CRITICAL GAPS AND FOLLOW-UP HEADWAYS AT CONGESTED ROUNDABOUTS

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ABSTRACT

Roundabouts are relatively new to the United States but are being constructed rapidly. Critical gap and follow-up headway are two important factors in determining capacity of roundabouts. . Data were collected at four approaches of three congested roundabouts in Wisconsin to estimate critical gaps and follow-up headways. Congestion was determined by presence of queued vehicles on the approach. . Primary analyses on critical gap and follow-up headway include value comparison 1) between current study and previous findings, 2) between vehicle types, and 3) between whether or not exiting vehicles are considered. The analyses results show that 1) critical gap and follow-up headways were typically lower at congested roundabouts, 2) larger vehicles had higher critical gap and follow-up headway values, 3) by considering exiting vehicles, critical gap and follow-up headway estimates decreased significantly,. Critical gap and follow-up headway estimates were slightly more consistent across sites as queue length increased, and the variability of gap acceptance was reduced. The reduced variability in gap acceptance provides a better approximate for the upper bound of driver randomness.

INTRODUCTION

A modern roundabout is an unsignalized intersection where entering traffic is required to yield to the circulating traffic. The yield-to-circulating rule is one of the main differences between modern roundabouts and traditional traffic circles. While modern roundabouts were first designed in the United Kingdom in the 1960s, their prevalence in the United States (U.S.) did not begin until 1990 *(1)*. A number of research studies have shown that roundabouts are successful in not only reducing the frequency of crashes but also the injury severity of crashes *(1-7)*. Studies have shown that roundabouts operate more efficiently than signalized intersections and conventional unsignalized intersections (two-way stop and four-way stop) *(8)*.

According to the 2010 Highway Capacity Manual roundabout capacity depends on critical gap and follow-up headway (ref?). However, limited studies have been performed on operational characteristics of congested roundabouts in the US. *(1,9)*. Additionally, critical gaps and follow-up headways were not reported for different vehicle types. Heavy vehicles are expected to have significantly larger critical gaps and follow-up headways at roundabouts than passenger cars as is the case at other unsignalized intersections *(9)*. Previous research reported that considering exiting vehicles significantly decreased critical gaps at single-lane roundabouts (*10*). However, no research has studied effect of exiting vehicles on follow-up headways or at multi-lane roundabouts.

The primary objective of this research is to study critical gaps and follow-up headways at congested roundabouts. Data were collected at three congested roundabouts in Wisconsin. Results are compared with previously reported values and effects of vehicle type and exiting vehicles on critical gaps and follow-up headways are determined.

LITERATURE REVIEW

Critical gap and follow-up headway (also termed critical headway and follow-up time in literature, respectively) are key parameters for most of the capacity models of roundabouts. A gap is the time difference between two successive circulating vehicles passing the conflicting line. A critical gap is the minimum gap that an entering driver would use to enter the roundabout. A follow-up headway is the time difference between two successive vehicles entering the roundabout using a same gap, under saturated condition.

Many methods have been proposed to estimate critical gap from gap data *(11-19)*. Miller and Brilon, et al. evaluated several critical gap estimation methods and both reported that the maximum likelihood method gives the best results *(20, 21)*. Maximum likelihood method was originally introduced by Miller and Pretty in calculating the critical gap of overtaking behavior *(19)*. Due to the similarity of gap acceptance mode, maximum likelihood method can be applied in many scenarios such as two-way-stop controlled intersections, permissive left turns at signalized intersections, roundabouts, etc. Troutbeck further specified how to use maximum likelihood method to determine critical gaps from traffic movements *(22)*. The maximum likelihood method was adopted by NCHRP 572 as the method of estimating critical gaps *(1)*.

NCHRP Report 572 reported critical gaps and follow-up headways based on data collected from 25 approaches of 15 roundabouts (11 single-lane roundabouts and 4 multi-lane roundabouts) *(1)*. Most queues at the 15 roundabouts were one or two minutes in duration, although the maximum continuous queue recorded was 31 minutes. Default values of critical gaps and follow-up headways were suggested in Highway Capacity Manual (HCM) *(9)*. Some recent studies also studied critical gaps and follow-up headway *(23, 24)*. Unfortunately, neither critical gaps nor follow-up headways have been reported by vehicle type.

Mereszczak et al. were the first to incorporate the effect of exiting vehicles on critical gaps at single-lane roundabouts *(10)*. When the effect of exiting vehicles is considered, critical gap was found to be smaller than that when the effect of exiting vehicles is not considered. Capacity predictions improved when the effect of exiting vehicles was considered *(10)*. However the effects of exiting vehicles on critical gaps at multi-lane roundabouts and on follow-up headways (single/multi-lane roundabouts) have not been studied.

A number of studies have been done to identify factors that influence driver's gap acceptance. Polus, et al. examined the critical gap as a function of average waiting time at roundabouts and found critical gap reduces with increasing waiting time *(25)*. This finding was similar to what has been discovered in scenarios other than roundabouts *(26)*. Mensah, et al. also reported that as people got accustomed to roundabouts, critical gaps decreased *(27)*. Wang, et al. modeled the inconsistency of drivers' gap acceptance behaviors at roundabouts using Cellular Automata and reproduced many features of traffic flow using the model *(28)*. The above findings, together with the randomness of driver behavior and observation errors, could explain why a driver's largest rejected gap was sometimes larger than the accepted gap. Additionally, whether the variability of gap acceptance would change by including exiting vehicles is worth studying.

DATA COLLECTION

Data were collected for four congested approaches at three roundabouts located in the southwest, southeast, and northeast regions of Wisconsin. The driver populations in the three regions are different. Two of the approaches were either single-lane-entering against multi-lane-circulating or multi-lane-entering against single-lane-circulating , and here after referred to as combined approaches; the other two approaches were two lanes for both entering and circulating , named multi-lane approaches. Detailed data collection information is included in Table 1. Data collection periods were chosen on weekdays in the afternoon including the PM peak. During the data collection period there were no incidents or inclement weather at the roundabouts.

