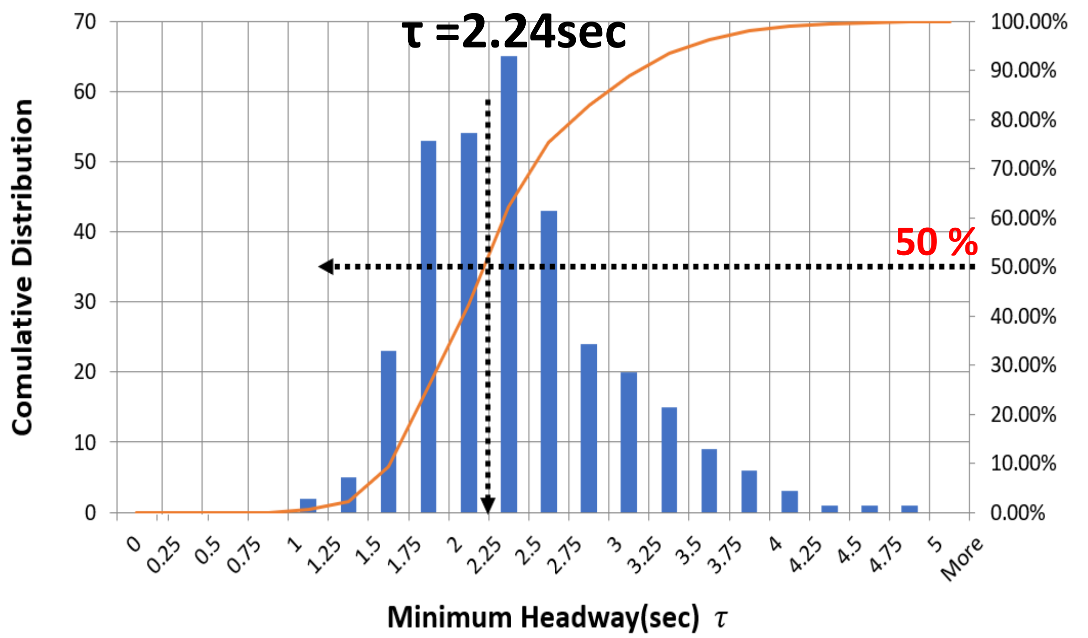



Figure 17 Cumulative distribution of minimum headway τ West Approach for site 1

2.24 seconds as shown in Figure 17. Table 7 summarize the Minimum headway of circulating roadway for each approach.

Table 7 Summary for the minimum headway τ for site 1

| Summary for the minimum headway τ for site 1 | |
|---|---|
| Approach | Minimum headway τ (sec) |
| North | 2.50 |
| South | 2.05 |
| East | 2.15 |
| West | 2.24 |

4.4 The critical gap *tc* for (site 2)

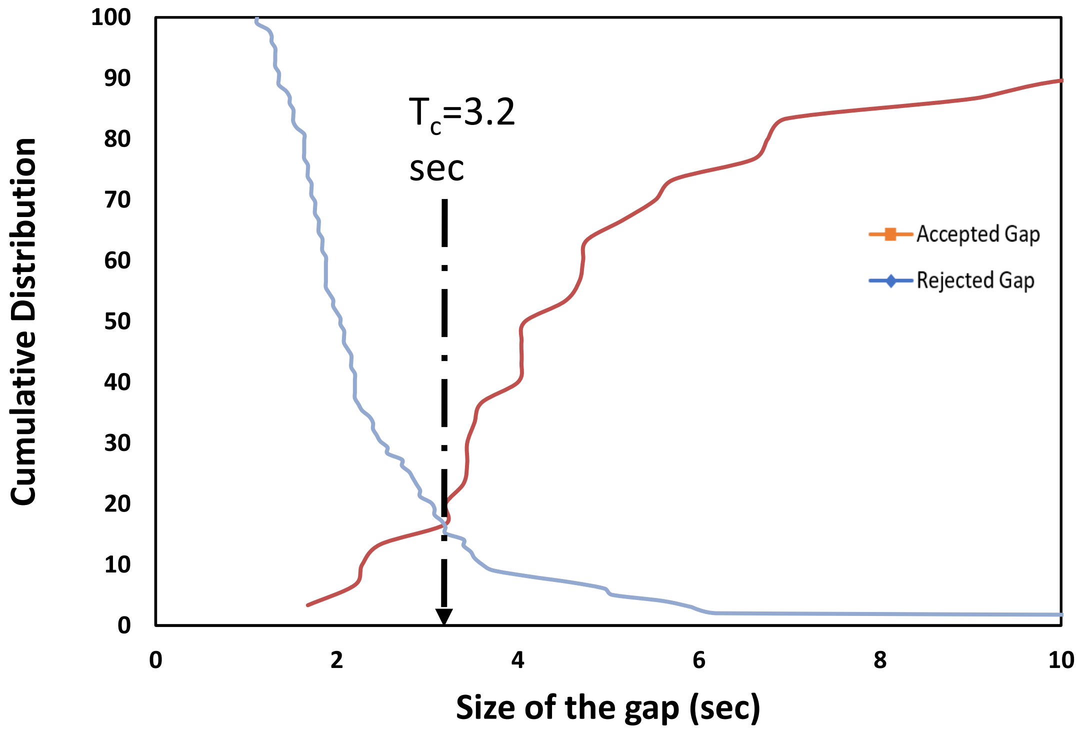


Figure 18 Site 2 North approach critical gap

Figure 18 illustrates the cumulative distribution of critical rejected and accepted gaps versus the size of the gap for the North approach for site number 2, Raff Method is used to estimate the value of $t_c$, the intersection point of the cumulative distribution of the accepted gaps and the rejected gaps is defined to be the critical gap for this approach which is equal to 3.2 seconds.

