QATAR UNIVERSITY

COLLEGE OF ENGINEERING

INVESTIGATION OF GAP ACCEPTANCE AT ROUNDABOUTS IN QATAR

BY

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ABSTRACT

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Modern roundabouts are a popular method to control traffic at intersections. In this type of roundabouts, priority is given to the circulating flow, and the approaching vehicles have to find a gap to merge with the flow under a yield condition. These types of maneuvers are impacted by many factors including the human behavior, the vehicle type, and the number of approaching lanes. In this work, one of the major factors that affect the capacity of roundabouts is investigated; that is the critical gap value. This work aims to evaluate the value of the critical gap at some of the most popular types of roundabouts in Qatar. The critical gap value was identified at a number of roundabouts with different configurations in Doha. The outcome of this work can benefit the engineering society and public agencies in Qatar and the region to plan and design similar facilities.

ACKNOWLEDGEMENTS

The author would like to thank his supervisor Dr. Khaled Shaaban for providing the means without which this work wouldn’t have been possible.

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INTRODUCTION

Roundabouts are circular intersections that consist of three or more legs and a central island. A roundabout is characterized with yield-on-entry approaches, and it can have bypass right-turn lanes. Vehicles entering the circulation lanes rotate around the central island in one direction (counterclockwise in Qatar). Circulating vehicles have priority where the vehicles at any approach entry have to wait for a gap in the circulating flow.

Roundabouts are popular in a lot of countries around the world, and they are gaining popularity in others lately. This is owed to the fact that roundabouts are efficient at lower volumes when compared to signalized intersections. In addition, they are also safer than other types of intersections at which the approaches intersect at about 90 degrees because the conflict angles at the roundabouts are acute which is less severe meaning that the conflicts are merging and diverging conflicts only (Kusuma and Koutsopoulos, 2011). Roundabouts are less complicated in operation than cross intersections because vehicles navigate in only one direction inside the roundabout. Also, roundabouts have fewer conflict points than simple one-lane cross intersections. If designed properly, roundabouts can reduce delays and handle high volumes well when compared to signalized intersections (Sisiopiku and Oh, 2001). This is due to the fact that vehicles are given the right-of-way in turns at the different approaches of signalized intersections while vehicles enter the roundabout when there are available gaps in the circulating flow; which in turn reduces the delays when the driver population is familiar with the operation of roundabouts.

The operation of roundabouts sometimes can be challenging to motorists especially for those who are not familiar with them. The legs of roundabouts are yield controlled, thus, acceptance of gaps depends on a number of factors, mainly the human behavior and taking decisions at the roundabout entry. This introduces the concept of gap acceptance, which is one of the factors that affect the capacity of roundabouts. In short, the human behavior, in taking decisions whether to accept a gap or reject it, ultimately has an effect on the capacity of approaches at roundabouts.

The capacity model of roundabouts in the highway capacity manual (HCM) requires a number of parameters. One of these parameters is the critical gap (i.e. critical headway) (National Research and Transportation Research, 2010). This parameter is defined, in short, as the gap size (in seconds) such that the vehicles are more likely to accept a gap with a bigger size than it or reject a gap with a smaller size than it.

Gap Acceptance Terminology

The gap is defined, in this work, as the difference in time between the tail of one circulating vehicle (gap vehicle) and the head of the following vehicle in the circulating lanes of a roundabout. The decision vehicle is the vehicle that waits at one of the approaches of the roundabout for a gap in the circulating flow. The decision vehicle more likely rejects gaps that are smaller than a certain value and accepts gaps that are larger than it; this value is called the critical gap value. Figure 1 describes the terms related to gap acceptance. The gap closes at the red line on the left side and re-opens at the green line on the right side.

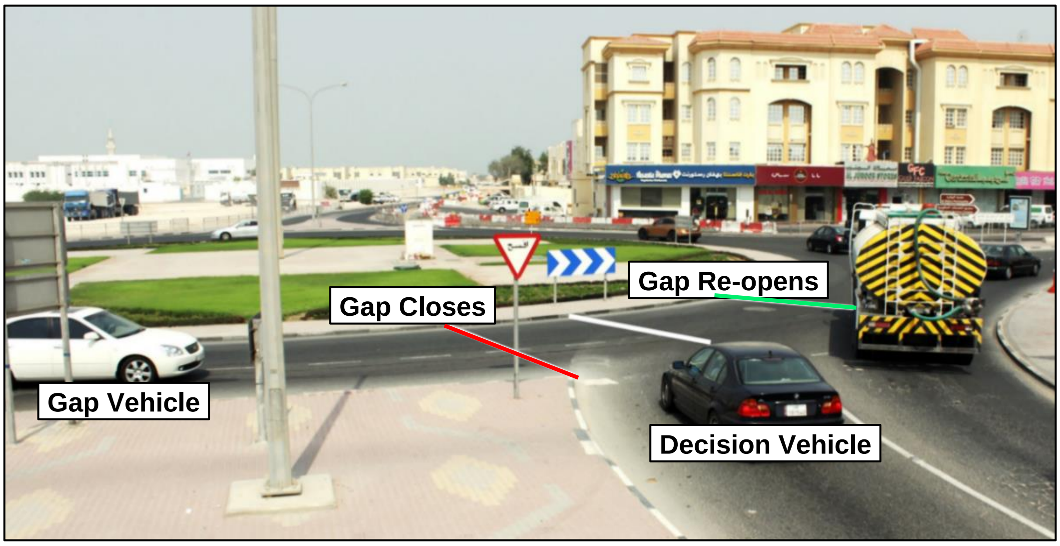


FIGURE 1: GAP ACCEPTANCE TERMINOLOGY

Aim and Objectives

As previously explained, the value of the critical gap is an important factor in designing or improving roundabouts. It is also an important parameter in modeling and simulation of roundabouts. In the Gulf region and before the economic boom that started in the past decades, roundabouts used to be the main type of intersections used all over the Gulf countries. The population increased abruptly in search for a living, and this lead to a traffic problem. Roundabouts in the Gulf, and specifically Qatar, were designed following international standards that only fit the driver population of the countries at which they were developed. The value of the critical gap is dependent on the driver's behavior which differs from one region to another. There is a noticeable lack of studies related to roundabouts in the Middle East and the Gulf region.

The aim of this study is to identify the critical gap value of roundabouts in the City of Doha and to present some sort of comparison between the obtained values and other values produced from other research efforts. The objectives of this study are: to find the critical gap values of at the different types of roundabouts in the City of Doha, taking in consideration factors like the types of vehicular interactions and vehicle types. The outcomes of this study are thought to reflect, more accurately, the behavior of the drivers in Qatar, and enable future research that is dependent on critical gap values produced in this work.

LITERATURE REVIEW

The earliest definition of one of the reliable and easy-to-use methods of estimating the critical gap was set by Morton Raff & Jack Hart in the late 1940's (Raff, 1950). After their definition, the critical gap value (t_c) is graphically determined by finding the point of intercept between the following two functions;

$$1 - F(t_r) \text{ and } F(t_a)$$

where t_r and t_a are the rejected and accepted gap times respectively. The value of t_c is affected by the existing traffic volumes at which this value has been evaluated (Miller, 1971, Brilon et al., 1999).

The original definition was set for the critical lag value, yet, the same concept applies to determine the critical gap value. It is the time (or distance) after which the probability of a decision vehicle to accept a gap in the circulating flow is higher than rejecting it. The method of analysis used was Raff's method. It was introduced in the late 1940's and was used in many studies since then. The critical gap is the intersection between the cumulative distribution curves of accepted and rejected gaps plotted on the same graph.

Raff (1950) has defined the critical lag L as "the size lag which has the property that the number of accepted lags shorter than L is the same as the number of rejected lags longer than L" (Figure 2). The same concept was adopted and applied to the critical gap in several studies. In the Highway Capacity Manual (HCM) (2010), the critical gap is defined as the median gap time accepted by drivers in a given situation. The HCM assumes that the critical gap is constant, although in reality, it varies according to factors such as study location, time of day (peak or slack times), maneuver being made, queue waiting time, driver waiting time at the yield line (number of gaps rejected or time spent waiting for an acceptable gap), vehicle classification, point of departure in the circulating lanes, driver demographics, and presence of a passenger next to the driver (Raff, 1950, Tupper et al., 2011).

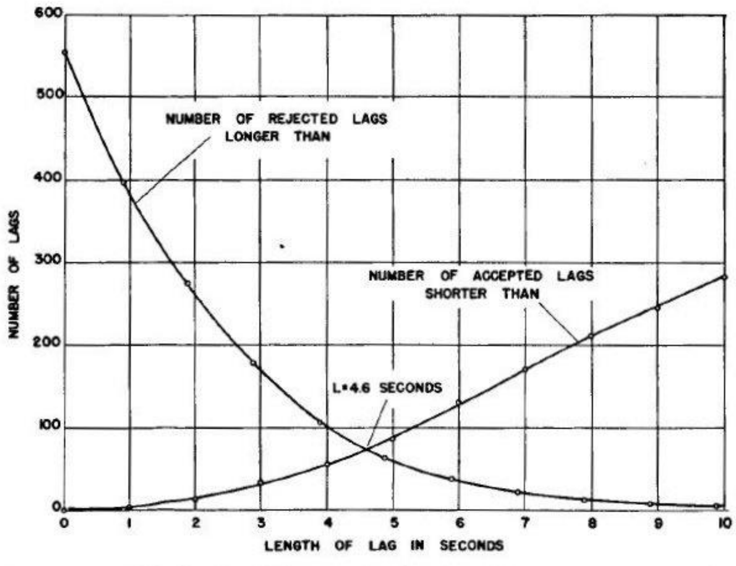


FIGURE 2: CRITICAL LAG BASED ON RAFF'S METHOD (SOURCE: (RAFF, 1950))

Some studies aimed to compare the different critical gap estimation techniques. Others have aimed to measure the effect of the different factors that the value of the critical gap depends on. And, others have used the critical gap value to generate capacity models for roundabouts and compare them with international standards. Troutbeck (2014) has reviewed the ability of the maximum likelihood technique and the probability equilibrium method to estimate the mean and standard deviation of the critical gap with a model that simulated 100 drivers and was repeated 100 times for each flow condition. Dahl and Lee (2012) aimed to do an empirical estimation of the capacity of roundabouts under the effect of some external factor on the value of the critical gap. They used adjusted gap-acceptance parameters for trucks in the derivation of the critical gap value used in the capacity model. Guo (2010) used various methods, such as 'Ashworth's Method', 'Raff's Method' and the 'Maximum Likelihood Method'

(MLM) to calculate the critical gap at roundabouts during rush hour. He also provided the justification to recommending some of the methods over the others in practical applications. Polus et al. (2003) studied the effect of the waiting time for the decision vehicle to accept a gap on the value of the critical gap and the effect that newly calculated value of the critical gap on the capacity of a modern roundabout. Mainly, it was found that the newly calculated capacity was more than that was calculated based on the HCM; it does not take into consideration the driver's behavior in reaction to extended waiting times in the calculation of the critical gap of a roundabout. Çalişkanelli et al. (2009) compared different capacity models for traffic circles. They compared the two most common methods used in the capacity analysis; the method of critical gap acceptance and the method of regression analysis. For comparison, Ashworth and Field method was looked into, and the applicability of the capacity models in Turkey was discussed. Both methods were found to provide satisfactory results. However, the existing methods should be modified for improved results taking the conditions in consideration. A study was performed on a set of data collected at a roundabout on the University of Massachusetts campus, Amherst by Fitzpatrick et al. (2013). Gap acceptance study was performed on a data sample of more than 1,500 vehicle interactions at the location. It was found that the temporal and the spatial gaps are related by the average circulating flow speed and the temporal gaps are more significant than the spatial gaps when calculating the critical gap.

Table 1 contains a summary of the reviewed work showing the output critical gap values, a short description of the conditions of the experiment, the analysis method(s), the roundabout size/type and the location of each study.

TABLE 1: SUMMARY OF LITERATURE

Year	Author(s)	Work Title	Analysis Method	Critical Gap (s)	Conditions	Intersection Type	City, Country
2007	Aimee Flannery; Tapan Datta	Operational Performance Measures of American Roundabouts	Maximum Likelihood Method	3.94	4 1-lane R/A's; During the morning and evening peaks; Commercial and residential areas; Flow rates of circ. flow range from 350 to 900 vph;	1-lane roundabout	Florida (3) and Maryland (1), USA
2008	Feng Xu; Zong Z. Tian	Driver Behavior and Gap-Acceptance Characteristics at Roundabouts in California	Maximum Likelihood Method	4.80	6 1-lane R/A's; Values are the average of 6 locations; No. of data points was not mentioned;	1-lane roundabout	California, USA
2010	Stephen Mensah; Sepideh Eshragh; Ardeshir Faghri	A Critical Gap Analyses of Modern Roundabouts	Raff's Method	2.55	2 1-lane R/A's; 2 hours of video data were collected; No. of data points was not mentioned; The effect of driver familiarity was measured;	1-lane roundabout	Maryland, USA
2013	Fitzpatrick, Cole D.; Abrams, Daniel S.; Tang, Yue; Knodler, Michael A., Jr.	Spatial and Temporal Analysis of Driver Gap Acceptance Behavior at Modern Roundabouts	Raff's Method	2.20	1-lane approach and 1-lane R/A; Local R/A with familiar commuters; >10 hrs of video survey; >1500 data points; 3 vehicle classes analyzed	1-lane roundabout	Amherst, Massachusetts, USA
2008	Feng Xu; Zong Z. Tian	Driver Behavior and Gap-Acceptance Characteristics at Roundabouts in California	Maximum Likelihood Method	L: 4.70 R: 4.40	3 2-lane R/A's; Values are the average of 3 locations; Number of data points was not mentioned;	2-lane roundabout	California, USA
2010	Guo, Rui-jun	Estimating Critical Gap of Roundabouts by Different Methods	Raff's Method	2.91	2-lane approach and 2-lane R/A with 1 extra right turn lane; 40 min of video survey; 100 data points; Flow rate of circulating stream is 1,842 pcu/h	2-lane roundabout	Dalian, China
			Revised Raff's Method	2.78			
			Maximum Likelihood Method	2.65			
			Ashworth Method	3.20			