A typical field setup is illustrated in Figure 1. Video cameras were installed at an upstream location and the intersection corner. The two different camera views were designed to capture four vehicle events: 1) arriving, 2) entering, 3) conflicting, and 4) exiting. The time stamp notations and definitions of the four events are also shown in Figure 1. For an arriving event, the situation could fall into either of the two: 1) the entering vehicle anticipated no conflicts and entered the roundabout with little deceleration or yielding; 2) the entering vehicle either slowed down to a very low speed or stopped in front of the yield bar before the driver found an acceptable gap to enter. In the first situation, the arrival event was identical to the entering event, so were their time stamps. In the second situation, the two events were distinct.

Congestion times at roundabouts used in this study were identified based on observed queuing. Table 1 shows the number of fully queued minutes for the four approaches and illustrates that the chosen approaches were congested for significant durations. For the multilane approach M1 left lane was fully queued for 268 minutes, right lane for 77 minutes and both lanes for 76 minutes. Similarly for approach M2, left, right and both lanes were fully queued for 107, 150 and 91 minutes respectively. At C1 79 fully queued minutes were observed. At C2, only the left lane was fully queued for 33 minutes, while the right lane was not fully queued.

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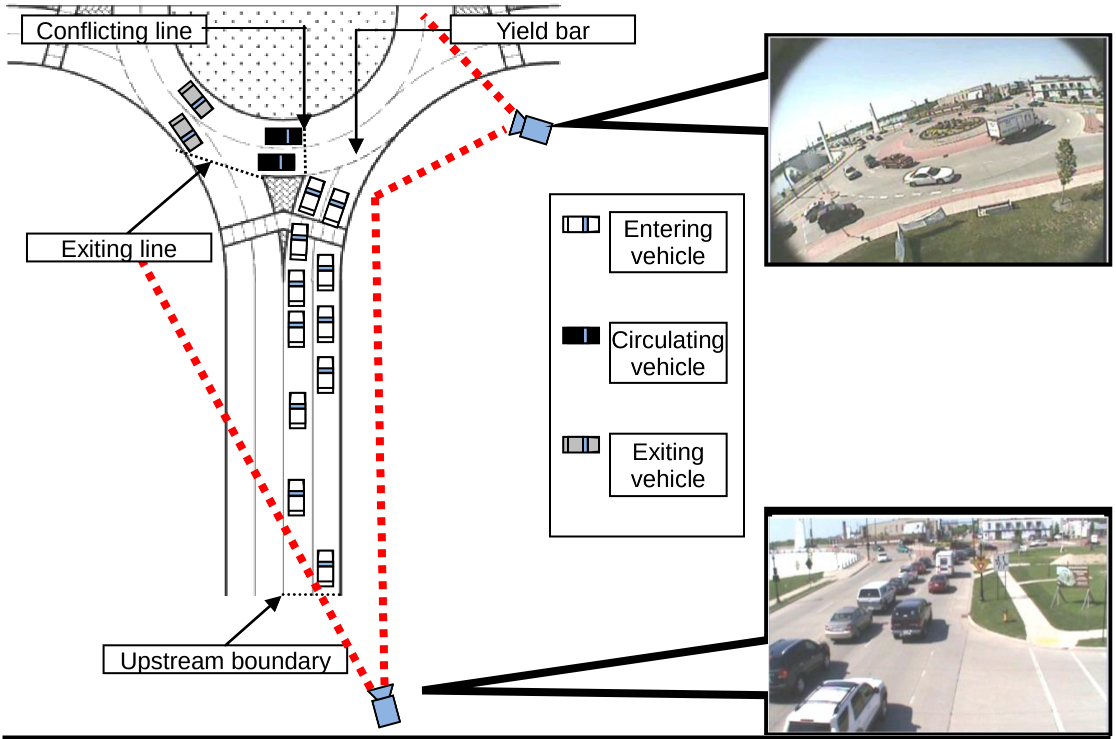
TABLE 1 Summary of Data Collection Information

Approach No.	**C1**	**C2**	**M1**	**M2**
Direction	SB	WB	NB	EB
Roundabout	Canal Street at 25th Street	STH 78 at CTH ID	STH 32 at STH 57	STH 32 at STH 57
Geometry	1 lane entering 2 lanes circulating	2 lanes entering 1 lane circulating	2 lanes entering 2 lanes circulating	2 lanes entering 2 lanes circulating
Date	April 15th, 2010 Thursday	April 8th, 2010 Thursday	May 19th, 2010 Wednesday	May 19th, 2010 Wednesday
Time Span	1:50 PM to 6:00 PM	1:20 PM to 5:50 PM	1:20 PM to 6:20 PM	2:50 PM to 6:00 PM
Peak Hour Entering Volume (veh/hr/lane)	554	635	325	1045
Sum of Fully Queuing Minutes	79	33 (left lane**) 0 (right lane**) 0 (both lanes**)	268 (left lane) 77 (right lane) 76 (both lanes)	107 (left lane) 150 (right lane) 91 (both lanes)
Equivalent Travel Time (s) *	1.3 (inner lane) 2.2 (outer lane)	1.7	1.1 (inner lane) 1.9 (outer lane)	1.2 (inner lane) 2.6 (outer lane)

** Equivalent Travel Time: a parameter for including the exiting vehicles into gap measuring. The equivalent travel time will be explained and defined later in the "Two Gap Measuring* Techniques*" section.*

*** left lane: either only queued in the left lane or queued in both lanes; right lane: either only queued in the right lane or queued in both lanes; both: queued in both lanes.*



Time Stamp Notation	Event Name	Event Definition
T_{arr}	Arrival	*An entering vehicle comes to a stop or reaches the lowest speed in front of the yield bar before it enters the roundabout. If the entering vehicle does not stop, the event refers to the vehicle's front reaches the yield bar and is the same as* T_{ent}.
T_{ent}	Entering	*The front of an entering vehicle reaches the yield bar, followed instantly by the vehicle getting into the circulating roadway.*
T_{con}	Conflicting	*The front of a circulating vehicle reaches the conflicting line.*
T_{ext}	Exiting	*The front of an exiting vehicle reaches the exiting line.*

FIGURE 1 A typical field setup.