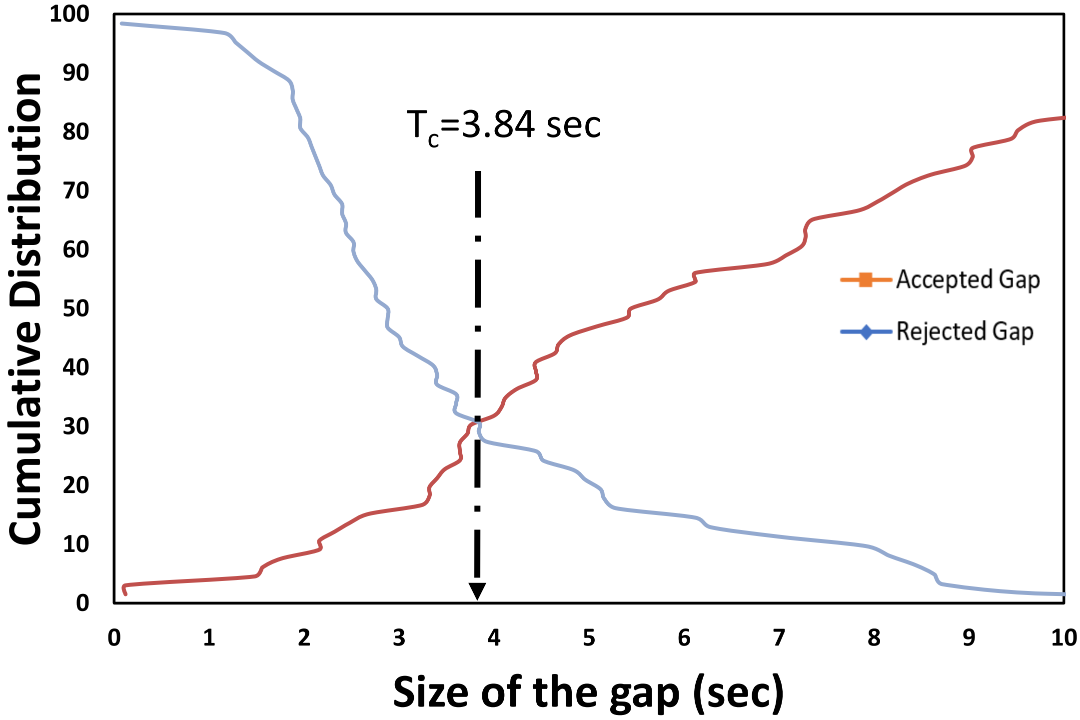



Figure 19 Site 2 South approach critical gap

Figure 19 demonstrates the cumulative distribution of critical rejected and accepted gaps versus the size of the gap for the North approach for site number 2, Raff Method is used to estimate the value of $t_c$, the intersection point of the cumulative distribution of the accepted gaps and the rejected gaps is defined to be the critical gap for this approach which is equal to 3.84 seconds.

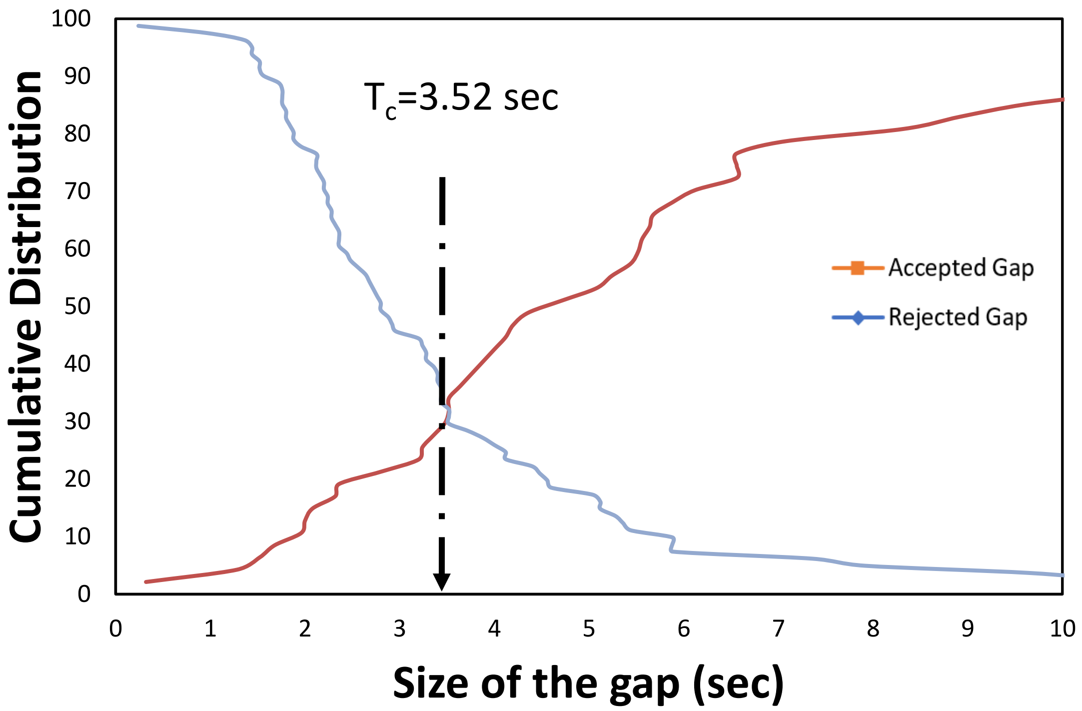


Figure 20 Site 2 East approach critical gap

As shown in Figure 20, the intersection point of the cumulative distribution of the accepted gaps and the rejected gaps is defined to be the critical gap for this approach which is equal to 3.52 seconds.