Year	Author(s)	Work Title	Analysis Method	Critical Gap (s)	Conditions	Intersection Type	City, Country
2011	Andyka Kusuma; Haris N. Koutsopoulos	Critical Gap Analysis of Dual Lane Roundabouts	Maximum Likelihood Method	3.58	2-lane R/A with 6 approaches; Data collected from 7:30 to 11:30 am; 369 data points	2-lane roundabout	Brommaplan, Stockholm, Sweden
2014	Rui-jun Guo; Xiao-jing Wang; Wan-xiang Wang	Estimation of Critical Gap Based on Raff's Definition	Raff's Method	3.53	Simulated data at different flow rates; Number of data points not mentioned;	Simulation	Simulation
			Revised Raff's Method	4.00			
			Ashworth Method	3.44			
			M3 (new model)	3.97			
2008	Feng Xu; Zong Z. Tian	Driver Behavior and Gap-Acceptance Characteristics at Roundabouts in California	Maximum Likelihood Method	L: 4.70 R: 4.40	3 2-lane R/A's; Values are the average of 3 locations; Number of data points was not mentioned;	2-lane roundabout	California, USA
2011	Andyka Kusuma; Haris N. Koutsopoulos	Critical Gap Analysis of Dual Lane Roundabouts	Maximum Likelihood Method	3.58	2-lane R/A with 6 approaches; Data collected from 7:30 to 11:30 am; 369 data points	2-lane roundabout	Brommaplan, Stockholm, Sweden
2008	CHENG Jie; YANG Xinmiao; DENG Wei; HUANG Xin	Driver's Critical Gap Calibration at Urban Roundabouts: A Case Study in China	Logit Modelling	4.75	3-lane R/A w/ 2-lane approach; Data collected on two days at 8:00-8:40 a.m. & 9:00-9:40 a.m.; One work day and one vacation day;	3-lane roundabout	China

METHODOLOGY

The method used to perform this study was standardized among all of the studied locations. Video footage was provided where the setup was done in a similar way at all locations. The same software was also used to extract the data and perform the video and data analysis. The process of measuring the gaps was also the same to eliminate discrepancies in the final results and for the data among all locations to be comparable. The used analysis method was the same across all of the types of roundabouts; that is Raff's Method. The vehicle types were grouped into three groups; passenger, medium and heavy vehicles. These groups were used in a similar manner among all the studied locations. The vehicular interaction cases are not similar amongst the different types of roundabouts because the number of lanes in each type of the roundabouts dictates the complexity of the interaction cases. Since the interaction cases of each type of roundabout are different, it is meaningless to compare the cases of the two-lane roundabout to those of the three-lane roundabout. However, comparing the cases of each type of roundabout to each other would yield meaningful conclusions. Further detailed explanation of the methodology specific to each type of roundabout in this study is shown in the following sections.

After receiving the videos, a simple procedure was followed to extract the data. Fifteen hours of video data where obtained at each location where video collection starts at 6:00 and ends at 21:00 covering the three peaks of the day. Video analysis software was used to analyze the videos frame-by-frame in order to obtain the required data for further analysis. Using the frame numbers, the gap time was measured accurately to 1/30 of a second.

Measuring the critical gap value was described in previous literature thoroughly, however, the followed procedure in this work has been done with slight modifications. A gap, whether accepted or rejected, has to satisfy a number of conditions for it to be counted in as a data entry. The decision vehicle in a correct gap should come to a full stop at the yield line of the approach. Also, the circulation lane(s) that are corresponding to an approach lane that is occupied by a decision vehicle has (have) to be occupied by at least two vehicles that form a gap. A gap is formed in the circulation lanes by having two gap vehicles following each other in the same or a different lane with a big enough gap that can fit a decision vehicle. A gap is considered accepted when the decision vehicle's driver takes the decision to go into a gap in the circulating flow moving from the state of full-stop at the approach. On the contrary, a gap is considered rejected when the driver of the decision vehicle decides not to move from the approach where there is a gap in the circulation flow regardless of its size. The gap value is measured as the difference in time (seconds) between the rear end of the first gap vehicle and the front end of the following gap vehicle measured at the same reference line extending from the nose of the splitter island at the entry of the approach pointing to the center of the roundabout. This line should be perpendicular to the circulation lanes to ensure consistent measuring of gaps across the circulation lanes.

Studies that has been done on the topic of the critical gap utilized different analysis methods, depending on the data they obtained and the degree of accuracy they are aiming to achieve. Examples of these techniques are the ‘Average Accepted Gap’, ‘Raff’s Method’, and ‘Cumulative Acceptance’ which are easy to use with some variation amongst them. Other methods like ‘Equilibrium of Probabilities’ are difficult to use. Tupper et al. (2013) compared the different methods of calculating the critical gap in terms of the ease of use and the use of data. Some methods are practical and easy to use and others are difficult for everyday use. Some methods utilize the data well and others utilize the data poorly. One of the methods that are very easy to use and utilize the data very well is Raff's method. In this work, Raff's method is thought to be more efficient and provides acceptable results when all gap data is used.

There are many vehicle categories defined in standards and regulations worldwide. For example, FHWA vehicle classification has thirteen vehicle classes; it is inefficient to use all the vehicle classes, also, it is out of the scope of this study to calculate the critical gap corresponding to each one of the vehicle classes due to lack of enough data for each vehicle class. As a compromise, vehicles were classified into three categories; passenger cars, medium-sized vehicles, and heavy vehicles. Each of the used classes is a group of vehicles that are approximately similar in dimensions and performance. Passenger cars group includes sedans, four-wheel drive sport utility vehicles (SUV's) and small vans. Medium vehicles group includes single-unit two-axle trucks, recreational vehicles (RV's), minibusses and ambulances. Heavy vehicles group includes large buses, trailers of all sizes and dump trucks. Figure 3 exhibits the different vehicle classes according to FHWA. The classification was applied to the decision vehicle, since it is thought to have the biggest impact on the critical gap value.

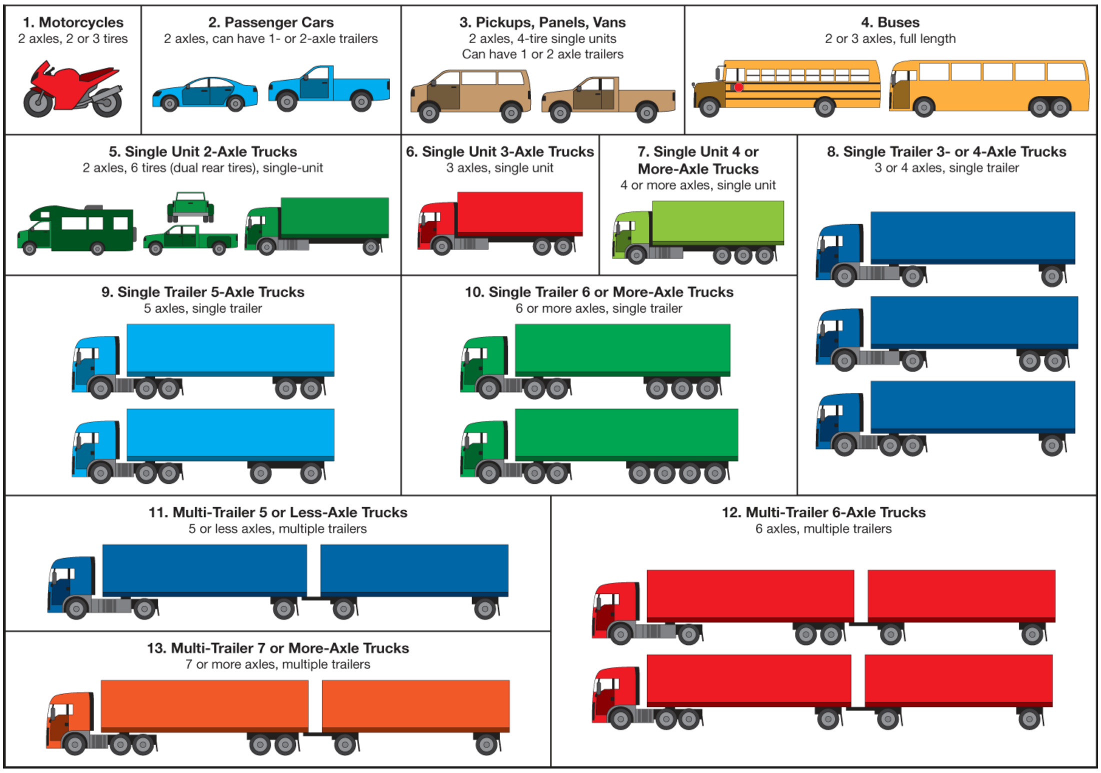


FIGURE 3: FWHA VEHICLE CLASSIFICATIONS (SOURCE: (RANDALL, 2012))

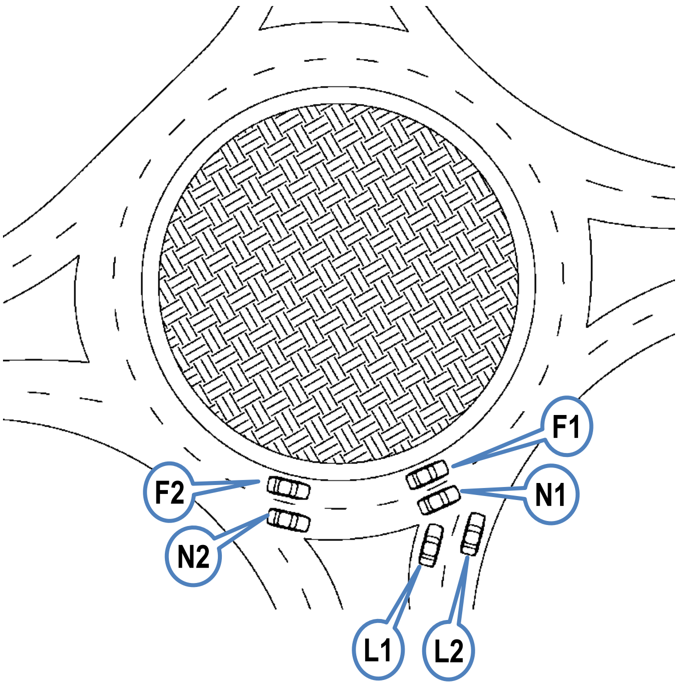
Vehicular Interaction Cases

Vehicular interactions are the interactions (action-reaction) between at least two vehicles at any given time and space. Vehicle interactions at the studied roundabouts are different. The reason to this is that each type of the studied roundabout is different in size; as the number of lanes increases, the complexity of the vehicular interactions increases. As demonstrated in the "One-lane Roundabout Location" section, the one-lane roundabout has only one interaction case, whereas, the two-lane and three-lane roundabouts have eight cases and twenty-seven cases respectively. Clearly, the number of interaction cases between vehicles increases exponentially in relation to the number of lanes in the roundabout and its entry lanes. Comparing the driver behavior across the different types of roundabouts requires a special experimental design, but the case in this study is to measure, in addition to the critical gap, any differences between interaction cases and whether the departure lanes affect the critical gap value or not.

Hence, the cases in each type of roundabout are compared to each other but not with the cases of other types of roundabouts.

Two-Lane Roundabout Cases

The effect of the interaction cases of the two-lane roundabout was being measured. There are eight interaction cases at 2-2 roundabouts (roundabouts with two-lane circulating lanes and two-lane entry); three of which are dismissed because of their incompatibility with the gap acceptance definition (cases listed in the table in Figure 4). If the decision vehicle is in the left lane of the approach, the following four cases apply. Case 1 and Case 2 take place when two gap vehicles following each other in the far circulation lane or two gap vehicles following each other in the near circulation lane respectively. The first two cases are recorded normally following the same assumptions used in the single-lane roundabout. Case 4 and Case 5 take place when one gap vehicle is in the far circulation lane and another gap vehicle is in the near circulation lane following each other or vice-versa respectively. If the decision vehicle is in the right lane of the approach, the following four cases apply. If the circulating flow is only occupying the far circulation lane (Case 6), then this interaction is ignored since the decision vehicle has the freedom to enter the roundabout without obstruction. Case 3 exists when both of the gap vehicles are following each other in the near circulation lane. Case 7 and Case 8 take place when one gap vehicle is in the far circulation lane and another gap vehicle is in the near circulation lane following each other or vice-versa respectively. In these two cases, lags will only occur unless there are other vehicles that are leading or following the ones in the circulation lanes. Lags are out of the scope of this paper. Summary of the mentioned eight cases is presented in Figure 4 and 5.