METHODOLOGY

Using the videos collected at the roundabouts, time stamps for the four vehicle events were manually extracted. Also, every entering vehicle was classified into one of three categories: passenger cars (including sedans, sport/utility vehicles, minivans, vans, and pick-up trucks), trucks (single-unit trucks, truck tractor-semitrailer combinations, and truck tractors with semitrailers in combination with full trailers), and motorcycles *(29)*. Additionally, for every entering vehicle, the number of vehicles waiting behind it in the same lane (queue length) was also recorded. The queue length information was used to ensure that the vehicles were queued as well as to study the effect of queue length on critical gap and follow-up headway. For follow-up headway, the samples were collected only when the vehicles were in queue . Gap and headway data were computed using the time stamps. Critical gaps and follow-up headways were estimated based on the gap and headway data, respectively, and categorized by vehicle type.

Two Gap Measuring Techniques

A gap is defined as the time difference between two consecutive conflicting events (Equation 1). For the two lane roundabouts, gaps were measured across both lanes, as was done in the NCHRP 572 study.

$$t_g = T_{con}^{(i+1)} - T_{con}^{(i)} \tag{1}$$

Where

t_g = A gap between circulating vehicle *i* and circulating vehicle *i+1*, second;

$T_{con}^{(i)}$ = Time stamp of the conflicting event of circulating vehicle *i*, second;

$T_{con}^{(i+1)}$ = Time stamp of the conflicting event of circulating vehicle *i+1*, second.

Another term usually associated with gap is a lag. A lag is defined as the time difference between an arrival event and next conflicting event (Equation 2).

$$t_l = T_{con} - T_{arr} \tag{2}$$

where

t_l = A lag, second;

T_{con} = Time stamp of the conflicting event of the first circulating vehicle faced by the entering vehicle, second;

T_{arr} = Time stamp of the arrival event of the entering vehicle, second.

Above definitions of gap and lag do not consider the effect of exiting vehicles. The technique used by Mereszczak et al. to measure gaps and lags considering the effect of exiting vehicles is summarized in Equation 3 *(10)*:

$$t = (T_{event\ 2} + \Delta t) - T_{event\ 1} \tag{3}$$

where

t = A gap when event 1 is a conflicting event or an exiting event; or a lag when event 1 is an arrival event, seconds;

$T_{event\ 1}$ = The time stamp of a conflicting event, an exiting event, or an arrival event, seconds;

$T_{event\ 2}$ = The time stamp of a conflicting event or an exiting event, seconds;

Δt = 0 second, when event 2 is a conflicting event;

Equivalent travel time (ETT), when event 2 is an exiting event.

In Equation 3, $T_{event\ 2}$ comes successively after $T_{event\ 1}$. The equivalent travel time (ETT) assigned to Δt when event 2 is an exiting event was first proposed by Mereszczak et al. as "the travel time that would have occurred between the exit point and conflict point had the exiting vehicle remained in the circulating flow"*(10)*. Mereszczak et al. calculated the ETT by dividing the distance from the middle point of the exiting line to the conflicting line with the average circulating speed. For the present study, a modified approach was taken to measure ETTs for both single-lane roundabouts and multi-lane roundabouts. The approach is to equal the ETT to the sample average travel time of circulating vehicles running through an "equivalent segment". The concept of equivalent segment is illustrated in Figure 2 for both single-lane and multi-lane roundabouts. In Figure 2, Point D is the point from which the circulating center path and the exiting center path diverge; Point M is the intersection between the exiting line and the exiting center path; Point E is located such that the length of segment DE (of the circulating center path) equals the length of segment DM (of the exiting center path); and Point C is the intersection between the circulating center path and the conflicting line. Since segment DE equals segment DM, Point E is approximately where an exiting vehicle would have reached if it had continued circulating. Therefore, segment EC (of the circulating center path) is the equivalent segment of which the travel time matches the idea of ETT. About 20 vehicles per hour per lane were sampled to measure ETTs. The ETTs used for the studied approaches are summarized in Table 1.

For the current study, two techniques were used for measuring a gap (or a lag). The first technique did not consider the exiting vehicles, and thus only counts gaps between conflicting vehicles. The second technique considered the exiting vehicles as virtual conflicting vehicles, and counts gaps between both circulating vehicles and exiting vehicles, by applying an equivalent travel time when an exiting vehicle is involved.