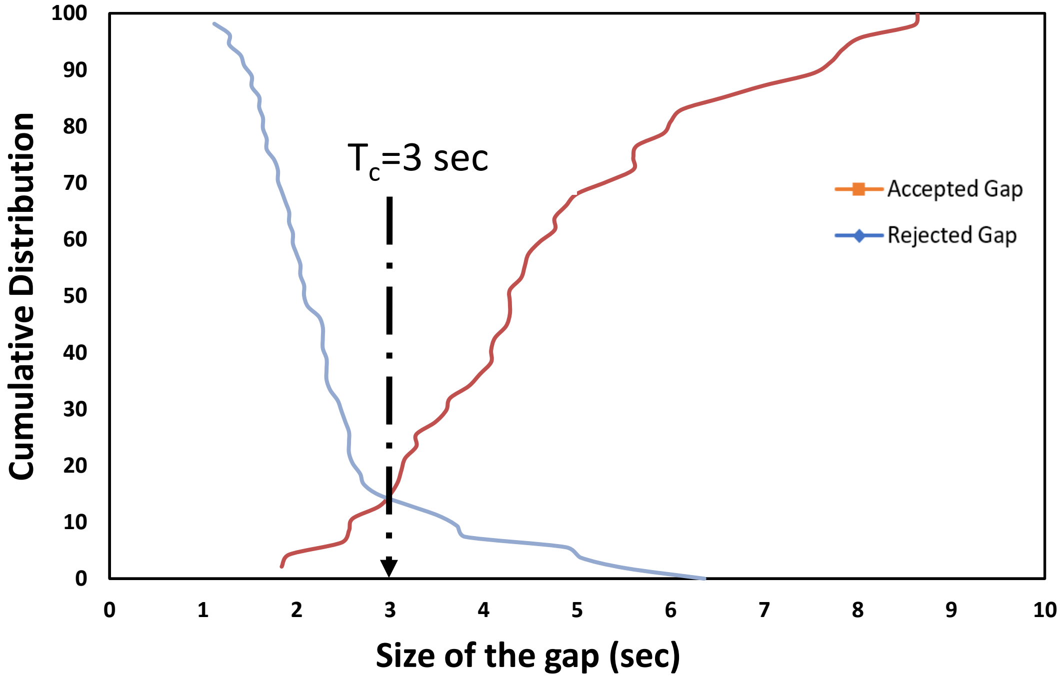


Figure 21 Site 2 West approach critical gap

For the West approach, the critical gap is observed to be 3.00 seconds as shown in Figure 21. Table 8 summarize the critical gap values for site 2 for each approach.

Table 8 Summary for the Critical gap $t_c$ for site 2

| Summary for the Critical gap $t_c$ for site 2 | |
|---|---|
| Approach | Critical gap $t_c$ (sec) |
| North | 3.20 |
| South | 3.84 |
| East | 3.52 |
| West | 3.00 |

4.5 The Follow-up time tf for (site 2)

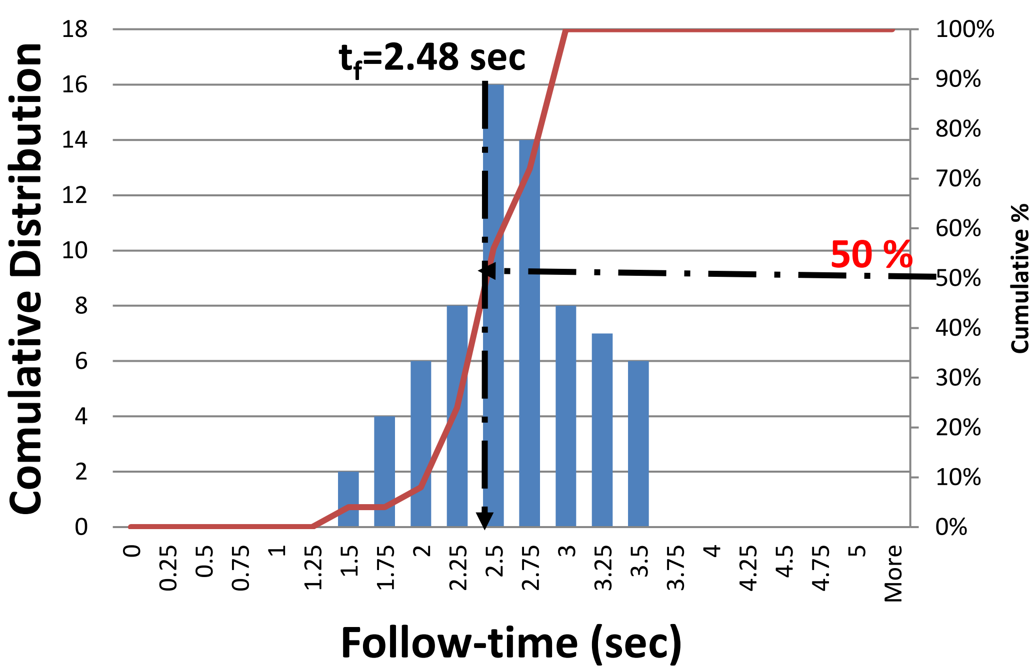



Figure 22 Cumulative distribution of follow-up time North Approach for site 2

Figure 22 shows the cumulative distribution of follow-up time for the North approach for site number 2, to get the value of the follow up time the 50 percentile of this curve is defined to be the follow up time for the North approach which is equal to 2.48 seconds.

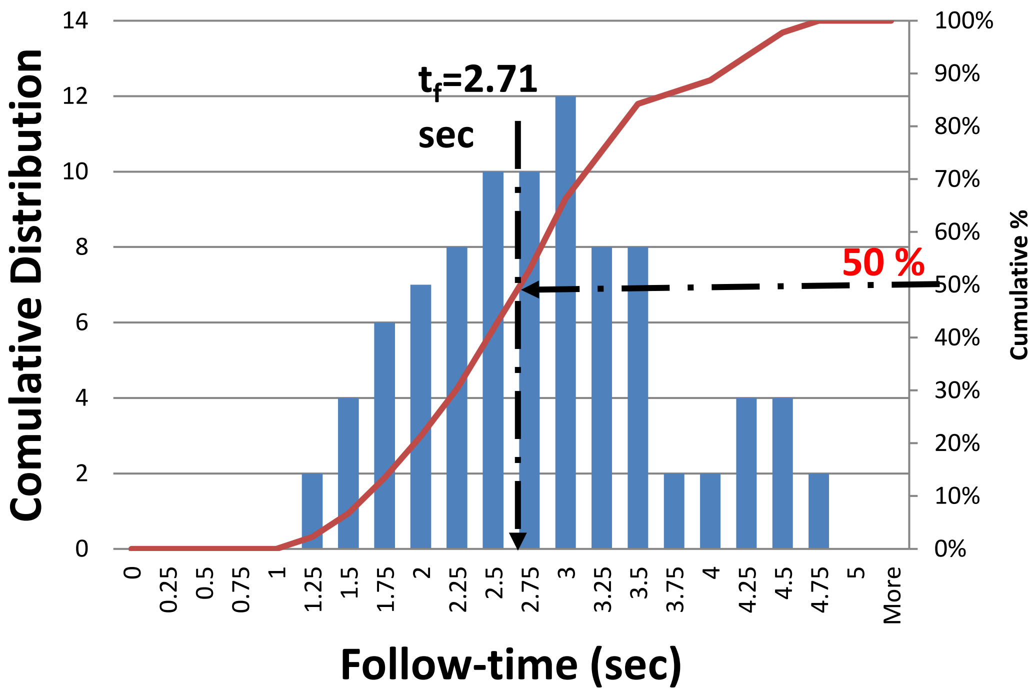



Figure 23 Cumulative distribution of follow-up time South Approach for site 2

Figure 23 demonstrates the cumulative distribution of follow-up time for the South approach for site number 2, to get the value of the follow up time the 50 percentile of this curve is defined to be the follow up time for the South approach which is equal to 2.71 seconds. Moreover, the gaps above 5 seconds was not taken into consideration because it is considered that these two vehicles are not following vehicle.