Case	Vehicle Interactions	Gap Data Use
1	Vehicle L1 with vehicles F1 & F2	Applicable
2	Vehicle L1 with vehicles N1 & N2	Applicable
3	Vehicle L2 with vehicles N1 & N2	Applicable
4	Vehicle L1 with vehicles F1 & N2	Applicable
5	Vehicle L1 with vehicles N1 & F2	Applicable
6	Vehicle L2 with vehicles F1 & F2	Not Applicable
7	Vehicle L2 with vehicles F1 & N2	Not Applicable
8	Vehicle L2 with vehicles N1 & F2	Not Applicable

FIGURE 4: SUMMARY OF INTERACTION CASES (2-LANE R/A)

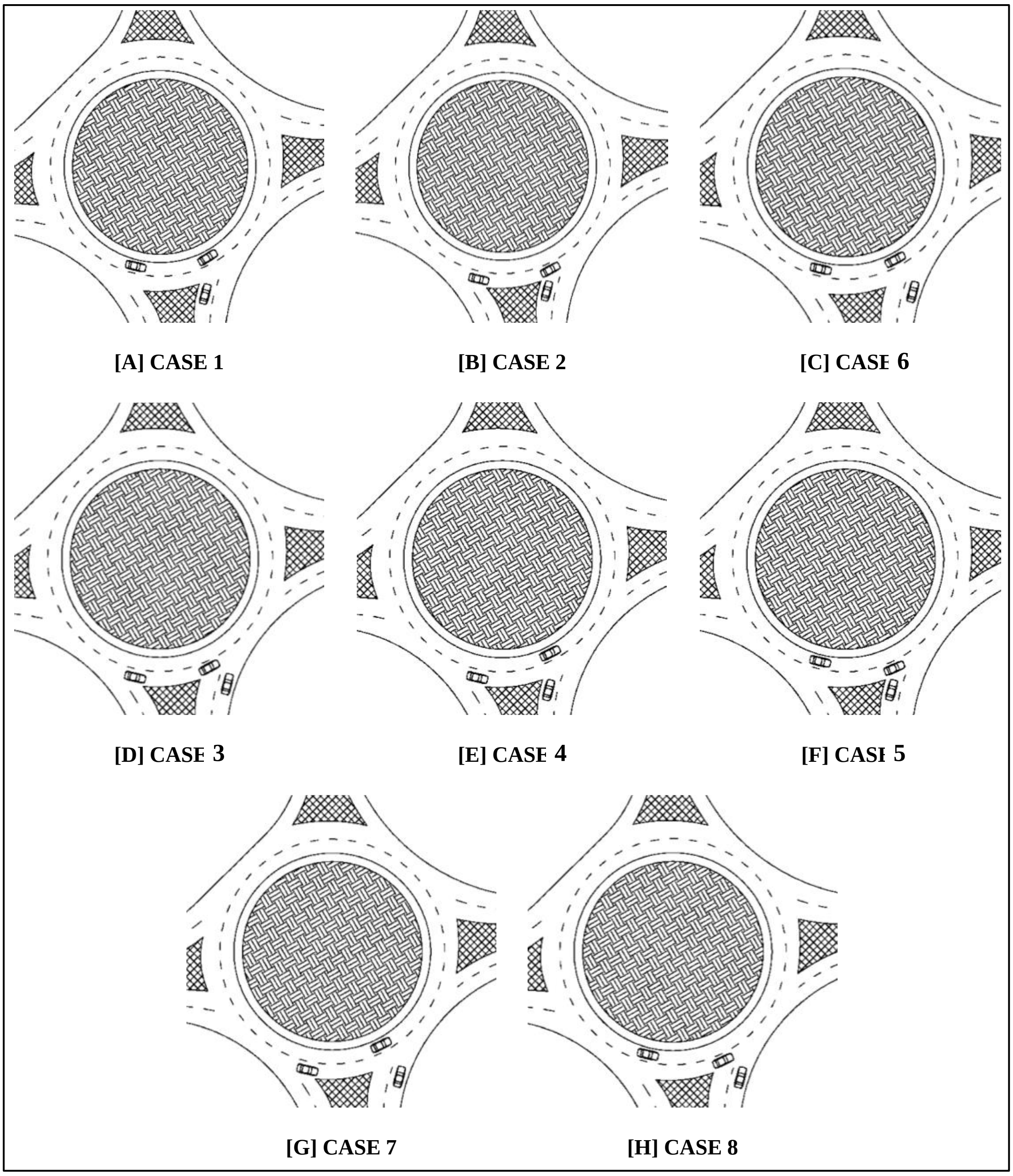


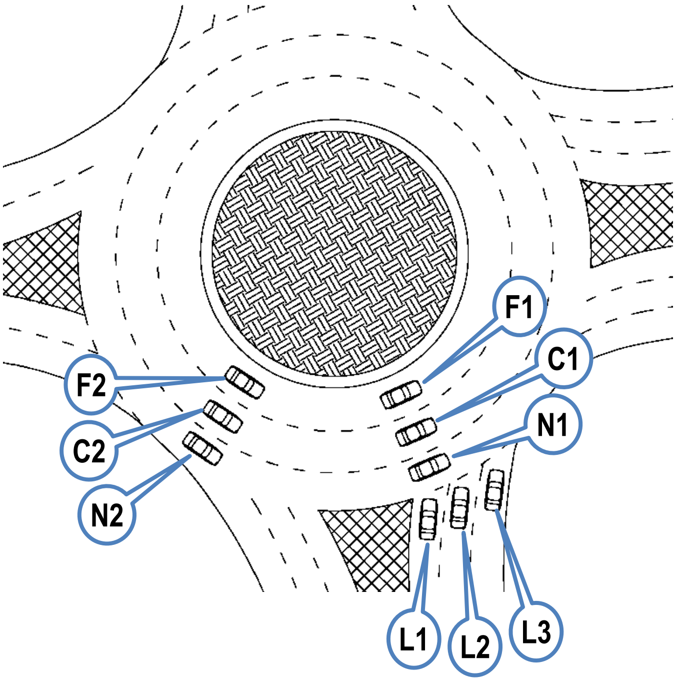
FIGURE 5: INTERACTION CASES (2-LANE R/A)

Three-Lane Roundabout Cases

The effect of the normal interaction cases was not considered due to the fact that 3-3 roundabouts (roundabouts with three-lane circulating lanes and three-lane entry) have the most complicated interaction patterns of all roundabouts. However, a new set of cases based on the gap acceptance behavior of the population of daily drivers has been demonstrated. First, comes the explanation of the regular, theoretically applicable, cases.

There are twenty-seven interaction cases at 3-3 roundabouts; thirteen of which are dismissed because of their incompatibility with the gap acceptance definition (listed in the table in Figure 6). If the decision vehicle is in the left lane of the approach, the following nine cases apply; cases 1 through 9 are all applicable since the path of the left-lane vehicle of the approach and all the possible paths of vehicles in the circulation lanes intersect. It should be noted that any two vehicles in the circulation lanes regardless of the lane they are occupying will make acceptable gap data entries. If the decision vehicle is in the center lane of the approach, the following nine cases; 10 through 18 are not all considered in the gap data. Four out of nine of the cases only qualify for the gap data since the center-lane vehicle of the approach doesn't intersect with the path of the far lane of the circulation lanes. Thus any interaction related to this lane is dismissed from the data. The same concepts also apply to the right-lane decision vehicle at the approach whose path intersects only with the near circulation lane. Therefore, only one case is applicable where the gap vehicle only occupies the nearer lane of the circulation lanes. Lags were not considered since they are out of the scope of this paper. Summary of the mentioned twenty-seven cases is presented in Figure 6.

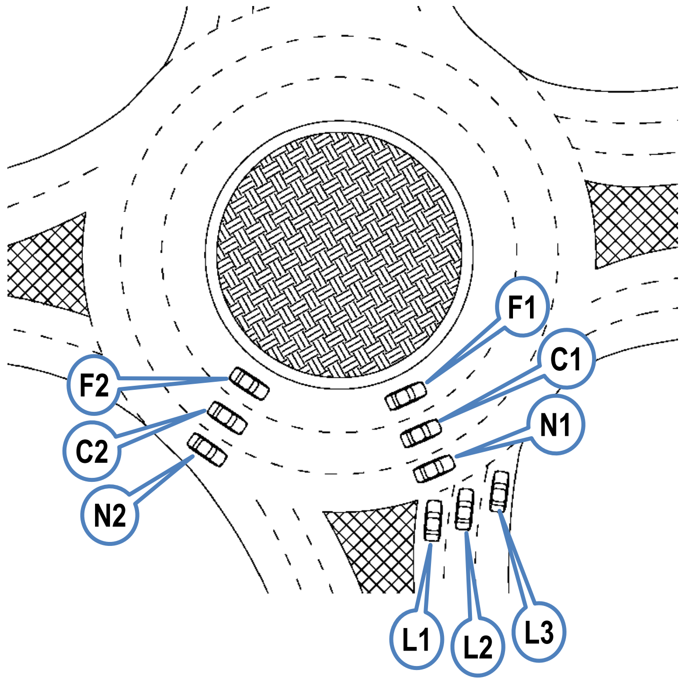
The new set of cases was based on the actual mechanics of accepting or rejecting gaps in any type of roundabouts (specifically multi-lane roundabouts) by the average daily driver. There are seven cases labeled from A to G. Case A is the one where all the decision vehicles in the approach accept a gap in the circulating flow. If the decision vehicle in the right lane of the roundabout entry doesn't accept the gap with the other two, this case is called case B. Case C is when the decision vehicle in the middle rejects a gap whereas the other two vehicles accept it. If the inner lane is empty, we are left with vehicles occupying the middle and the outer lane; this is case D. The rest of the cases only involve one decision vehicle. Case E is when the vehicle in the inner lane only accepts a gap, F is when the middle vehicle only accepts a gap while the inner lane is empty, and G is when the vehicle in the outer lane accepts the gap while the other two lanes are empty. All of the aforementioned cases were set with the assumption that the target circulation lanes are occupied with gap vehicles, otherwise, the interaction would be a lag or merely free flow (not a gap or lag). Also, there are some interactions that couldn't be put into a certain category; those are the rejected gaps that are followed by either a very large gap that enabled multiple decision vehicles to accept it or an acceptance decision where the target lanes are not occupied in order to create a gap based on the previously set definition. Illustrations of each individual case are shown in Figure 7, and a summary of all the cases is demonstrated in Figure 8.



Case	Vehicle Interactions	Gap Data Use
1	Vehicle L1 with vehicles F1 & F2	Applicable
2	Vehicle L1 with vehicles F1 & C2	Applicable
3	Vehicle L1 with vehicles F1 & N2	Applicable
4	Vehicle L1 with vehicles C1 & F2	Applicable
5	Vehicle L1 with vehicles C1 & C2	Applicable
6	Vehicle L1 with vehicles C1 & N2	Applicable
7	Vehicle L1 with vehicles N1 & F2	Applicable
8	Vehicle L1 with vehicles N1 & C2	Applicable
9	Vehicle L1 with vehicles N1 & N2	Applicable
10	Vehicle L2 with vehicles C1 & C2	Applicable
11	Vehicle L2 with vehicles C1 & N2	Applicable
12	Vehicle L2 with vehicles N1 & C2	Applicable
13	Vehicle L2 with vehicles N1 & N2	Applicable
14	Vehicle L3 with vehicles N1 & N2	Applicable

Case	Vehicle Interactions	Gap Data Use
15	Vehicle L2 with vehicles F1 & F2	Not Applicable
16	Vehicle L2 with vehicles F1 & C2	Not Applicable
17	Vehicle L2 with vehicles F1 & N2	Not Applicable
18	Vehicle L2 with vehicles C1 & F2	Not Applicable
19	Vehicle L2 with vehicles N1 & F2	Not Applicable
20	Vehicle L3 with vehicles F1 & F2	Not Applicable
21	Vehicle L3 with vehicles F1 & C2	Not Applicable
22	Vehicle L3 with vehicles F1 & N2	Not Applicable
23	Vehicle L3 with vehicles C1 & F2	Not Applicable
24	Vehicle L3 with vehicles C1 & C2	Not Applicable
25	Vehicle L3 with vehicles C1 & N2	Not Applicable
26	Vehicle L3 with vehicles N1 & F2	Not Applicable
27	Vehicle L3 with vehicles N1 & C2	Not Applicable

FIGURE 6: SUMMARY OF THE OLD INTERACTION CASES (3-LANE R/A)



Case	Proceeding Decision Vehicles*	Comment
A	L1, L2 and L3	–
B	L1 and L2	–
C	L1 and L3	–
D	L2 and L3	When L1 lane is empty
E	L1 only	–
F	L2 only	When L1 lane is empty
G	L3 only	When L1 and L2 lanes are empty

* Corresponding target lanes have to be occupied in order to record the gap

FIGURE 7: SUMMARY OF THE NEW INTERACTION CASES (3-LANE R/A)

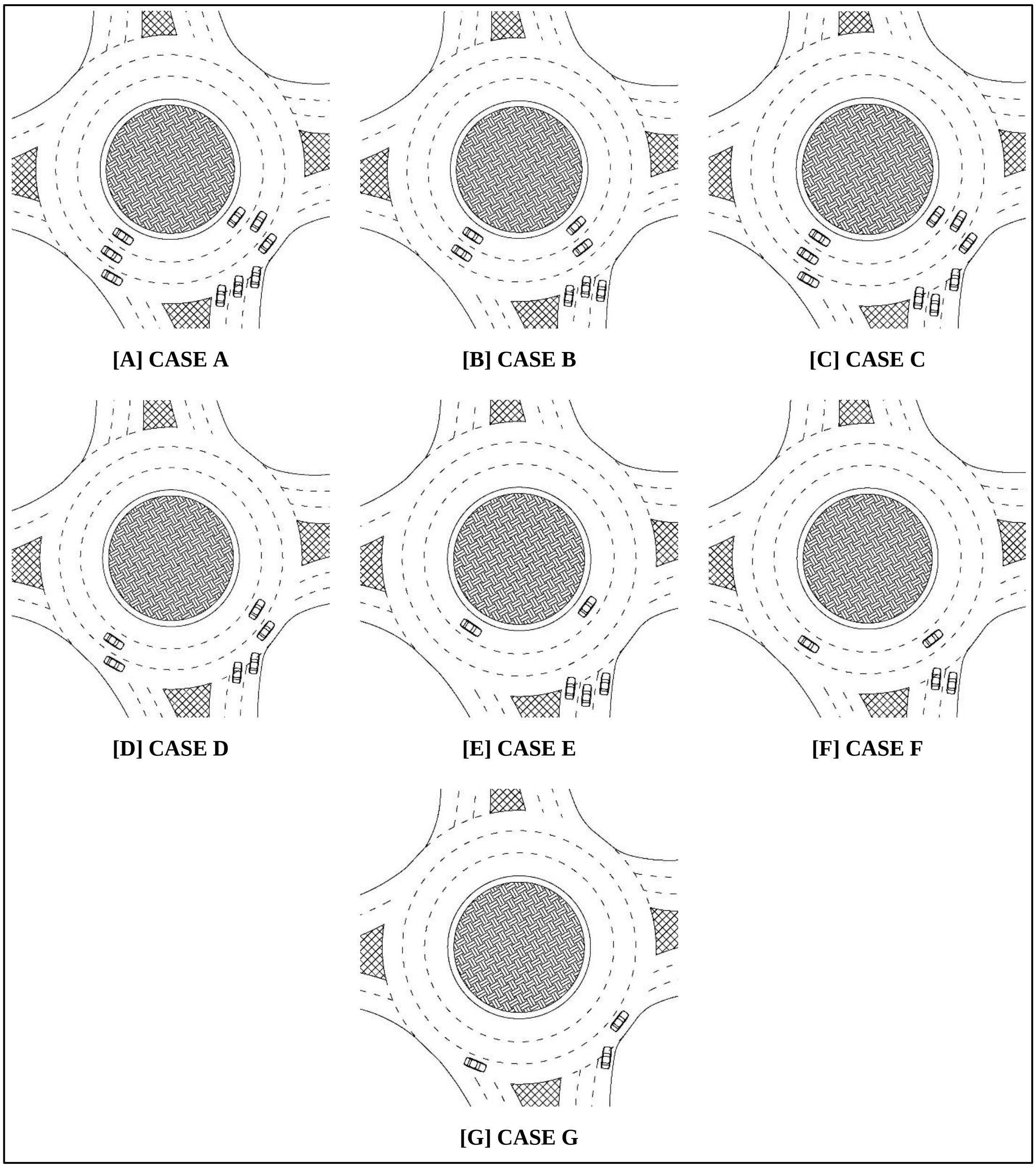


FIGURE 8: NEW INTERACTION CASES AT 3-LANE ROUNDABOUTS (VEHICLES THAT ACCEPT THE GAP ARE SHOWN CROSSING THE YIELD LINE AT THE APPROACH)