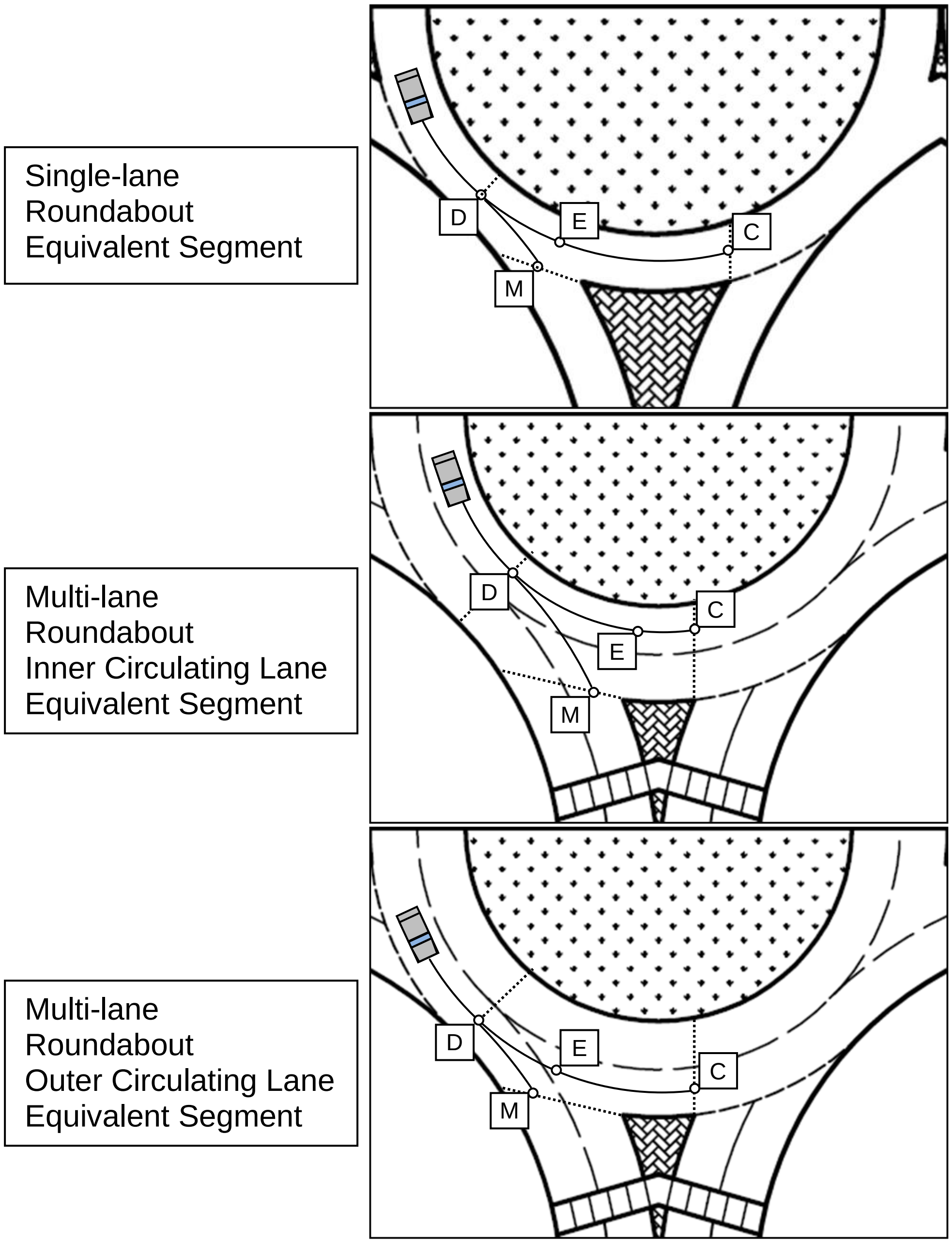


FIGURE 2 Illustrations of equivalent segments.

Estimation Methods of Critical Gap and Follow-up Headway

Maximum Likelihood Method (MLM) is the state-of-the-practice to estimate critical gaps *(20, 21)*. In the current study, MLM was used to estimate the mean and the standard deviation of critical gap, assuming a log-normal distribution for critical gap. Only entering vehicles that rejected at least one gap (or lag) were used as samples for MLM. Procedures of finding the MLM solutions were based on Troutbeck *(22)*. For follow-up headway, averages and standard deviations were taken from sample follow-up headways. Only those vehicles that were in queue were used for computing follow-up headway.

RESULTS AND ANALYSES

Table 2 summaries the sample sizes, means, and standard deviations of critical gaps (n_c, t_c, and sd_c, respectively) and of follow-up headways (n_f, t_f, and sd_f, respectively). The sample size n_c for critical gaps only included vehicles that rejected a lag. The estimates were categorized by vehicle type for both scenarios of considering and not considering the exiting vehicles. When the sample sizes of the three vehicle types did not sum up to that of all vehicle types, one bike or one bus could have appeared and resulted in the minor difference.

TABLE 2 Critical Gaps and Follow-Up Headways

	Not considering exiting vehicles						**Considering exiting vehicles**					
	n_c	t_c (s)	sd_c (s)	n_f	t_f (s)	sd_f (s)	n_c	t_c (s)	sd_c (s)	n_f	t_f (s)	sd_f (s)
Approach C1												
Passenger Cars	536	5.5	1.9	1203	2.6	1.4	575	4.6	1.2	814	2.3	1.0
Trucks	10	6.3	0.1	5	3.9	2.1	10	5.1	1.5	2	1.9	0.1
Motorcycles	2	4.9	5.5	15	1.6	0.9	2	3.2	2.3	12	1.5	1.0
All	548	5.5	1.9	1223	2.6	1.4	587	4.6	1.2	828	2.3	1.0
Approach C2												
Left lane												
Passenger Cars	236	4.9	1.5	765	4.4	2.5	263	3.8	0.9	459	3.7	2.1
Trucks	3	9.3	1.5	9	6.3	3.6	4	7.2	2.0	5	5.4	3.3
Motorcycles	-[1]	-[1]	-[1]	-[1]	-[1]	-[1]	-[1]	-[1]	-[1]	-[1]	-[1]	-[1]
All	239	5.0	1.7	774	4.4	2.5	267	3.9	1.0	464	3.7	2.1
Right lane												
Passenger Cars	58	4.4	0.4	121	4.9	2.7	64	4.0	0.7	60	4.0	2.4
Trucks	2	2.8	0.4	1	2.36	-[2]	2	4.1	0.1	1	2.4	-[2]
Motorcycles	-[1]	-[1]	-[1]	1	4.67	-[2]	-[1]	-[1]	-[1]	1	4.7	-[2]
All	60	4.4	0.4	123	4.9	2.7	66	4.0	0.7	62	4.0	2.3
Approach												
Passenger Cars	294	4.9	1.4	886	4.4	2.5	327	3.9	0.9	519	3.7	2.1
Trucks	5	7.8	3.9	10	5.9	3.7	6	6.0	2.2	6	4.9	3.2
Motorcycles	-[1]	-[1]	-[1]	1	4.67	-[2]	-[1]	-[1]	-[1]	1	4.7	-[2]
All	299	4.9	1.5	897	4.4	2.5	333	3.9	1.0	526	3.7	2.1
Approach M1												
Left lane												
Passenger Cars	870	4.1	0.9	638	3.1	1.2	787	3.3	0.6	214	2.5	0.9
Trucks	76	5.0	1.1	36	3.7	1.2	73	3.6	0.7	6	3.1	0.9
Motorcycles	20	3.7	0.6	23	2.0	1.4	15	2.9	0.6	12	1.5	1.1
All	966	4.2	1.0	698	3.1	1.3	875	3.3	0.6	233	2.5	1.0
Right lane												
Passenger Cars	638	3.3	1.0	406	3.0	1.2	610	3.0	0.6	125	2.6	1.2
Trucks	20	4.7	2.1	15	3.4	0.8	18	3.6	1.0	2	2.3	0.7
Motorcycles	12	3.4	0.3	4	2.5	1.2	11	3.0	0.3	1	0.7	-
All	670	3.4	1.0	425	3.0	1.2	639	3.1	0.6	128	2.6	1.2
Approach												