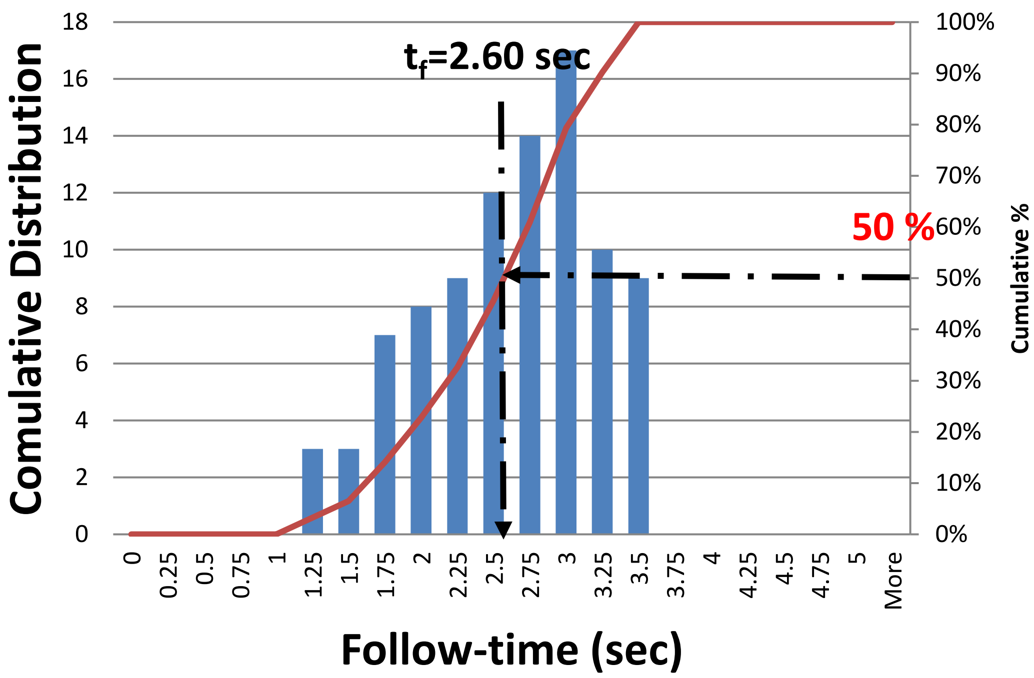



Figure 24 Cumulative distribution of follow-up time East Approach for site 2

As shown in Figure 24 the 50 percentile of this curve is defined to be the follow up time for the East approach which is equal to 2.60 seconds.

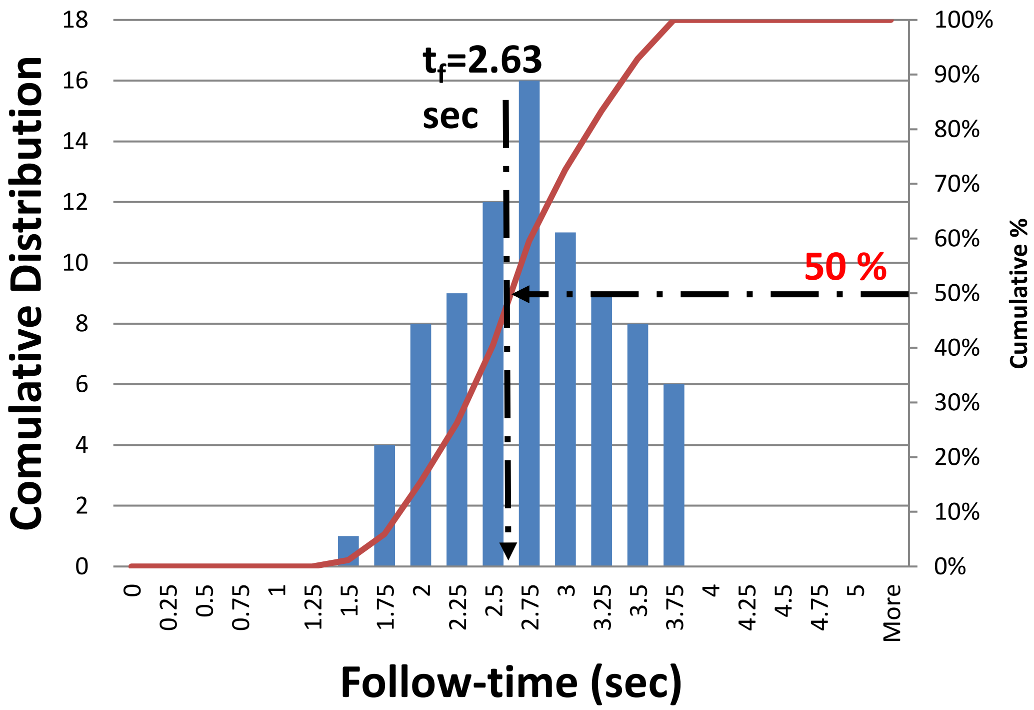



Figure 25 Cumulative distribution of follow-up time West Approach for site 2

For the West approach, the follow up time for this approach is be 2.63 seconds as shown in Figure 25 Table 9 summarize the Follow-time tf values for site 2 for each approach.

Table 9 Summary for the Follow-time tf for site 2

| Summary for the Follow-time tf for site 2 | |
|---|---|
| Approach | Follow-time tf (sec) |
| North | 2.48 |
| South | 2.71 |
| East | 2.60 |
| West | 2.63 |