Scope of the Methodology

This study focuses on the operation of the roundabouts of different sizes. All locations are bound by the borders of the State of Qatar. The study doesn't include the effect of pedestrians or cyclists on the critical gap values at all locations. Motorbikes were not included in the data for the fact that the motorbike driver behavior is not consistent with the rest of the studied subjects. The effect of adjacent traffic control devices such as signalized intersections or interchanges was not accounted for. Not all the types of roundabouts in Qatar were looked into. The most popular cases only were investigated; circular roundabouts of size up to three lanes. The vehicular interaction cases that were investigated in this work were the regular interaction cases; all the irregular cases were eliminated. The irregular cases happen when the decision vehicle changes lanes when accepting a gap. Those cases do not resemble a proper gap acceptance maneuver, and they are considered in most cases careless or high-risk maneuvers. All locations have four legs where the studied approaches don't have slip lanes. The vehicle type of gap vehicles traveling in the circulating lanes was not studied.

DATA COLLECTION

Data, in this study, were collected at different seasons of the year. However, this rather strengthens the study; it would reflect the driver behavior during different times of the year in a more realistic manner. Nonetheless, it should be noted that holiday months were eliminated because it doesn't represent the general behavior of the driver population throughout most of the year. A standardized procedure was followed in selecting the locations and many variables were eliminated by doing so. For example, all of the studied approaches of the selected roundabouts had no bypass right-turn lanes, which means that all movements were made by going through the circulation lanes of the roundabout. Also, the data collection was made during either of the three days in the middle of the working week to eliminate any bias due to abnormal driver behavior affected by the weekend routines of the residents of the city of Doha. More than fifteen hours of video data were captured at each location covering the three peaks of the day, thus eliminating the time-of-day bias. The number of vehicular interactions is a random variable that depends mainly on the driver behavior and reaction time, hence the number of interactions is not related to the size of the roundabout whether it is two- or three-lane. The following sections are dedicated to describing the data collection of each case and will show the special assumptions related to each of them. Information about the roundabouts investigated in this study is shown in Table 2 listing their names, locations, and sizes. More detailed description of the location and the data collection of each roundabout is in the following sections.

TABLE 2: SUMMARY OF ROUNDABOUTS IN THE STUDY

R/A Name	R/A No.	R/A Location	R/A Size	Approach Size
Rawdat Al Khail R/A	RA01	Al Muntazah, Central Doha	1-lane	1 lane
Wukair Road R/A	RA02	Wakra, South Doha	2-lane	2 lanes
Haloul R/A	RA03	Wholesale Market, Southwest Doha	3-lane	3 lanes
Eid Bin Mohammad R/A	RA04	Al Gharrafa West Doha	3-lane	3 lanes

One-lane Roundabout Location

The one-lane roundabout that was selected for the study is located at Al Muntazah area in the city of Doha at the intersection between Wadi Rasheeda Street (North-South) and Hiteen Street (East-West). This roundabout has a wide circulation lane that is able to handle two vehicles circulating side-by-side, but when exiting the roundabout, there is only one lane so most of the vehicles use the wide circulation lane as one lane. The wide circulation lane is also useful for larger trucks to navigate without colliding with other vehicles or hitting fixed objects in the roundabout as they have a larger footprint than regular vehicles. This roundabout is a typical single-lane roundabout that can be found in local areas in the city of Doha, and it wouldn't fall into any special case or category when looking into the majority of single-lane roundabouts in Doha or even in other countries of the world. Cameras, as it is the case with all the other study locations, were set up on a telescopic mast that has been put up at maximum height (15 feet) to provide a clear view of the target approach and the whole movement of vehicles in the roundabout and its surrounds. The studied approach was Wadi Rasheeda Street's southbound approach. Figure 9 shows an example of a typical frame from the footage recorded at the location, where the studied approach is seen at the top right corner of the frame. The view may not seem very clear to most but some consideration had to be taken since this is a residential local area and there are numerous private establishments surrounding the roundabout.

FIGURE 9: AN ACTUAL FRAME FROM THE 1-LANE R/A LOCATION

The selected location was a one-lane roundabout with a one-lane approach (1-1 roundabout). The roundabout has an inside diameter of 10 meters and an outside diameter of 18 meters approximately. The roundabout was selected to have heavy peak volumes to ensure a large sample size that would result in accurate values in the analysis stage. There is only one wide lane in the approach and a single wide circulation lane in the roundabout, so the interactions are simple and straight forward in contrast to the cases at the two-lane and the three-lane roundabouts. There is only one interaction case where the decision vehicle (D1) interacts with the gap vehicles (G1 and G2) shown in Figure 10. Lags were not considered since they are out of the scope of this work.

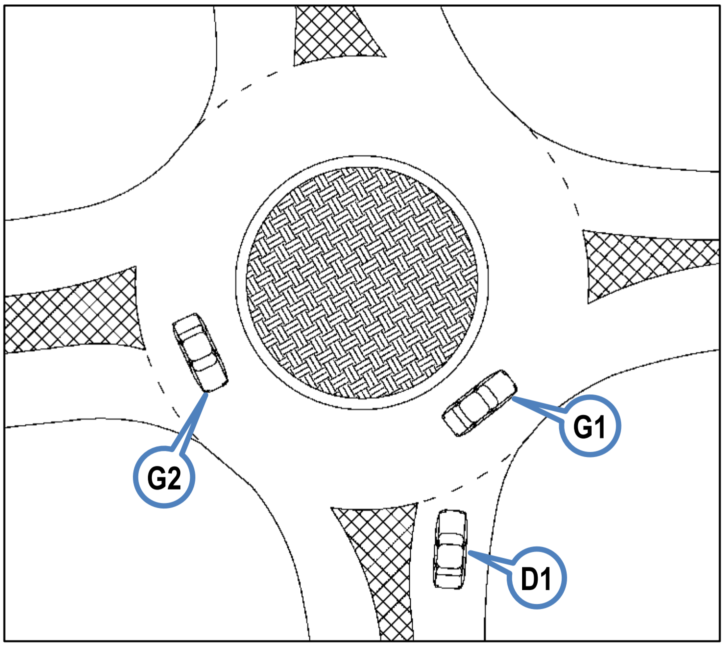


FIGURE 10: ILLUSTRATION OF THE INTERACTION CASE OF THE 1-LANE R/A

One-lane Roundabout Data Collection

Videos were taken from the one-lane roundabout RA01's south-bound approach at Wadi Rasheeda Street. More than 15 hours of footage were captured in October 2015 covering the morning, noon, and evening peaks. Data collection was performed from 6:00 to 21:00 at clear weather conditions. The number of observed interactions exceeded 1,500 interactions over the duration of the data collection at the studied approach of this roundabout. Statistics of the collected data are presented in Table 3. There is only one case of vehicular interactions, as this is a one-lane roundabout with a one-lane approach as mentioned before in the methodology section.

TABLE 3: GAP ACCEPTANCE STATISTICS OF THE 1-LANE R/A

Classification	Type	Count	Percentage
Gap Acceptance	*accepted*	461	29.4%
	rejected	1106	70.6%
	Total	*1567*	*100.00%*
Vehicle Type	*passenger car*	1443	92.1%
	medium vehicle	94	6.0%
	heavy vehicle	30	1.9%
	Total	*1567*	*100%*

Two-lane Roundabout Location

The roundabout that has been observed for obtaining the empirical data is located at Wakra municipality south of Doha at the intersection between Al Jamiyah Street (North-South) and Al Wukair Road (East-West). This roundabout represents the geometry and the operation conditions of a typical two-lane roundabout in the city of Doha. Cameras were placed on a telescopic pole, at maximum height, nearby to provide a wide outlook that enables a clear view of the interactions and the queuing at the roundabout. Figure 11 shows an example of a typical frame from the footage recorded at the location. Al Wukair Road (westbound) approach was analyzed.

FIGURE 11: AN ACTUAL FRAME FROM THE 2-LANE R/A LOCATION

The selected two-lane roundabout has an inside diameter of 25 meters and an outside diameter of 33 meters approximately. The roundabout was selected to have heavy peak volumes to ensure a large sample size that can result in accurate values in the analysis stage. The left lane of the approach is the primary lane, since the vehicle at the right lane will try to follow the left lane vehicle when accepting or rejecting a gap most of the time. The vehicle at the right lane can be included in the counted gaps in the case where no vehicle occupies the left lane, or the vehicle on the left lane is not fully stopped at the yield line at the end of the approach.

Two-lane Roundabout Data Collection

Video data were taken from the two-lane roundabout RA02's east-bound approach at Wukair Road. More than 15 hours of footage were captured covering the morning, noon, and evening peaks. Data collection was performed from 6:00 to 21:00 (+03 GMT) at clear weather conditions. The number of observed interactions exceeded 4,000 interactions over the duration of the data collection at the studied approach of this roundabout. Statistics of the collected data with classifications are presented in Table 4. Only five out of eight of the cases explained in the methodology section of the two-lane roundabout conform to the definition of the gap, therefore not all of the rows have values.

TABLE 4: GAP ACCEPTANCE STATISTICS OF THE 2-LANE R/A

Classification	Type	Count	Percentage
Gap Acceptance	*accepted*	1468	34.3%
	rejected	2806	65.7%
	Total	*4274*	*100%*
Vehicle Type	*passenger car*	4081	95.5%
	medium vehicle	153	3.6%
	heavy vehicle	40	0.9%
	Total	*4274*	*100%*
Case	1	2824	66.1%
	2	286	6.7%
	3	24	0.6%
	4	551	12.9%
	5	589	13.8%
	6	-	-
	7	-	-
	8	-	-
	Total	*4274*	*100%*

Three-lane Roundabouts Location

In this study, one three-lane roundabout was investigated at first. It is located at Al Gharrafa municipality west of Doha at the intersection between Al Gharrafa Road (North-South) and Al Maszhabiya Street (East-West); it is called Eid Bin Mohammed R/A, and it was given the code name 'RA04'. After data collection and analysis, it has been found that the critical gap value of the three-lane roundabout is lower than the critical gap of the two-lane roundabout. Thence, another location had to be investigated in order to confirm whether the obtained results are correct or not. The other three-lane roundabout is located at Al Rayyan municipality west of Doha at the intersection between Mesaimeer Road (North-South) and Haloul Street (East-West); this roundabout is called Haloul R/A and it was given the code name 'RA03'. RA03 data were collected before RA04, but it was not analyzed until the results of RA04 came out. The two selected roundabouts are very similar in geometry. In addition, they represent the typical configuration of three-lane roundabouts in the city of Doha. The roundabout RA04 has an inside diameter of 60 meters and an outside diameter of 85 meters, while RA03 has an inside diameter of 60 meters and an outside diameter of 82 meters. Both roundabouts were as well selected to have heavy peak volumes to ensure a large sample size that can yield accurate results. Cameras were installed at different angles at the studied approach of each roundabout as shown in Figure 12. The cameras were put up at maximum height on a 15-foot telescopic pole to enable a wider field of view and to observe the movements at the roundabouts much clearer without the obstruction of larger-sized vehicles. Data were collected from Al Gharrafa Road's northbound approach at RA04, and from Mesaimeer Road's northbound approach at RA03 for the study. Both of the approaches are very similar in geometry and they both don't have bypass right-turn lanes.

FIGURE 12: ACTUAL FRAME FROM THE 3-LANE R/A LOCATION (RA03)

Three-lane Roundabouts Data Collection

Video data were taken from the three-lane roundabout RA04's northbound approach at Al Gharrafa Road. More than 15 hours of footage were captured in May 2015 covering the morning, noon, and evening peaks. Data collection was performed from 6:00 to 21:00 at clear weather conditions. The number of observed interactions exceeded 3,000 interactions over the duration of the data collection at the studied approach of this roundabout. Statistics of the collected data are presented in Table 5. The cases of the three-lane roundabouts are different as explained in their methodology section. Some of the cases rarely occur such that there are not enough data points to perform the analysis. Only the cases that have an abundance of data points have been analyzed.

Early in the study, only one three-lane roundabout was analyzed. The critical gap value for that roundabout was lower than that of the two-lane roundabout. This wasn't consistent with the original hypothesis that the critical gap value of the three-lane roundabout was expected to be the largest of all roundabouts as it is the biggest in size and the most complicated type in terms of vehicular interactions. Therefore, another three-lane roundabout at a different location was studied in order to confirm whether the results of the first one were erroneous or not. More data were collected at the three-lane roundabout RA03's northbound approach at Mesaimeer Road. More than 15 hours of footage were captured in October 2015 covering the morning, noon, and evening peaks. Data collection was performed from 6:00 to 21:00 at clear weather conditions. The number of observed interactions exceeded 3,000 interactions over the duration of the data collection at the studied approach of this roundabout. Statistics of the collected data are presented in Table 6.