	Not considering exiting vehicles						Considering exiting vehicles					
	n_c	t_c (s)	sd_c (s)	n_f	t_f (s)	sd_f (s)	n_c	t_c (s)	sd_c (s)	n_f	t_f (s)	sd_f (s)
Passenger Cars	1508	3.8	1.1	1044	3.0	1.2	1397	3.2	0.6	339	2.6	1.0
Trucks	96	4.9	1.4	51	3.6	1.1	91	3.6	0.8	8	2.9	0.9
Motorcycles	32	3.6	0.5	27	2.1	1.4	26	3.0	0.5	13	1.4	1.1
All	1636	3.8	1.1	1123	3.0	1.2	1514	3.2	0.6	361	2.5	1.1
Approach M2												
Left lane												
Passenger Cars	332	4.2	1.2	1700	2.9	1.1	402	3.7	0.7	450	2.2	0.7
Trucks	4	7.4	1.0	23	3.1	1.0	5	3.8	0.9	6	2.6	0.6
Motorcycles	7	3.6	0.8	45	2.1	1.3	7	3.4	0.6	19	1.6	0.8
All	343	4.2	1.2	1768	2.8	1.2	414	3.7	0.7	475	2.2	0.7
Right lane												
Passenger Cars	255	3.8	1.1	2087	2.8	1.1	306	3.5	0.8	560	2.3	0.8
Trucks	10	4.8	0.9	61	3.8	1.7	9	3.8	0.5	14	2.5	0.8
Motorcycles	3	5.1	0.4	57	1.9	0.9	4	3.5	1.1	26	1.5	1.0
All	268	3.8	1.2	2206	2.8	1.1	319	3.5	0.8	600	2.2	0.8
Approach												
Passenger Cars	587	4.0	1.2	3787	2.8	1.1	708	3.6	0.8	1010	2.3	0.7
Trucks	14	4.9	0.9	84	3.6	1.5	14	3.8	0.6	20	2.5	0.7
Motorcycles	10	3.6	0.8	103	2.0	1.0	11	3.5	0.6	46	1.6	0.9
All	611	4.0	1.2	3975	2.8	1.1	733	3.6	0.8	1076	2.2	0.8

[1] *-: missing data*
[2] *-: value not applicable*

1

Comparison with Previous Studies

A number of U.S. studies have been conducted to estimate critical gaps and follow-up headways at roundabouts. Among them, NCHRP Report 572 is one of the most comprehensive studies based on 18 single-lane roundabout approaches and seven multi-lane roundabout approaches *(1)*. Also, some default critical gap and follow-up headway values are suggested in the HCM *(9)*. In 2011, Schroeder, et al and Wei, et al. presented estimates of critical gaps and follow-up headways for two congested triple-lane roundabout approaches in Michigan and three single-lane roundabout approaches in Carmel, IN, respectively *(23, 24)*. Except for the study by Schroeder, et al in Michigan, all the above findings were not solely focused on congested roundabouts. Table 3 compares the critical gaps and follow-up headways between the current study and the above studies, with particular anticipation of the current congested values being lower than general estimates. Standard deviations are given, if available, inside parentheses.

Approaches M1 and M2 (two lanes entering and circulating) had significant congestion as reflected in the number of fully queued minutes (shown in Table 1). Critical gaps observed at M1 and M2 are lower than the average critical gaps reported in NCHRP 572 report, but similar to the minimum critical gaps observed in the NCHRP 572 study. The critical gaps found in this research are lower than the critical gaps reported from the two Michigan roundabouts, possibly because the roundabouts in the Michigan study were not congested. Follow-up headways at M1 and M2 are similar to values reported in the NCHRP 572 study and slightly smaller than values reported in Michigan study.

Critical gaps at approach C2 (two lanes entering and one lane circulating) were slightly higher than the average but within the range of values reported in the NCHRP 572 study. Follow-up headways at C2 were considerably higher than the average values reported in NCHRP 572 study. The higher critical gaps and follow-up headways could be due to limited congestion as well as an upgrade of four percent on the approach to the roundabout.

Critical gap observed at C1 was higher than the average but within the range of critical gap values reported in NCHRP 572 study for a single lane approach. Also the critical gap at C1 (5.5 s) is considerably higher than the critical gaps reported in the Carmel study (3.79 and 3.39 s). Possible reasons could be higher congestion as well as better driver familiarity with roundabouts in Carmel which has over 60 roundabouts currently. The follow-up headway at C1 was same as the lower bound reported in NCHRP 572 study but higher than the values reported in Carmel study.