4.6 Minimum headway of circulating roadway τ for (site 2)

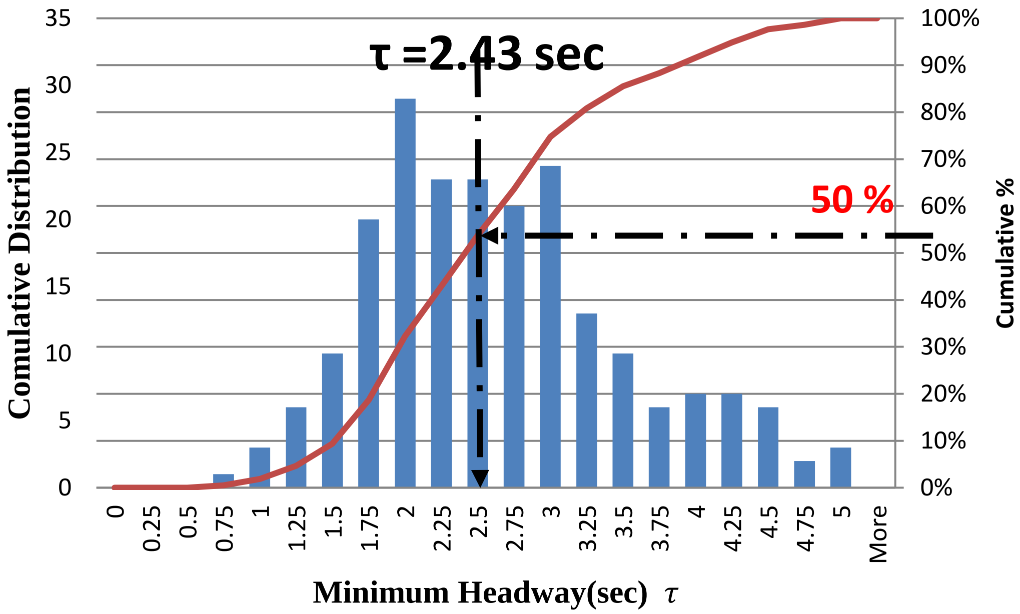



Figure 26 Cumulative distribution of minimum headway τ North Approach for site 2

Figure 26 shows the cumulative distribution of headway of circulating roadway for the North approach for site number 2, to get the value of the Minimum headway of circulating roadway of this curve is defined to be the as the minimum headway for the North approach which is equal to 2.48 seconds.

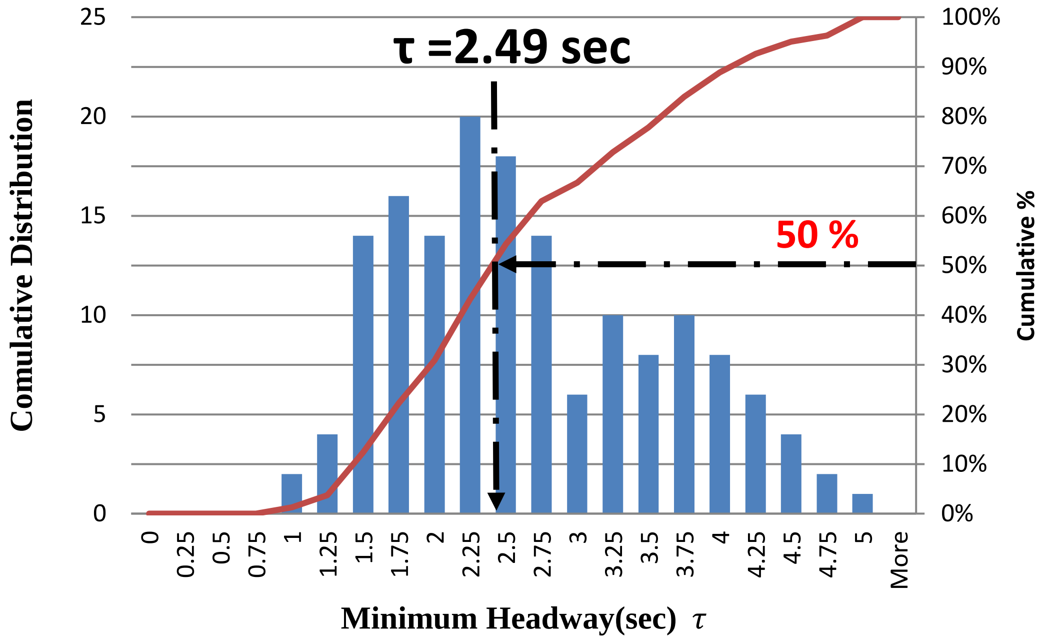



Figure 28 Cumulative distribution of minimum headway τ South Approach for site 2

Figure 27 demonstrates the cumulative distribution of headway of circulating roadway for the South approach for site number 2, the methodology of calculating minimum headway is the same as $t_f$, which is considered 50 percentile of the cumulative distribution of headway of circulating roadway as the minimum headway which is equal to 2.49 seconds.

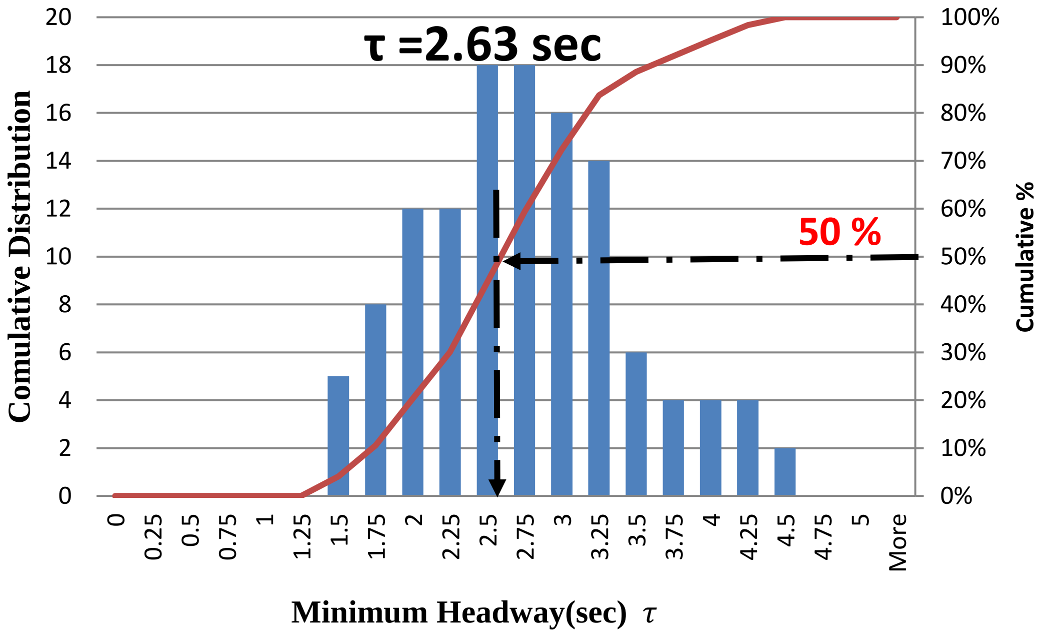



Figure 27 Cumulative distribution of minimum headway τ East Approach for site 2

As shown in Figure 28, the 50 percentile of this graph is defined to be the of minimum headway τ East Approach which is equal to 2.63 seconds.