TABLE 5: GAP ACCEPTANCE STATISTICS OF THE 3-LANE R/A RA03

Classification	Type	Count	Percentage
Gap Acceptance	*accepted*	1112	33.9%
	rejected	2173	66.1%
	Total	3285	100%
Vehicle Type	*passenger car*	3130	95.3%
	medium vehicle	85	2.6%
	heavy vehicle	70	2.1%
	Total	3285	100%
Case	A	1652	50.3%
	B	302	9.2%
	C	180	5.5%
	D	4	0.1%
	E	239	7.3%
	F	5	0.2%
	G	1	0.0%
	Out of count	902	27.5%
	Total	3285	100%

TABLE 6: GAP ACCEPTANCE STATISTICS OF THE 3-LANE R/A RA04

Classification	Type	Count	Percentage
Gap Acceptance	accepted	1026	31.6%
	rejected	2223	68.4%
	Total	3249	100%
Vehicle Type	passenger car	3125	96.2%
	medium vehicle	93	2.9%
	heavy vehicle	31	1.0%
	Total	3249	100%
Case	A	1860	57.2%
	B	118	3.6%
	C	205	6.3%
	D	23	0.7%
	E	87	2.7%
	F	6	0.2%
	G	2	0.1%
	Out of count	948	29.2%
	Total	3249	100%

The data from both of the three-lane roundabouts were combined together since the results of both locations are quite similar. Statistics of the collected data are presented in Table 7, and results of both of them combined are provided in the analysis section. The total number of data points at the two three-lane roundabouts exceeds 6,500 points yielding the results more accurate.

TABLE 7: GAP ACCEPTANCE STATISTICS OF ALL 3-LANE DATA

Classification	**Type**	**Count**	**Percentage**
Gap Acceptance	accepted	2138	32.7%
	rejected	4396	67.3%
	Total	6534	100%
Vehicle Type	passenger car	6255	95.7%
	medium vehicle	178	2.7%
	heavy vehicle	101	1.5%
	Total	6534	100%
Case	A	3512	53.7%
	B	420	6.4%
	C	385	5.9%
	D	27	0.4%
	E	326	5.0%
	F	11	0.2%
	G	3	0.0%
	Out of count	1850	28.3%
	Total	6534	100%

EVALUATION OF OBSERVED GAPS

The analysis was performed by following Raff's method. The different results are compared to showcase the difference between the two types of roundabouts and other studies.

Raff's Method

Raff's method is one of the favorable methods used in the critical gap calculations due to its ease of use, less data demand and it produces reasonably accurate results. The non-complicatedness of Raff's method also makes it a good candidate for use in the field of transportation engineering (Tupper et al., 2013). Based on Raff's method, the critical gap is defined as the intersection between the cumulative distribution functions (CDFs) of the rejected and accepted gaps at which the probability of rejecting or accepting a gap is equal. Having a gap with a value larger than this value, the probability of a driver rejecting a gap becomes less than that of accepting a gap, and the opposite is true. This value can be obtained either graphically or by equalizing the sigmodal functions of the cumulative distribution plots. Near the intersection point between the CFDs, regression curves have been generated to get an equation for each curve at the intersection point. Equating the equations of the two curves shall produce the gap value at the intersection point (i.e. the critical gap value). This method also applies in the vehicular interaction cases and vehicle types at each roundabout.

One-lane Roundabout Analysis and Results

The Critical Gap: Raff's Method

Based on Raff's method, the critical gap of the one-lane roundabout was determined. The overall critical gap of this one-lane roundabout was found to have a value of 2.24 seconds. The CDFs that yielded this value can be seen in Figure 13. A summary of the critical gap and the different classifications of vehicle types can be found in Table 8.

TABLE 8: SUMMARY OF THE CRITICAL GAPS OF THE 1-LANE R/A

Classification	Type	Critical Gap (s)
Overall	*Raff's method*	*2.24*
Vehicle Type	*Passenger car*	*2.24*
	medium vehicle	*2.27*
	heavy vehicle	*2.93*

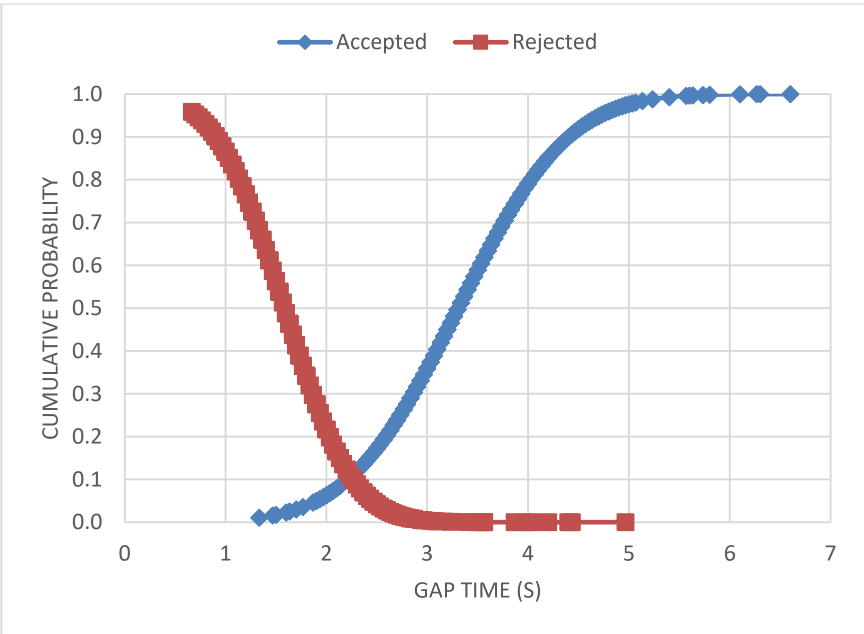


FIGURE 13: THE OVERALL CRITICAL GAP (1-LANE R/A)

The Critical Gap: Vehicle Classes

The type of vehicle, whether it being a passenger car, a medium-sized truck or a heavy vehicle, affected the critical gap value. Passenger cars had a critical gap value of 2.24

s, however, medium and heavy vehicles had critical gap values of 2.27 s and 2.93 s respectively. The number of data points for medium and heavy vehicles shows that more data points are required to obtain more accurate results (see Table 3). It was observed that the gap values of the passenger car, medium vehicle, and heavy vehicle are in an ascending order. Figure 14 through 16 show the graphical representation of raff's method by which the results were obtained.

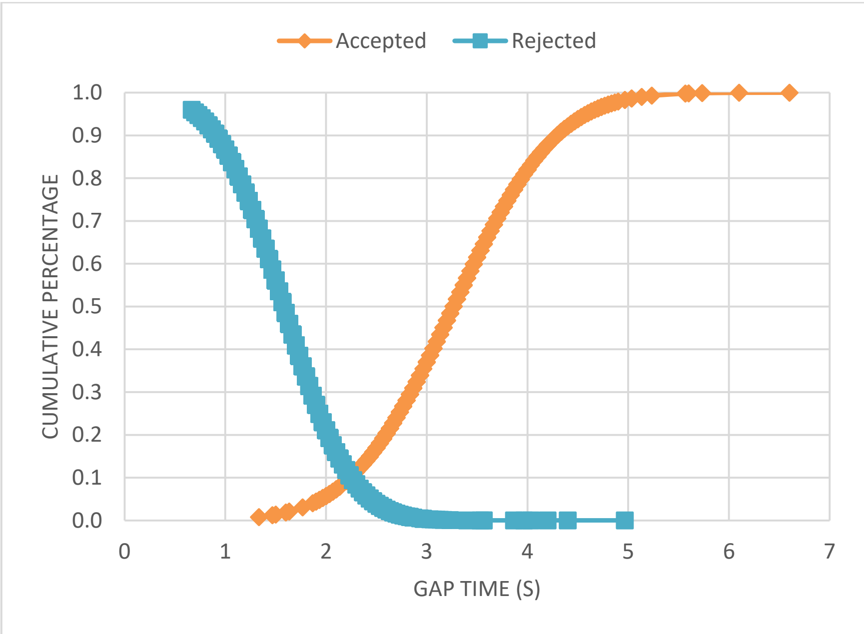


FIGURE 14: CRITICAL GAP OF PASSENGER CARS (1-LANE R/A)

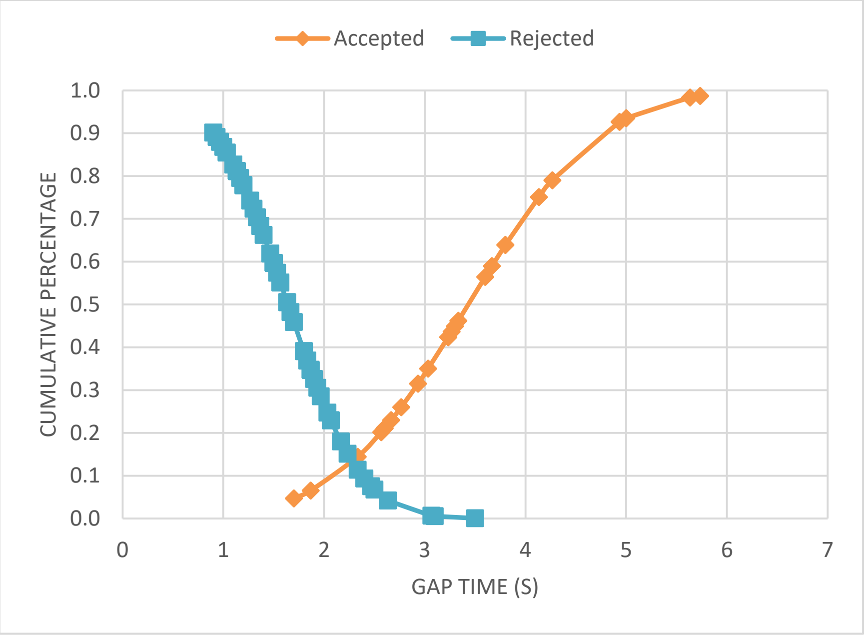


FIGURE 15: CRITICAL GAP OF MEDIUM VEHICLES (1-LANE R/A)

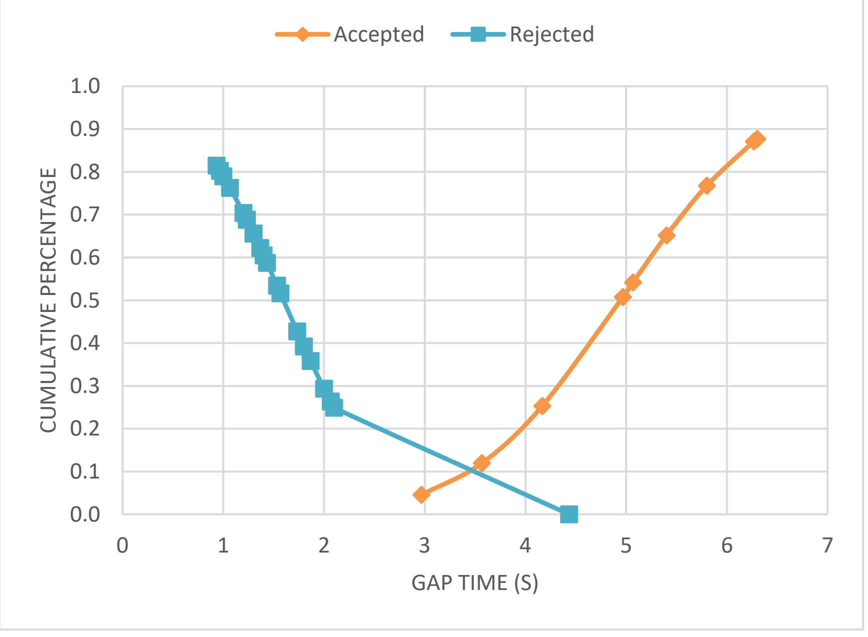


FIGURE 16: CRITICAL GAP OF HEAVY VEHICLES (1-LANE R/A)

Two-lane Roundabout Analysis and Results

The Critical Gap: Raff's Method

Based on Raff's method, the critical gap of the two-lane roundabout was determined. The overall critical gap of this two-lane roundabout was found to have a value of 2.55 seconds. Figure 17 shows the CDFs that yielded this value. A summary of the overall critical gap, the critical gaps of the different interaction cases and vehicle types can be found in Table 9.

TABLE 9: SUMMARY OF THE CRITICAL GAPS OD THE 2-LANE R/A

Classification	Type	Critical Gap (s)
Overall	*Raff's method*	*2.55*
Vehicle Type	*passenger car*	*2.50*
	medium vehicle	*2.95*
	heavy vehicle	*2.90*
Interaction Case	*1*	*2.55*
	2	*2.50*
	3	*2.90*
	4	*2.30*
	5	*2.80*
	6	-
	7	-
	8	-

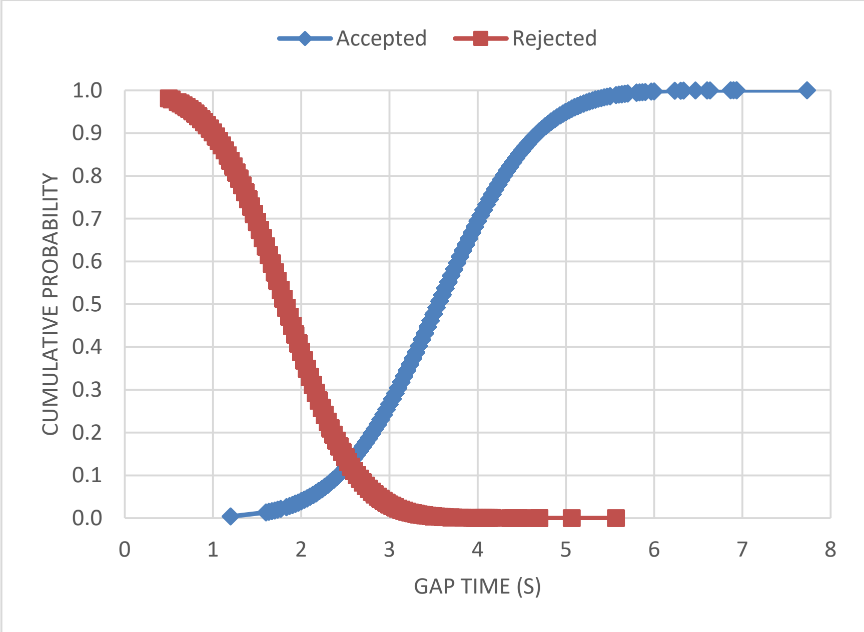


FIGURE 17: THE OVERALL CRITICAL GAP (2-LANE R/A)

The Critical Gap: Interaction Cases

The interaction cases had an effect on the value of the critical gap. Most of the interactions involved vehicles of type L1 (see Figure 4 for reference), and they have almost the same critical gap value with a mean of 2.54 s. The critical gap that involves vehicles of type L2 seems to have a higher value of 2.90 s. Figure 18 through 22 show the graphical representation of the data prepared for analysis based on Raff's definition to obtain the critical gap for each vehicular interaction case.