Table 3 COMPARISON WITH PREVIOUS FINDINGS

	Single entering lane		**Multiple entering lanes**		
Critical gap (s)					
*Current study***	*C1 (1e-2c*)*	5.5 (1.9)	*C2*	*Left*	5.0 (1.7)
			(2e-1c)*	*Right*	4.4 (0.4)
				Both	4.9 (1.5)

			M1	*Left*	4.2 (1.0)
			(2e-2c)*	*Right*	3.4 (1.0)
				Both	3.8 (1.1)
			M2	*Left*	4.2 (1.2)
			(2e-2c)*	*Right*	3.8 (1.2)
				Both	4.0 (1.2)
NCHRP 572	*Average*	5.0 (1.2)	*Left*	*Average*	4.8 (2.1)
(Method 2)	*Range*	4.2 – 5.9		*Range*	4.2 – 5.5
			Right	*Average*	4.3 (1.5)
				Range	3.4 – 4.9
			Both	*Average*	4.5 (1.7)
HCM 2010	*1e-1c**	5.19	*2e-1c**		5.19
	*1e-2c**	4.11	*2e-2c**		4.29
Carmel study	*Site A - WB*	3.79 (0.59)			
	Site B - SB	-			
	Site B - EB	3.39 (0.49)			
*Michigan study***			*Site 1*		4.58
			Site 2		5.41
			Combined		4.66
Follow-up headways (s)					
*Current study***	*C1(1e-2c*)*	2.6 (1.4)	*C2*	*Left*	4.4 (2.5)
			(2e-1c)*	*Right*	4.9 (2.7)
				Both	4.4 (2.5)
			M1	*Left*	3.1 (1.3)
			(2e-2c)*	*Right*	3.0 (1.2)
				Both	3.0 (1.2)
			M2	*Left*	2.8 (1.2)
			(2e-2c)*	*Right*	2.8 (1.1)
				Both	2.8 (1.1)
NCHRP 572	*Average*	3.4 (1.2)	*Left*	*Average*	3.1 (1.4)
(Method 2)	*Range*	2.6 – 3.7		*Range*	2.9 – 5.0
			Right	*Average*	3.0 (1.2)
				Range	2.8 – 4.4
			Both	*Average*	3.1 (1.3)
HCM 2010	*Default*	3.2	*Default*		3.2
Carmel study	*Site A - WB*	2.43 (0.63)			
	Site B - SB	2.10 (0.66)			
	Site B - EB	-			
*Michigan study***			*Site 1*		3.37 (1.36)
			Site 2		3.27 (1.40)
			Combined		3.34 (1.37)

** 1e (2e) - 1c (2c): one (or two) entering lane(s) against one (or two) circulating lane(s);*
*** : studies on congested roundabouts*
- : data not available

Differences among Vehicle Types

In HCM, for a minor stream of a two-way stop-control intersection, the critical gap and the follow-up headway are calculated in the form of a base value plus one or more adjustments *(9)*. The proportion of heavy vehicles is considered one of the adjustments for both critical gap and follow-up headway *(9)*. However, for roundabouts, the differences in critical gaps and follow-up headways among vehicle types have not been examined yet. In the current study, critical gaps and follow-up headways were estimated for three vehicle types. The comparisons between vehicle types are summarized in Table 4, where PC stands for passenger car, TK stands for truck, and MC stands for motorcycle.

For M1 and M2, a consistent decreasing trend was observed from trucks to motorcycles. When the exiting vehicles were not considered, the trucks were 0.9 – 1.1 seconds higher than passenger cars in critical gap and 0.6 – 0.8 seconds higher in follow-up headway. The passenger cars were 0.2 – 0.4 seconds higher than motorcycles in critical gap and 0.8 – 0.9 seconds higher in follow-up headway. When the exiting vehicles were considered, the differences generally reduced. The trucks were 0.2 – 0.4 seconds higher than passenger cars in critical gap and 0.2 – 0.3 seconds higher in follow-up headway. The passenger cars were 0.1 – 0.2 seconds higher than motorcycles in critical gap and 0.7 – 1.2 seconds higher in follow-up headway.

For C1 and C2, the sample sizes were relatively small and the trends from trucks to motorcycles were less consistent. However, without considering the estimates based on small samples (* values in Table 4), , the trucks still had highest critical gaps and follow-up headways than passenger cars, and the passenger cars were higher than motorcycles in follow-up headway.

TABLE 4 Comparison of Critical Gaps and Follow-up Headways among Vehicle Types

	Actual Values (s)					
	Not Considering Exiting Vehicles			Considering Exiting Vehicles		
Approach	**TK**	**PC**	**MC**	**TK**	**PC**	**MC**
Approach based critical gap (s)						
C1	6.3	5.5	4.9*	5.1	4.6	3.2*
C2	7.8*	4.8	-	6.0*	3.9	-
M1	4.9	3.8	3.6	3.6	3.2	3.0
M2	4.9	4.0	3.6	3.8	3.6	3.5
Approach based follow-up headway (s)						
C1	3.9*	2.6	1.6	1.9*	2.3	1.5
C2	5.9	4.4	4.7*	4.9*	3.7	4.7*
M1	3.6	3.0	2.1	2.9	2.6	1.4
M2	3.6	2.8	2.0	2.5	2.3	1.6

- : data not available

** : estimates based on no more than ten samples*

Effects of Considering Exiting Vehicles

Consideration of exiting vehicles changes the samples for gaps. With a new sample of gaps, the estimated critical gap is subject to change as well. By considering the influence of exiting vehicles, two successively entering vehicles that used the same circulating gap might be using different gaps. As a result, the headway between two such successively entering vehicles is no longer a follow-up headway sample. Such change in follow-up headway samples could change the average follow-up headway. Further, since critical gap and follow-up headway might change with considering exiting vehicles, so might their trends with certain factors, such as queue length. More fundamentally, the change in gaps could also affect the observation of drivers' gap acceptance behavior.

Reduction of Estimates

In the research by Mereszczak, et al., a significant average reduction of 1.0 seconds in critical gap was found at single-lane roundabouts when exiting vehicles were considered *(10)*. In the current study, effects of exiting vehicles was considered on critical gap and follow-up headway and at single-lane and multi-lane entry roundabout approaches.

Comparison results are shown in Table 2. Standard t-test was used for testing significance. For critical gaps, since log-normal distribution is assumed, a transformation to normal distribution is needed before applying t-test. All reductions were found to be significant at the 0.05 level. For single entry lane approach C1, the reduction of critical gap is 0.9 seconds, close to what Mereszczak et al. found for single-lane roundabouts *(10)*. Additionally, the follow-up headway was reduced by 0.3 seconds. For multi entry lane approaches (C2, M1, and M2), the reductions of critical gap range from 0.5 seconds to 0.9 seconds in left lanes, 0.3 seconds to 0.4 seconds in right lanes, and 0.4 seconds to 1.0 seconds in both lanes. The reductions of follow-up headway range from 0.6 seconds to 0.7 seconds in the left lanes, 0.4 seconds to 1.0 seconds in right lanes, and 0.5 seconds to 0.7 seconds in both lanes.