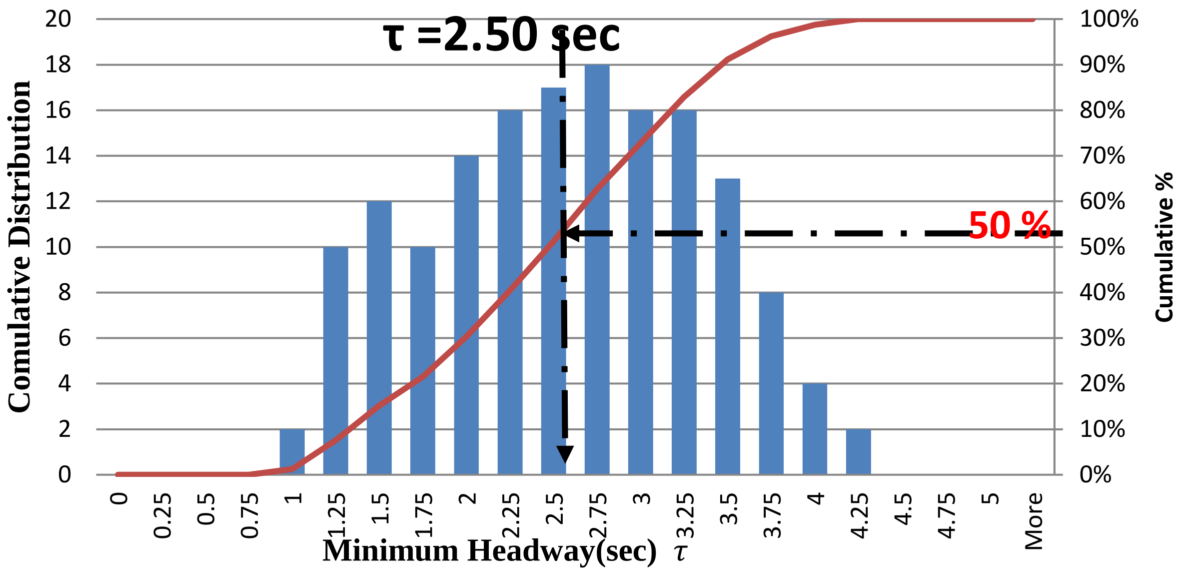


Figure 29 Cumulative distribution of minimum headway τ West Approach for site 2

For the West approach, the minimum headway of circulating roadway is found to be 2.50 seconds as shown in Figure 29 Table 7 summarize the Minimum headway of circulating roadway for each approach.

Table 10 Summary for the minimum headway τ for site 2

| Summary for the minimum headway τ for site 2 | |
|---|---|
| Approach | Minimum headway τ (sec) |
| North | 2.43 |
| South | 2.49 |
| East | 2.63 |
| West | 2.50 |

# CHAPTER 5: MODEL AND ANALYSIS

Based on Raff's method, the critical gap for both sites was determined, by evaluating the intersection point between the cumulative distribution of rejected gaps and accepted gaps. The overall critical gaps for Site 1 were 2.65, 2.32, 2.63 and 2.85 seconds in North (N), South (S), East (E) and West (W) approaches respectively. Similarly, the analysis for the critical gap was conducted for Site 2 and the critical gaps were 3.20, 3.84, 3.52 and 3.0 seconds in North (N), South (S), East (E) and West (W) approaches respectively. It was noted that the critical gaps for site 1 in all approaches were less than this of site 2, which can be attributed to the roundabout geometry as site 2 has larger diameter and radius of 41 m and 25 m respectively, compared to site 1 which has diameter and radius of 24 m and 10 m respectively as reported in Table 4. Furthermore, it was observed from analysis of the video footage that speed of the vehicles entering the roundabout in site 1 was significantly lower than this of site 2 affecting the critical gap values reported in this study.

In the case of the Follow-up time tf, only the gap below 5 sec was considered. Gaps over 5 sec are indicating that these two vehicles are not following vehicle. To calculate the follow up time, the 50th percentile of the cumulative distribution of follow up time of each approach is defined as the tf of this approach. The follow-up headway for site 1 were 2.75, 2.62, 2.80, 2.50 seconds in North (N), South(S), East (E) and West (W) approaches, respectively. On the other hand, the follow-up headway for site 2 were 2.48,   1, 2.60 and 2.63 s in North (N), South(S), East (E) and West (W) approaches, respectively. For site 1 the follow up headway were slightly different from site 1. This can be related to derivers' behavior approaching the roundabout at lower speeds in Site 1 than Site 2.

In the case of the Minimum headway of circulating roadway τ, also only the gap under 5 sec was collected, because when the gap is over 5 sec, it can't be considered as following vehicles. The methodology of calculating minimum headway is the same as tf, which is considered 50th percentile of the cumulative distribution of headway of circulating roadway as the minimum headway. The circulating headway gaps for site 1 were 2.50, 2.05, 2.15 and 2.24 seconds in North (N), South (S), East (E) and West (W) approaches, respectively. The circulating headway gaps for site 2 were 2.43, 2.49, 2.63 and 2.50 seconds in North (N), South (S), East (E) and West (W) approaches, respectively. The circulating headway for site 2 was very similar to site 1.

The parameters used to for the estimation of the capacity are summarized in Table 11. It was calculated based on equations 2.1-2.3. For site 2 it can be noted that the lowest capacity attained were in the south approach as it is characterized by the highest critical gap and circulating headway. However, it can be noted that the capacity of all approaches decreases where the circulating flow increases. Fig.28 illustrates the critical condition for estimating the capacity of single lane roundabouts according to HCM. Similarly, it was calculated for site 1 and site 2. It can be noted that both site 1 and site 2 are way off from HCM in estimating the capacity at higher circulating flow rate. However, for lower circulating flow rate the HCM procedures is adequate for estimating the capacity. As shown in Fig 28, the capacity of site 1 and site 2 are higher than the estimated HCM capacity. In addition, the difference between the actual capacity and HCM capacity increases as the volume of circulating vehicle increase. In Qatar the average values for tf , τ and tc are 2.64 sec, 2.38 sec and 3.0 sec, respectively. Equation 5.1 is generated to estimate the capacity of single lane roundabout in Qatar.