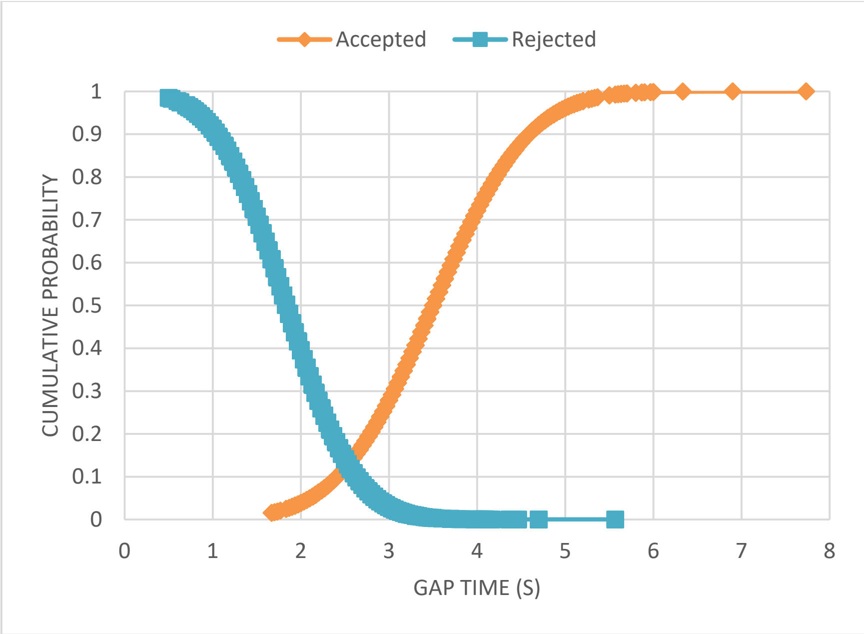


FIGURE 18: CRITICAL GAP OF CASE 1 (2-LANE R/A)

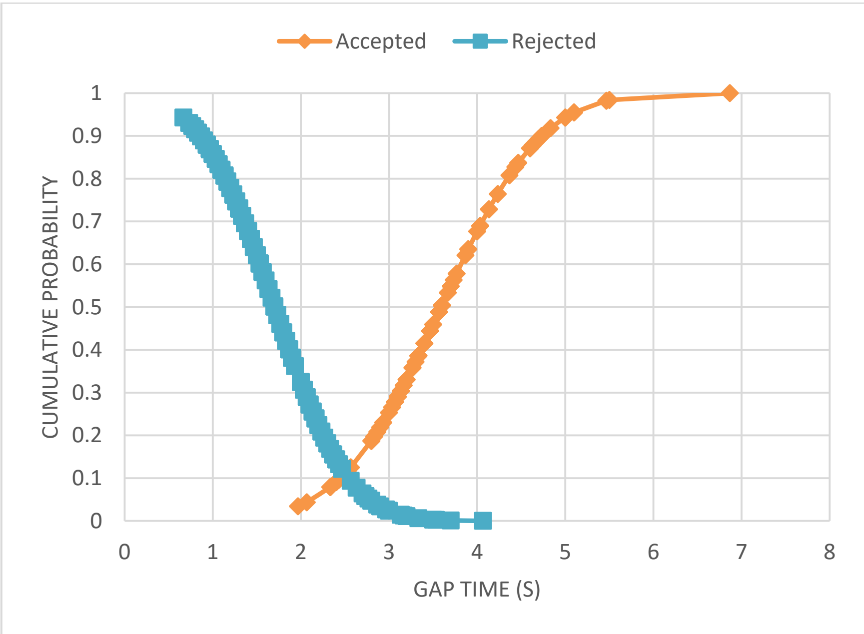


FIGURE 19: CRITICAL GAP OF CASE 2 (2-LANE R/A)

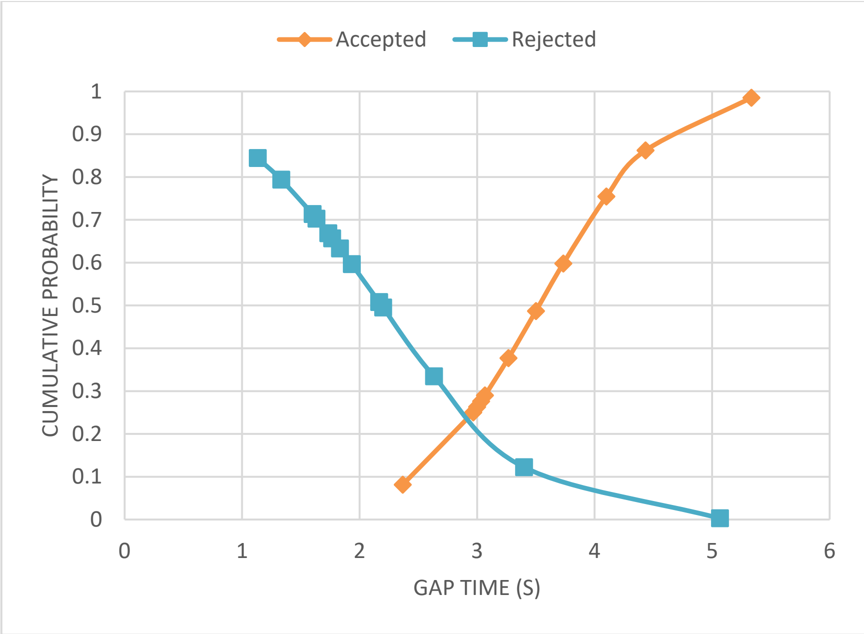


FIGURE 20: CRITICAL GAP OF CASE 3 (2-LANE R/A)

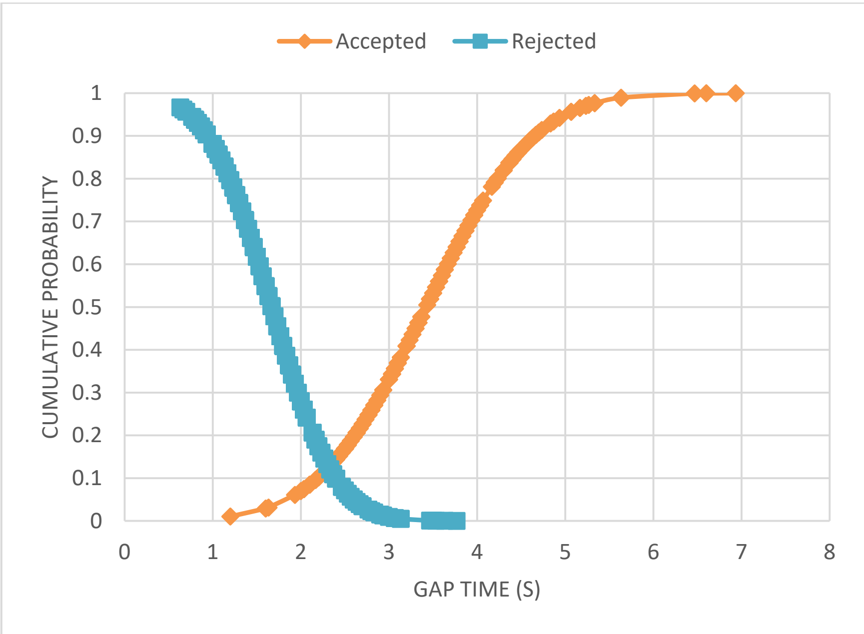


FIGURE 21: CRITICAL GAP OF CASE 4 (2-LANE R/A)

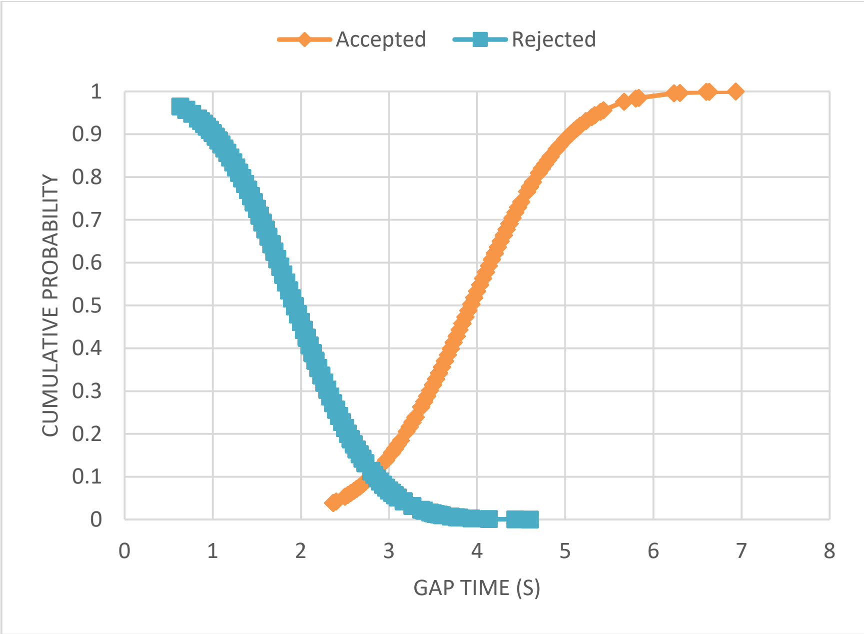


FIGURE 22: CRITICAL GAP OF CASE 5 (2-LANE R/A)

The Critical Gap: Vehicle Classes

The type of vehicle affected the critical gap values. Passenger cars had a critical gap value of 2.50 s, however, medium and heavy vehicles had critical gap values of 2.95 s and 2.90 s respectively. It was observed that the gap values of the passenger car, heavy vehicle, and medium vehicle are in an ascending order. This is against the order of acceleration capabilities of each vehicle type, but the results might not be accurate due to the fact that the number of data points of the medium and the heavy vehicles is not large enough to guarantee accurate results (see Table 4). Thus, further investigation is required to confirm the original hypothesis. Figure 23 through 25 show the graphical representation of raff's method by which the results were obtained.

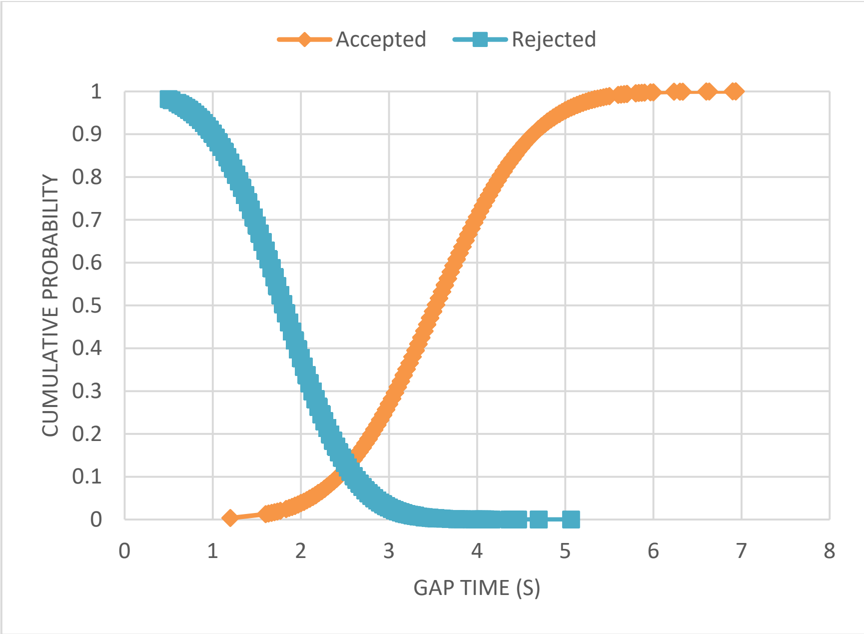


FIGURE 23: CRITICAL GAP OF PASSENGER CARS (2-LANE R/A)

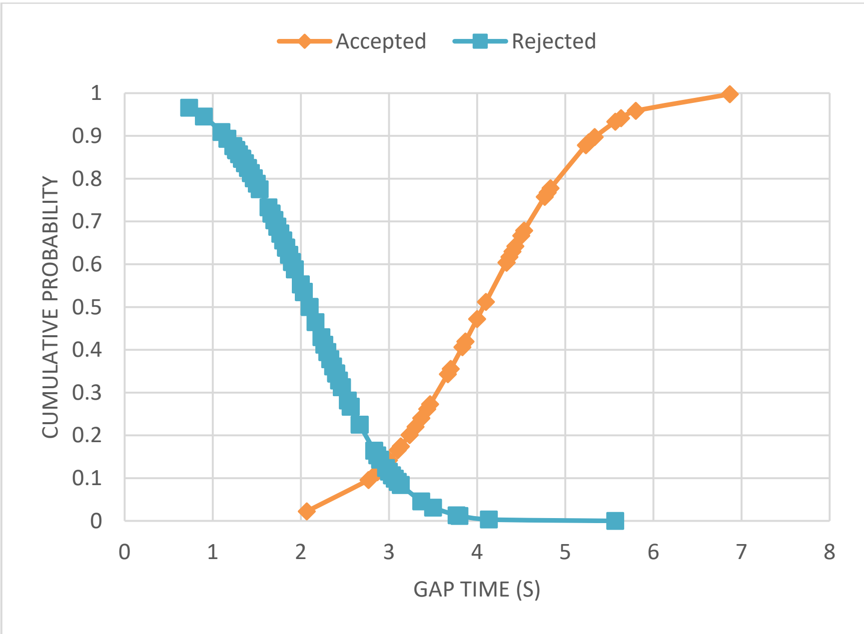


FIGURE 24: CRITICAL GAP OF MEDIUM VEHICLES (2-LANE R/A)