TABLE 5 Primary Effects of Considering the Exiting Vehicles

Approach		Not Considering Exiting Vehicles			Considering Exiting Vehicles			Reduction(s)	p	Significant Difference? α = 0.05
		Samples	Mean (s)	Std. Dev (s)	Samples	Mean (s)	Std. Dev (s)			
Critical gap										
C1		548	5.5	1.9	587	4.6	1.2	0.9	$< 10^{-67}$	Yes
C2	*Left*	239	5.0	1.7	267	3.9	1.0	1.1	$< 10^{-48}$	Yes
	Right	60	4.4	0.4	66	4.0	0.7	0.4	$< 10^{-5}$	Yes
	Both	299	4.9	1.5	333	3.9	1.0	1.0	$< 10^{-55}$	Yes
M1	*Left*	966	4.2	1.0	875	3.3	0.6	0.9	$< 10^{-191}$	Yes
	Right	670	3.4	1.0	639	3.1	0.6	0.3	$< 10^{-15}$	Yes
	Both	1636	3.8	1.1	1514	3.2	0.6	0.6	$< 10^{-145}$	Yes
M2	*Left*	343	4.2	1.2	414	3.7	0.7	0.5	$< 10^{-22}$	Yes
	Right	268	3.8	1.2	319	3.5	0.8	0.3	$< 10^{-6}$	Yes
	Both	611	4.0	1.2	733	3.6	0.8	0.4	$< 10^{-25}$	Yes
Follow-up headway										
C1		1223	2.6	1.4	828	2.3	1.0	0.3	$< 10^{-18}$	Yes
C2	*Left*	774	4.4	2.5	464	3.7	2.1	0.7	$< 10^{-6}$	Yes
	Right	123	4.9	2.7	62	3.9	2.3	1.0	$< 10^{-1}$	Yes
	Both	897	4.4	2.5	526	3.7	2.1	0.7	$< 10^{-7}$	Yes
M1	*Left*	698	3.1	1.3	233	2.5	1.0	0.6	$< 10^{-32}$	Yes
	Right	425	3.0	1.2	128	2.6	1.2	0.4	$< 10^{-10}$	Yes
	Both	1123	3.0	1.2	361	2.5	1.1	0.5	$< 10^{-39}$	Yes
M2	*Left*	1768	2.8	1.2	475	2.2	0.7	0.6	$< 10^{-71}$	Yes
	Right	2206	2.8	1.1	600	2.2	0.8	0.6	$< 10^{-102}$	Yes
	Both	3975	2.8	1.1	1076	2.2	0.8	0.6	$< 10^{-184}$	Yes

Effect of Queue Length

Previous studies have shown that longer waiting times result in shorter critical gaps *(25, 26)*. Whether or not critical gaps and follow-up headways would change with the queue length behind the vehicle is worth studying. As a result, critical gaps and follow-up headways from the four studied approaches were plotted against queue length behind the vehicle, under both scenarios of considering and not considering exiting vehicles (Figure 3). For critical gaps, the queue lengths refer to the numbers of vehicles behind the entering vehicles. For follow-up headways, the queue lengths refer to the numbers of vehicles behind the following vehicles. A minimum sample size requirement of six was chosen for estimating each data point in Figure 3. In fact, most of the sample sizes ranged from 10 to 300. Only eight data points (out of the entire 123 data points) had sample sizes below ten.

In Figure 3a, the critical gaps are randomly distributed across the range of 3 to 6 seconds, no particular trend could be found as the queue length increases. When the exiting vehicles were considered (Figure 3b), the bandwidth of critical gaps narrows between 3 and 5 seconds, and as the queue length increases, the critical gaps converge slightly better. In Figure 3c, the follow-up headway of C2 decreases dramatically as the queue length increases, while the follow-up headways of other approaches remain relatively constant within a 1-second bandwidth. When the exiting vehicles were considered (Figure 3d), the decreasing trend of S2 is alleviated, and the follow-up headways of other approaches decrease further but still remain approximately in a 1-second bandwidth, with only a slight decreasing trend. In summary, without considering exiting vehicles, no consistent trend was found for critical gap or follow-up headway as queue length changed; when exiting vehicles were considered, both critical gap and follow-up headways tended to be slightly more consistent across roundabout sites as queue length increased.