Table 11 Gap analysis summary table for both sites

| Site | Approach | North | South | East | West | Average |
|---|---|---|---|---|---|---|
| Site 1 | $t_f$ (sec) | 2.75 | 2.62 | 2.8 | 2.5 | 2.67 |
| | $\tau$ (sec) | 2.5 | 2.05 | 2.15 | 2.24 | 2.24 |
| | $t_c$ (sec) | 2.65 | 2.32 | 2.63 | 2.85 | 2.61 |
| | **C (vph)** | **1348** | **1333** | **1355** | **1348** | **1346** |
| Site 2 | $t_f$ (sec) | 2.48 | 2.71 | 2.6 | 2.63 | 2.61 |
| | $\tau$ (sec) | 2.43 | 2.49 | 2.63 | 2.5 | 2.51 |
| | $t_c$ (sec) | 3.2 | 3.84 | 3.52 | 3 | 3.39 |
| | **C (vph)** | **1354** | **1342** | **1348** | **1353** | **1349** |

Table 12 Average value for tf, τ and tc for both sites combined

| | |
|---|---|
| $\boldsymbol{t_f}$ | 2.640 sec |
| $\boldsymbol{\tau}$ | 2.380 sec |
| $\boldsymbol{t_c}$ | 3.000 sec |

$$C_{pce} = \frac{3600}{t_f}\left(1 - \tau\frac{V_c}{3600}\right)\exp\left(-\frac{V_c}{3600}\left(t_c - \frac{t_f}{2} - \tau\right)\right)$$

Substituting the values for $t_f$, τ and $t_c$.

$$C_{pce} = \frac{3600}{2.64}\left(1 - 2.38\frac{V_c}{3600}\right)\exp\left(-\frac{V_c}{3600}\left(3 - \frac{2.64}{2} - 2.38\right)\right)$$

$$C_{pce} = 1363\left(1 - 2.38\frac{V_c}{3600}\right)exp\left(0.7\frac{V_c}{3600}\right) \tag{5.1}$$

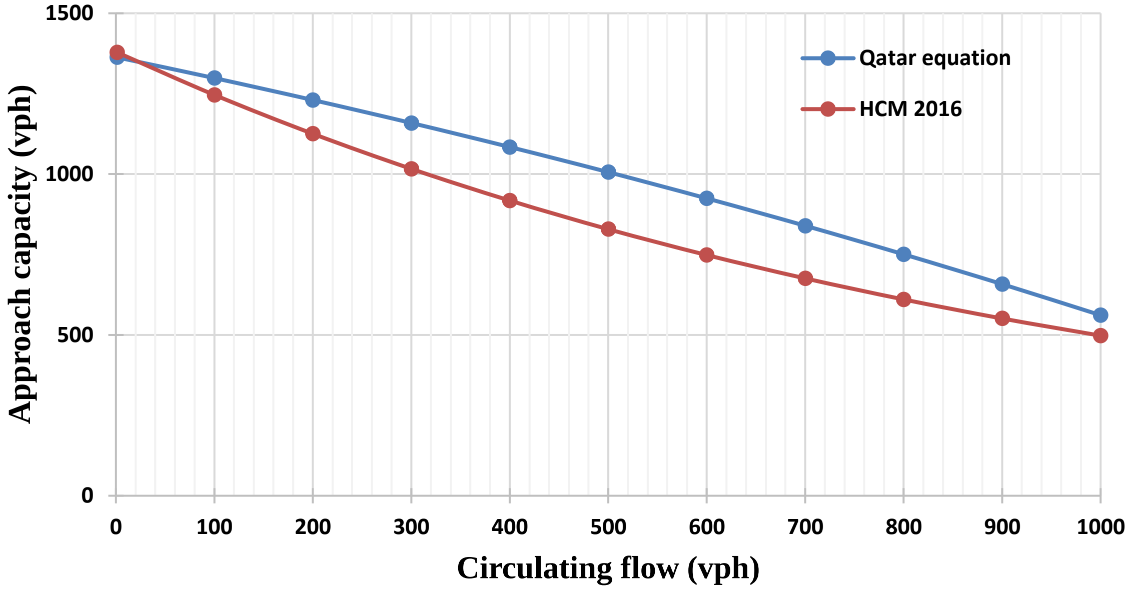



Figure 30 Circulating flow vs. Approach capacity

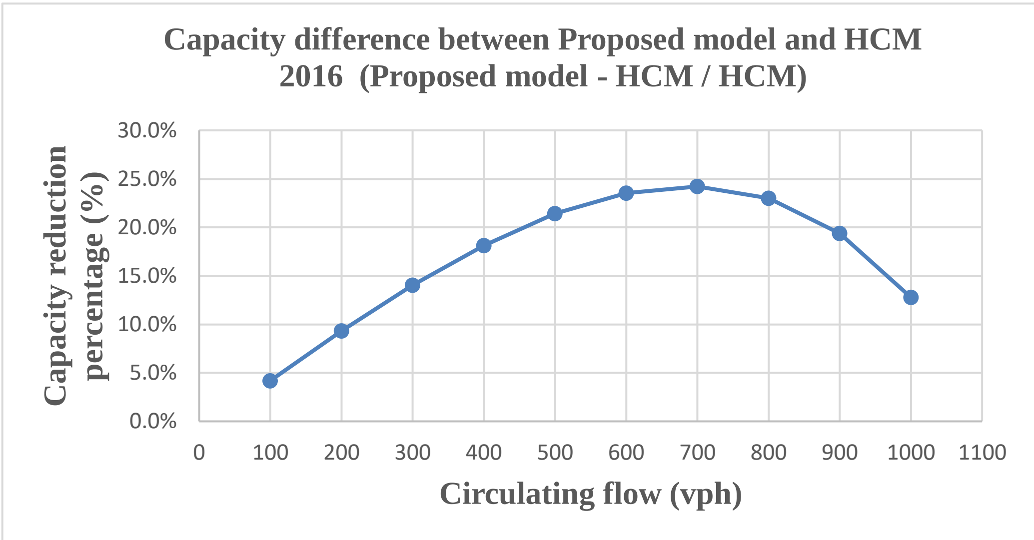



Figure 31 Capacity difference between Proposed model and HCM 2016 (Proposed model - HCM / HCM)

Figure 31 shows the capacity difference between proposed model and HCM 2016 (Proposed model - HCM / HCM), the maximum different is when the circulating flow is between 600-700 vph and this difference is about 24%. For lower circulating flow between 100-200 vph and from 200-300 vph the percentage difference is below 15%. Therefore, Equation 5.1 was proposed based on empirical data collected from real sites in Qatar for a single lane roundabout. On the other hand, HCM underestimates the capacity for the roundabout.