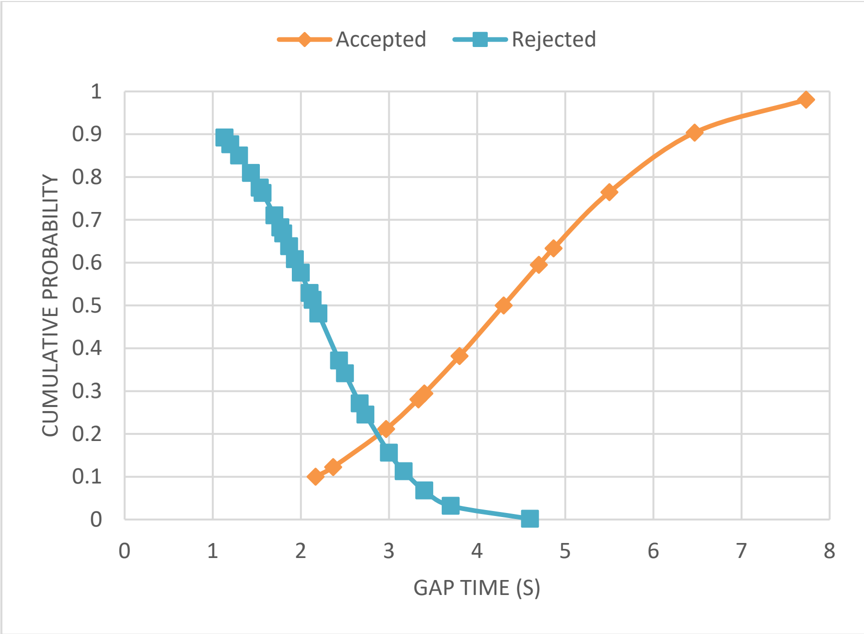


FIGURE 25: CRITICAL GAP OF HEAVY VEHICLES (2-LANE R/A)

Three-lane Roundabouts Analysis and Results

The Critical Gap: Raff's Method

Based on Raff's method, the critical gap of the three-lane roundabout was determined. The overall critical gap of the two three-lane roundabouts was found have a value of 2.40 seconds. Figure 26 shows the CDFs that yielded the critical gap value of all three-lane roundabout data. A summary of the overall critical gap, the critical gaps of the different interaction cases and vehicle types can be found in Table 10.

TABLE 10: SUMMARY OF THE CRITICAL GAPS OF ALL 3-LANE DATA

Classification	Type	Critical Gap (s)
Overall	*Raff's method*	*2.40*
Vehicle Type	*passenger car*	*2.39*
	medium vehicle	*2.53*
	heavy vehicle	*3.03*
Interaction Case	*A*	*2.45*
	B	*2.22*
	C	*2.33*
	D	*2.47*
	E	*2.11*
	F	-
	G	-

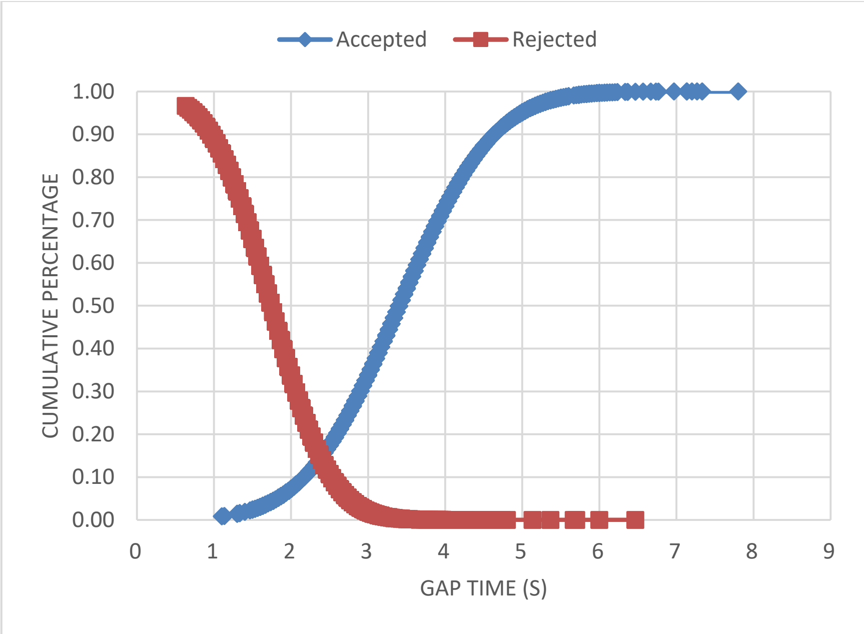


FIGURE 26: THE OVERALL CRITICAL GAP OF ALL 3-LANE R/A DATA

The Critical Gap: Interaction Cases

The interaction cases had an effect on the value of the critical gap. Most of the interactions of case A, such that the vehicles at the roundabout entry move together (see Figure 7 for reference). This case affected the overall critical gap at the roundabout where the critical gap value for case A was 2.45 s which is close to the overall critical gap value. The rest of the critical gap values are listed in Table 10. Some of the data points were not able to be attributed to interaction cases because the classification only targets the accepted gaps and the rejected gaps of the same vehicles; some vehicles had rejected gaps followed by a very wide gap that fit more than one vehicle in the same lane. Figure 27 through 31 show the graphical representation of the data prepared for analysis based on Raff's definition to obtain the critical gap for each vehicular interaction case.

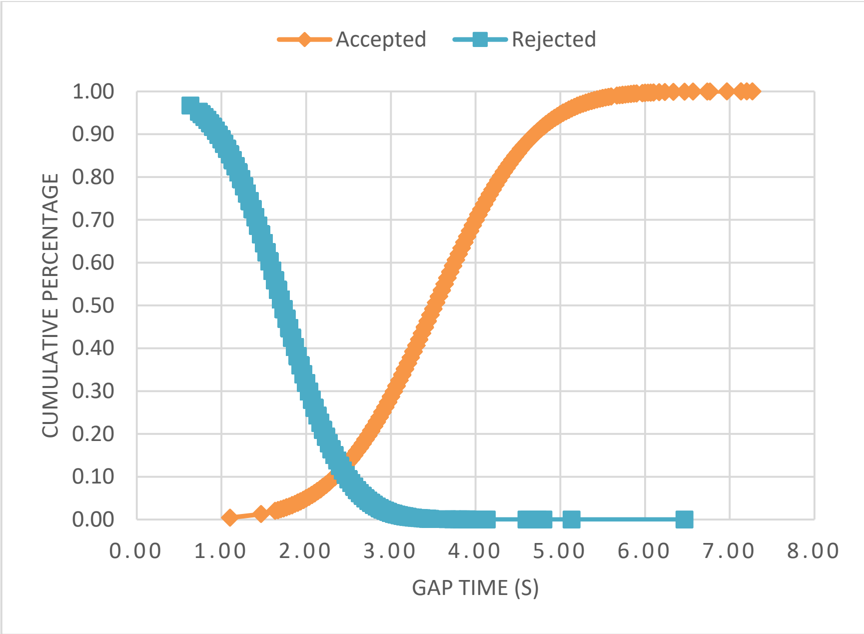


FIGURE 27: CRITICAL GAP OF CASE A (3-LANE R/A)

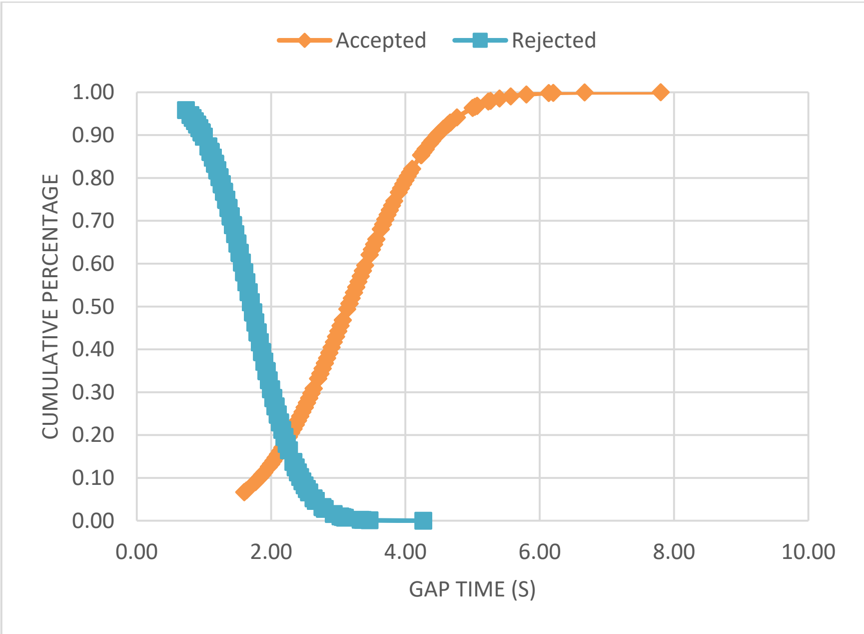


FIGURE 28: CRITICAL GAP OF CASE B (3-LANE R/A)

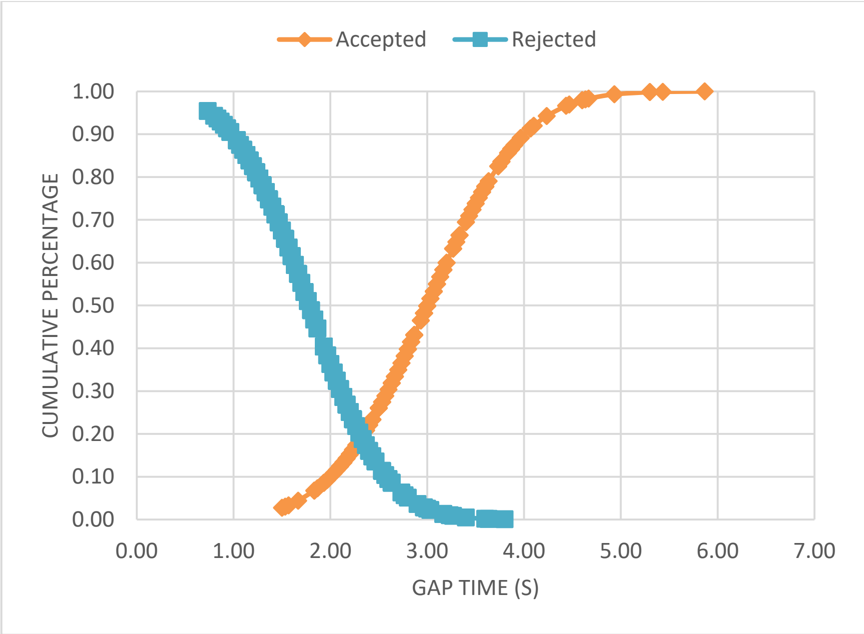


FIGURE 29: CRITICAL GAP OF CASE C (3-LANE R/A)

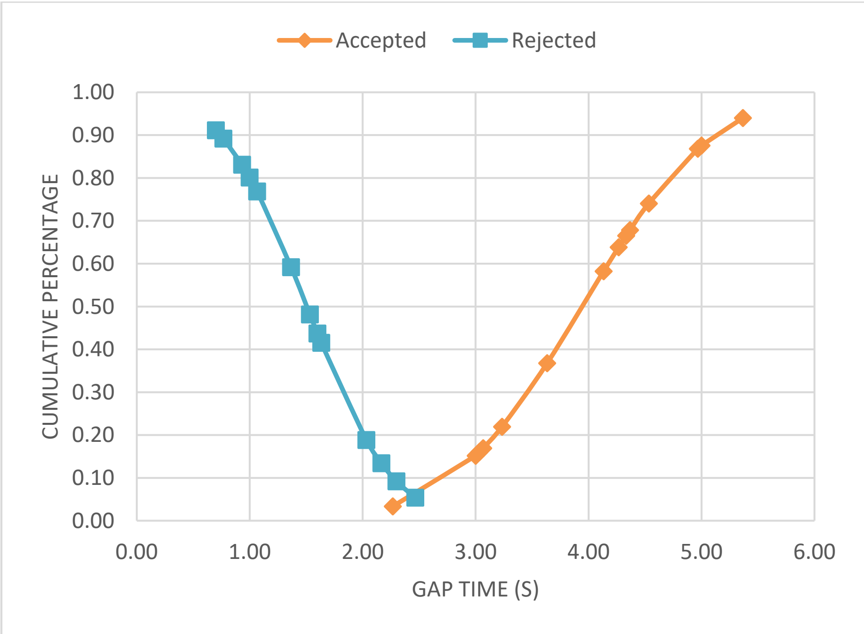


FIGURE 30: CRITICAL GAP OF CASE D (3-LANE R/A)

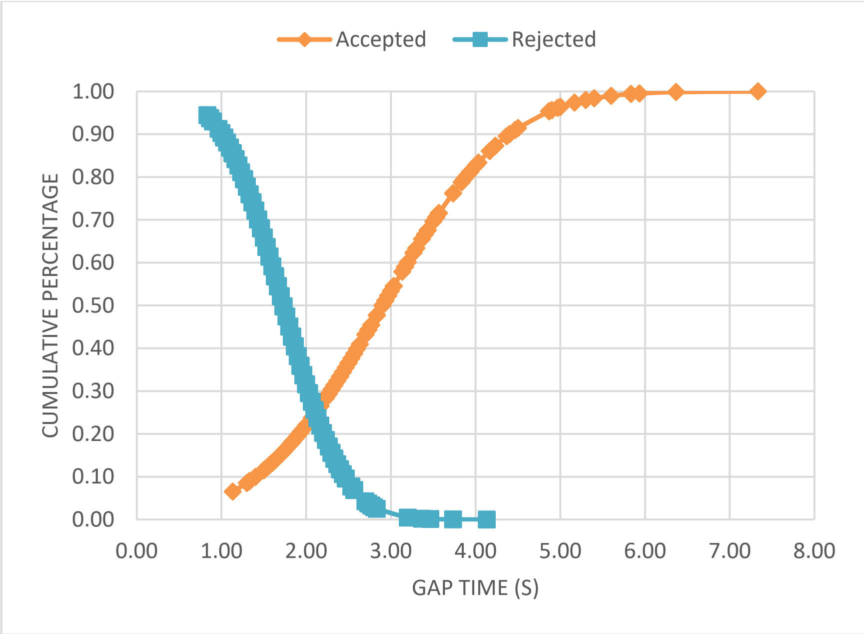


FIGURE 31: CRITICAL GAP OF CASE E (3-LANE R/A)

The Critical Gap: Vehicle Classes

The critical gap values of the different types of vehicles were not equal. Passenger cars had a critical gap value of 2.62 s, however, medium and heavy vehicles had critical gap values of 2.80 s and 3.41 s respectively. It was observed that the gap values of the passenger car, medium vehicle, and heavy vehicle are in an ascending order. The number of data points for medium and heavy vehicles shows that more data points are required to obtain more accurate results (see Table 5). Figure 32 through 34 show the graphical representation of raff's method by which the results were obtained.