## 4.6 IMPACT OF THE ROUNDABOUT GEOMETRY ON DRIVERS' BEHAVIOR

The existing traffic signs (view obstruction objects) such as signs surrounding the roundabout should be built at a safe distance where approaching vehicles can clearly see cars circulating the roundabouts. This distance is often described as sight distance. In the two cases investigated in this study for site 2 three approaches North, East and West were having surrounding buildings around the roundabout that might affect the behavior of the drivers who are approaching the roundabout. It was noted in the North approach that there were enough sight distance where approaching vehicles can observe vehicles coming from the East approach and vehicles circulating the roundabout. However, for the East and West approaches, it was observed that the drivers tend to be more uncertain to enter the roundabout even if there are no vehicles circulating the roundabout. This might be directly related to the smaller sight distance compared to all the other approaches. Similar findings were reported by (Flannery, 2001), (Xu & Tian, 2008) (Stanimirović, Bogdanović, Davidović, Zavadskas, & Stević, 2019). For site 1 roundabout, geometry clearly has affected the critical gap parameters as vehicles approaching the roundabout were slower than those of site 2.

# CHAPTER 6: CONCLUSION & RECOMMENDATIONS

## 6.1 CONCLUSION:

Capacity estimation of two single-lane roundabouts located in Qatar was investigated in the present study. In addition, the impact of the geometry of the roundabouts was evaluated. A comparison between capacity estimation procedure of the HCM 2016 and the capacity at the two locations was performed. The main findings of this study are:

- The HCM is adequate in estimating the approach capacity at low circulating flow around 200 vph.
- The capacity of sub-urban roundabouts is high at low circulating flow.
- It was observed that the critical gap is affected by vehicle type entering the roundabout.
- The critical gap is higher in sub-urban area than urban areas in Qatar, this is might be related to drivers' behavior.
- The diameter of the roundabout clearly affects the critical gap parameters, thus affecting the capacity estimation.

Equation 5.1 was proposed based on empirical data collected from real sites in Qatar for a single lane roundabout. On the other hand, HCM underestimates the capacity for the roundabout.

## 6.2 RECOMMENDATION:

Further studies can be carried out to build a database for roundabouts with similar characteristics to establish a capacity information data in Qatar for traffic studies. In addition, the effect of heavy vehicles should be considered and analyzed for more reliable traffic studies in Qatar and GCC countries. Furthermore, due to data limitations, more work could be done by collecting more data from more roundabouts and this data can be extracted and increase the accuracy of the equation to estimate the capacity. Also, the impact of heavy vehicles and vehicles types impact on capacity could be evaluated if the more data were collected.

REFERENCES


Alhajyaseen, W. K., Asano, M., & Nakamura, H. (2012). Estimation of left-turning vehicle maneuvers for the assessment of pedestrian safety at intersections. *IATSS research, 36*(1), 66-74.

Brown, M. (1995). *The design of roundabouts*.

Cassidy, M. J., Madanat, S., Wang, M. H., & Yang, F. (1995). Unsignalized intersection capacity and level of service: revisiting critical gap. *Transportation research record*(1484), 16-23.

Cheng, W., Zhu, X., & Song, X. (2016). Research on Capacity Model for Large Signalized Roundabouts. *Procedia engineering, 137*(Supplement C), 352-361.

Dahl, J., & Lee, C. (2012). Empirical estimation of capacity for roundabouts using adjusted gap-acceptance parameters for trucks. *Transportation research record, 2312*(1), 34-45.

Flannery, A. (2001). Geometric design and safety aspects of roundabouts. *Transportation Research Record, 1751*(1), 76-81.

Goto, A., & Nakamura, H. (2017). a Study on Estimation Procedure of Critical Gaps at Roundabouts (Japanese Title: ラウンドアバウトにおけるクリティカルギャップ推定手法に関する考察). *Journal of Japan Society of Civil Engineers, Ser. D3 (Infrastructure Planning and Management), 73*.

Guo, R., Liu, L., & Wang, W. (2019). Review of roundabout capacity based on gap acceptance. *Journal of Advanced Transportation, 2019*.

HCM. (2010). Transportation Research Board of the National Academies, Washington, DC, 2010. *Google Scholar*.

HCM. (2016). A guide for multimodal mobility analysis. *Transportation Research*

*Board, Washington, DC*.

Johnson, M. T., & Lin, T.-L. (2018). Impact of Geometric Factors on the Capacity of Single-Lane Roundabouts. *Transportation Research Record, 2672*(34), 10-19.

Kang, N., & Nakamura, H. (2014). An estimation method of roundabout entry capacity considering pedestrian impact. *Procedia-social and behavioral sciences, 138*, 460-469.

Kang, N., & Nakamura, H. (2016). An analysis of heavy vehicle impact on roundabout entry capacity in Japan. *Transportation research procedia, 15*, 308-318.

Lee, C. (2014). *Passenger car equivalents for heavy vehicles at roundabouts: estimation and application to capacity prediction*. Retrieved from

Muley, D., & Al-Mandhari, H. (2014). Performance evaluation of Al Jame'Roundabout using SIDRA. *World Academy of Science, Engineering and Technology, International Journal of Civil, Environmental, Structural, Construction and Architectural Engineering, 8*(12), 1296-1301.

Raff, M., & Hart, J. (1950). A volume warrant for urban stop signs. The Eno Foundation for Highway Traffic Control. *Saugatuck, Connecticut*.

Robinson, B. W., Rodegerdts, L., Scarborough, W., Kittelson, W., Troutbeck, R., Brilon, W., . . . Mason, J. (2000). *Roundabouts: An informational guide*. Retrieved from

Stanimirović, D., Bogdanović, V., Davidović, S., Zavadskas, E. K., & Stević, Ž. (2019). The influence of the participation of non-resident drivers on roundabout capacity. *Sustainability, 11*(14), 3896.

Tanyel, S., Çalişkanelli, S. P., Aydin, M. M., & Utku, S. B. (2013). An investigation of heavy vehicle effect on traffic circles. *Teknik Dergi, 24*(120).

Wang, W., & Yang, X. (2012). Research on capacity of roundabouts in Beijing.

*Procedia-Social and Behavioral Sciences, 43*, 157-168.

Wu, N. (2012). Equilibrium of probabilities for estimating distribution function of critical gaps at unsignalized intersections. *Transportation research record, 2286*(1), 49-55.

Wu, N. (2015). Traffic Quality Assessment at Signalized Intersections—Procedures in the New German Highway Capacity Manual (HBS 2015). In *CICTP 2015* (pp. 2474-2485).

Xu, F., & Tian, Z. Z. (2008). Driver behavior and gap-acceptance characteristics at roundabouts in California. *Transportation Research Record, 2071*(1), 117-124.