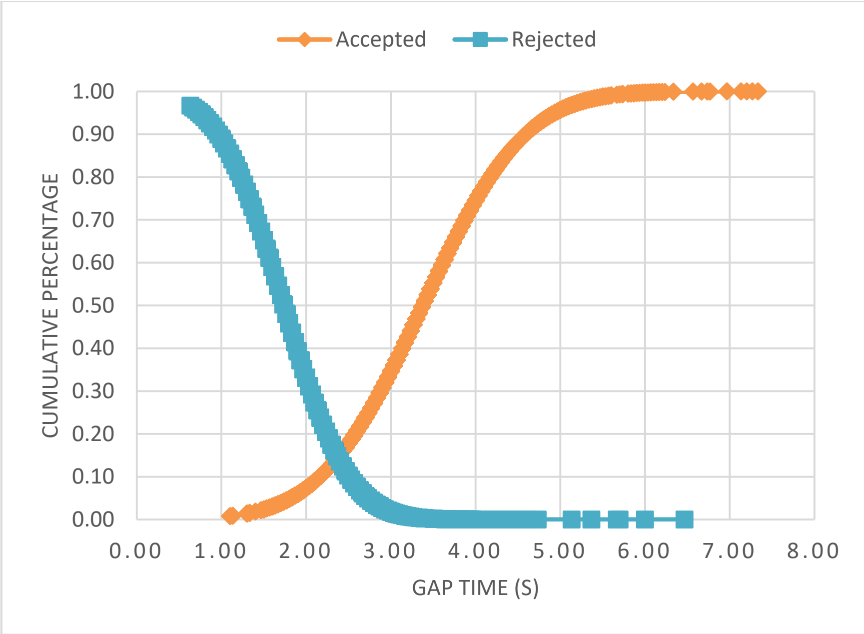


FIGURE 32: CRITICAL GAP OF PASSENGER CARS (3-LANE R/A)

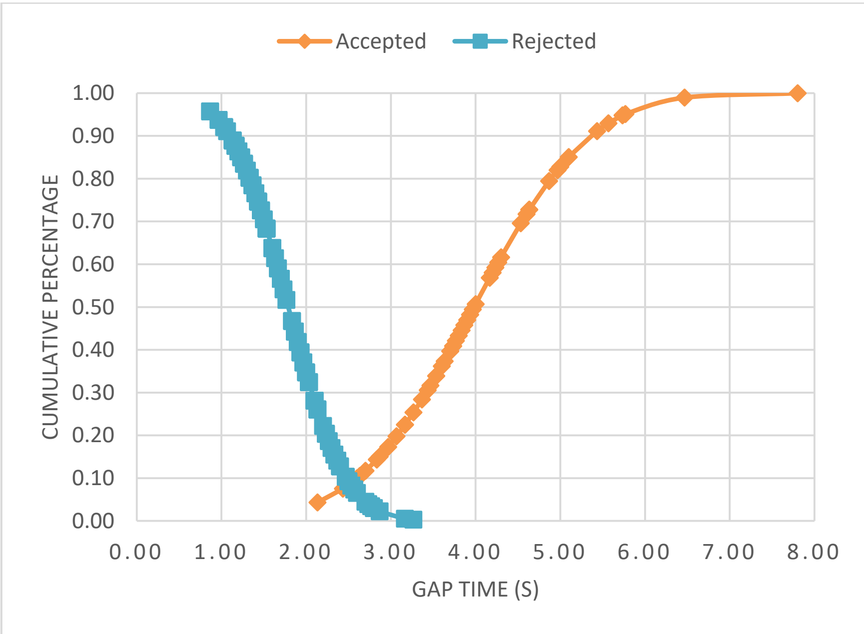


FIGURE 33: CRITICAL GAP OF MEDIUM VEHICLES (3-LANE R/A)

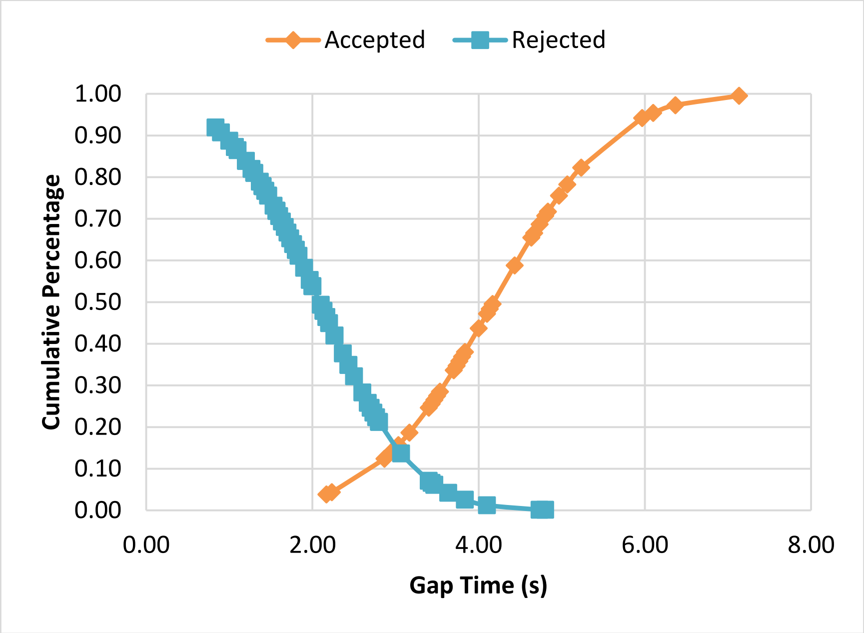


FIGURE 34: CRITICAL GAP OF HEAVY VEHICLES (3-LANE R/A)

DISCUSSION AND CONCLUSION

The presented work was performed in order to identify the critical gap value of roundabouts in Qatar. Data were collected from multiple locations with different layouts; a one-lane roundabout with a one-lane approach, a two-lane roundabout with a two-lane approach and two three-lane roundabouts with three-lane approaches. Interactions spanning from 1500 to more than 4000 were recorded per location. Data were classified based on vehicle types and interaction cases. The analysis was performed to estimate the critical gap value using Raff's procedure. Further discussion specific to each of the studied cases is found in the following sections.

One-lane Roundabout

1. The overall critical gap value was found to be 2.24 s based on Raff's method.
2. There is a significant difference between the critical gap values corresponding to different vehicle types; passenger cars had a critical gap value of 2.24 s; the medium and heavy vehicle had critical gap values of 2.27 s and 2.93 s respectively.
3. Most of the interaction cases involved passenger cars constituting more than 92% of the collected data points. The critical gap of the passenger car type is 2.24 s which is approximately equal to the overall critical gap value.

Two-lane Roundabout

1. The overall critical gap value was found to be 2.55 s based on Raff's method.
2. There was a significant difference between the critical gap values of different interaction cases; cases 1,2,4 and 5 had an average critical gap value of 2.54 s (std. dev. = 0.21); case 3 had a critical gap value of 2.90 s
3. There was also a significant difference between the critical gap values corresponding to different vehicle types; passenger cars had a critical gap value of

2.50 s; the medium and heavy vehicle had critical gap values of 2.95 s and 2.90 s respectively.

4. It has been found that the interaction case can affect the gap acceptance behavior of the drivers. Comparing the recorded cases, most of the interactions that involve vehicles of type L1 (i.e. cases 1, 2, 4 and 5) have almost the same critical gap value with mean of 2.54 s and std. dev. of 0.21. The critical gap that involves vehicles of type L2 seems to have a slightly higher critical gap value of 2.90 s.
5. Most of the data points belong to the cases that involve a decision taken by vehicle L1 drivers. The overall critical gap value (2.55 s) is closer to this value (2.54 s). Also, most of the interaction cases involved passenger cars making up more than 95% of the collected data points. The critical gap of the passenger car type is 2.50 s which is also the closest to the overall critical gap value.

Three-lane Roundabouts

1. The overall critical gap value was found to be 2.40 s based on Raff's method.
2. Interaction cases had an impact on the value of the critical gap. The results show that the interaction cases A and D are looking similar with an average critical gap value of 2.46 s and standard deviation of 0.01. Whereas cases B and C are also looking similar with an average critical gap value of 2.28 s and standard deviation of 0.08. Case E has the smallest critical gap value (2.11 s) of all cases, which was expected as only one vehicle takes the acceptance decision since the gap is small enough to allow only one vehicle to merge with the flow.
3. Also, there was a significant difference between the critical gap values corresponding to different vehicle types; passenger cars had a critical gap value of 2.40 s; medium and heavy vehicle had critical gap values of 2.53 s and 3.03 s respectively.

4. Most of the data points belong to the cases that involve the main decision vehicle L1 and following decision vehicles L2 and L3. Case A was the dominant case making up more than 53% of the data points collected from the two locations. The critical gap value of case A (2.45 s) is the closest to the overall critical gap value (2.40 s) out of all the interaction cases. Also, most of the interaction cases involved passenger cars constituting more than 95% of the collected data points. The critical gap of the passenger car type is 2.39 s which is also the closest to the overall critical gap value.

Based on the observations listed previously, there is a relationship between the portion of data points that belong to certain interaction cases or vehicle types and the overall critical gap of a certain roundabout. Thus, knowing the estimated critical values of the different types of vehicles and interaction cases nationwide in addition to the percentages of the different interactions cases and vehicle types can ultimately give an accurate prediction of the value of the critical gap at existing or future locations. Some results from previous work were collected in Table 1, where the critical gap values for different sizes of roundabouts were calculated using different methods. When compared to the results of this work, taking into consideration the method of analysis, the results of Doha seem to differ greatly from the results obtained in other countries/regions of the world at locations with comparable conditions. The human factor clearly has an effect on the value of the critical gap which in turn has an effect on the capacity of roundabouts.

Comparison of Results

One-Lane vs. Two-Lane Roundabouts

When comparing the results of one-lane and two-lane roundabouts in Doha, it is noted that the critical gap value of the former is lower than the latter. This result could be guessed right away (sensible) as it is evident that the interaction cases in two-lane roundabouts are far more complex (with 8 interaction cases) than that of the one-lane (with only one case). The results produced from cumulative distribution curves after Raff's method show a significant difference between different types of roundabouts. The critical gap value of the one-lane roundabout is 2.24 s (Raff) whereas that of the two-lane roundabout is 2.55 s (Raff). Statistical analysis could have been performed on the result if more critical gap values for different roundabouts were provided. Future work can target this issue by analyzing more roundabouts and performing simple statistical methods such as T-test.

One-Lane & Two-Lane vs. Three-Lane Roundabouts

The methodology of the three-lane roundabouts and its classification of cases is different from that of the one-lane or two-lane roundabouts that it wouldn't make sense to compare the results of these roundabouts to each other. So, only one-lane and two-lane roundabouts were compared to each other.

Use of the Outcomes

The outcomes of this work were the critical gap values of three different types of roundabouts. The vehicular interaction cases and vehicle types were also investigated for each location if applicable. These values can be used in numerous applications such as: designing new roundabouts that have similar attributes to the ones in this study (the critical gap value is one parameter in the capacity calculation of roundabouts, and values produced from similar existing locations could predict capacity at future locations); generating capacity models and assessing the level of service of existing roundabouts by using a critical gap value corresponding to roundabouts of similar nature; this value can be input in the capacity model to estimate the capacity of existing facilities without the need to perform field measurements; simulation and traffic modeling of roundabouts for future projects or research projects; the critical gap values produced from this work could be used instead of the currently used ones in the international codes.

Limitations of the Outcomes

The studied locations didn't cover all the types of roundabouts that are found in Qatar. The outcomes describe the specific conditions mentioned in previous sections. The limitations of this work are: only the three types of roundabouts previously described were studied due to shortage in time, funds and resources; this work didn't investigate the effect of the slip lanes at the studied approaches; motorbikes were eliminated from the collected data; the effect of pedestrians and cyclists at the roundabout was not considered; the effect of adjacent interchanges or signalized intersections was not measured.

Future Work

There is room for contribution in the field of gap acceptance and roundabouts in general, especially in the Middle East region. More roundabouts need to be investigated in neighboring countries of the GCC, as an example, to confirm whether the parameters that impact the critical gap value are similar or not. Additional factors that can have an effect on the critical gap values such as crossing pedestrians or adjacent signalized intersections also can be investigated as part of future work.

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