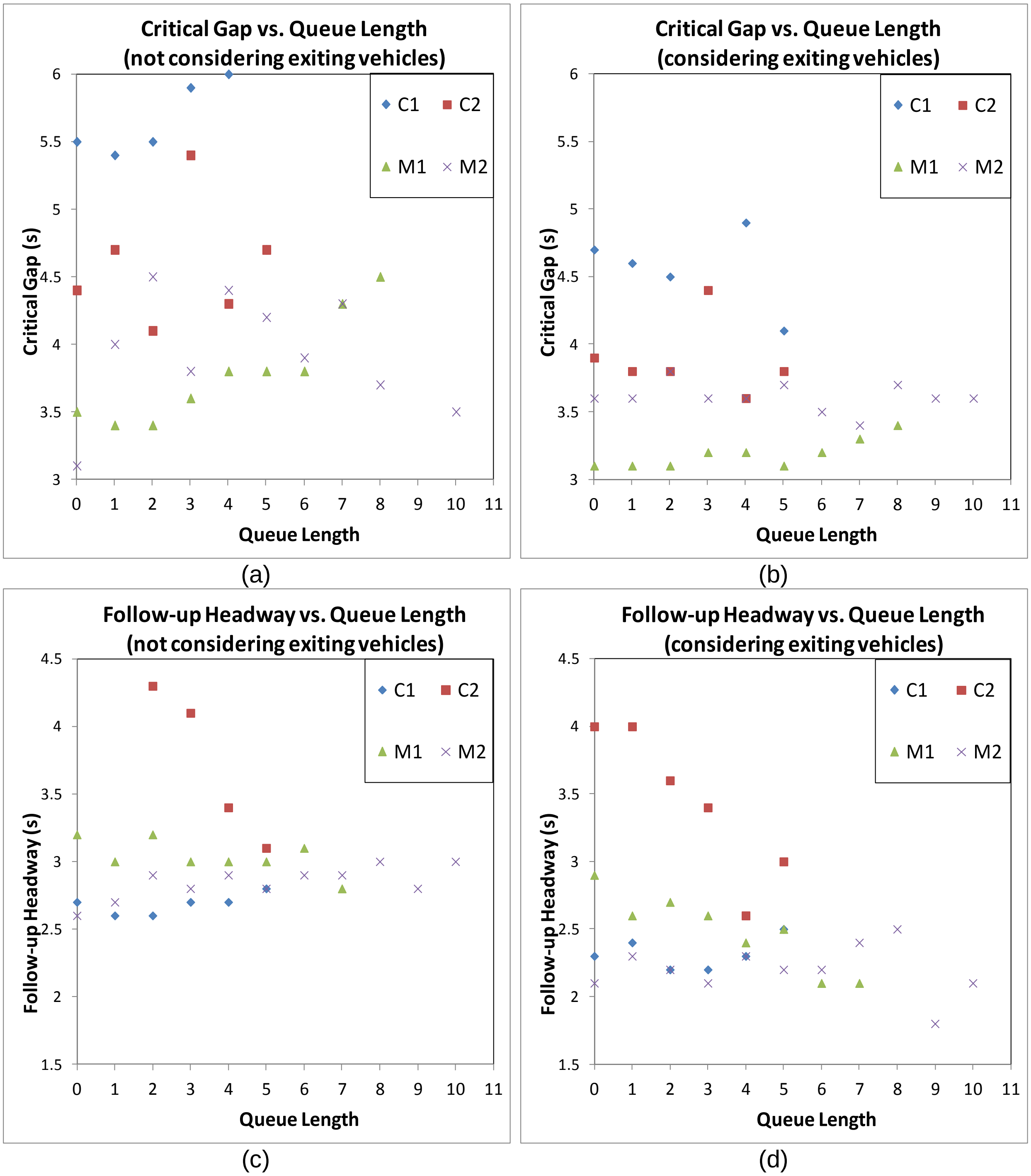


FIGURE 3 Effects of queue length: (a) critical gap vs. queue length without exiting vehicles; (b) critical gap vs. queue length with exiting vehicles; (c) follow-up headway vs. queue length without exiting vehicles; (d) follow-up headway vs. queue length with exiting vehicles.

Reducing Variability of Gap Acceptance

In the current study, when exiting vehicles were not considered, 187 drivers were observed with smaller accepted gaps compared with the largest rejected gaps, which violated the assumption of MLM and have been called "inconsistent drivers" *(22)*. Several reasons could have resulted in these observations. First, with certain factors, such as increased waiting time, drivers might tend to accept smaller gaps and become inconsistent in critical gaps *(25-27, 30)*. Second, randomness might exist when drivers evaluated gaps. Third, random errors could occur during the data collection (e.g., time stamp extraction) and lead to imprecise gap measuring. Last, without considering exiting vehicles, two or more small gaps involving exiting vehicles might be counted as a large gap but still be rejected. Thus, the below analysis aims to answer to what extent the variability of gap acceptance could be affected by including exiting vehicles.

For quantitative measurement, acceptance variation is defined as the difference between accepted gap and largest rejected gap, when the former is smaller than the later. Table 6 summarizes the statistics of acceptance variations. The cumulative distributions of acceptance variations are shown in Figure 4. The results indicate that when the exiting vehicles were considered, 1) the range of average acceptance variations dropped from 0.73 – 2.15 seconds to 0.66 – 1.20 seconds and 2) the whole cumulative distribution of acceptance variations shifted to the smaller side. However, shown by Figure 4, the reduction shift is much larger at approach C2 than at M1 and M2, while that of C1 is in between. The potential explanation is, since M1 and M2 are multi-lane approaches, gaps were measured across circulating lanes and were already small. By considering the exiting vehicles, the sample gaps had little to decrease in length; while on the other hand, C2 is multi-entry against single circulating lane, large gaps were measured within lane and could be reduced considerably when exiting vehicles were considered. C1, although has two circulating lane, only showed heavy volume in one circulating lane for most of the data collection period, thus, resulting in a reduction between C2 and multi-lane approaches.

For practical purposes, the average reduced acceptance variation of 0.92 seconds (considering exiting vehicles) is recommended as an upper bound of driver randomness. Drivers with acceptance variation smaller than 0.92 seconds could be excluded from "inconsistent drivers". Further study is needed to determine if such drivers can be included in the calculation of critical gap and how the estimate will be affected.

TABLE 6 Statistics of Acceptance Variation (in second)

	Sample Size	Maximum (s)	3rd Quartile (s)	Median (s)	1st Quartile (s)	Minimum (s)	Average (s)	Standard Deviation (s)
Not Considering Exiting Vehicles								
C1	25	5.37	2.43	1.30	0.52	0.26	1.69	1.49
C2	5	4.13	2.56	1.53	1.31	1.22	2.15	1.23
M1	127	4.31	1.18	0.60	0.23	0.01	0.73	0.64
M2	30	7.15	1.72	1.17	0.44	0.04	1.37	1.39
Considering Exiting Vehicles								
C1	73	6.43	1.33	0.84	0.28	0.03	1.08	1.12
C2	20	2.08	0.94	0.57	0.16	0.02	0.66	0.55
M1	411	4.24	1.10	0.60	0.23	0.01	0.73	0.64
M2	225	6.42	1.66	0.91	0.48	0.01	1.20	1.04

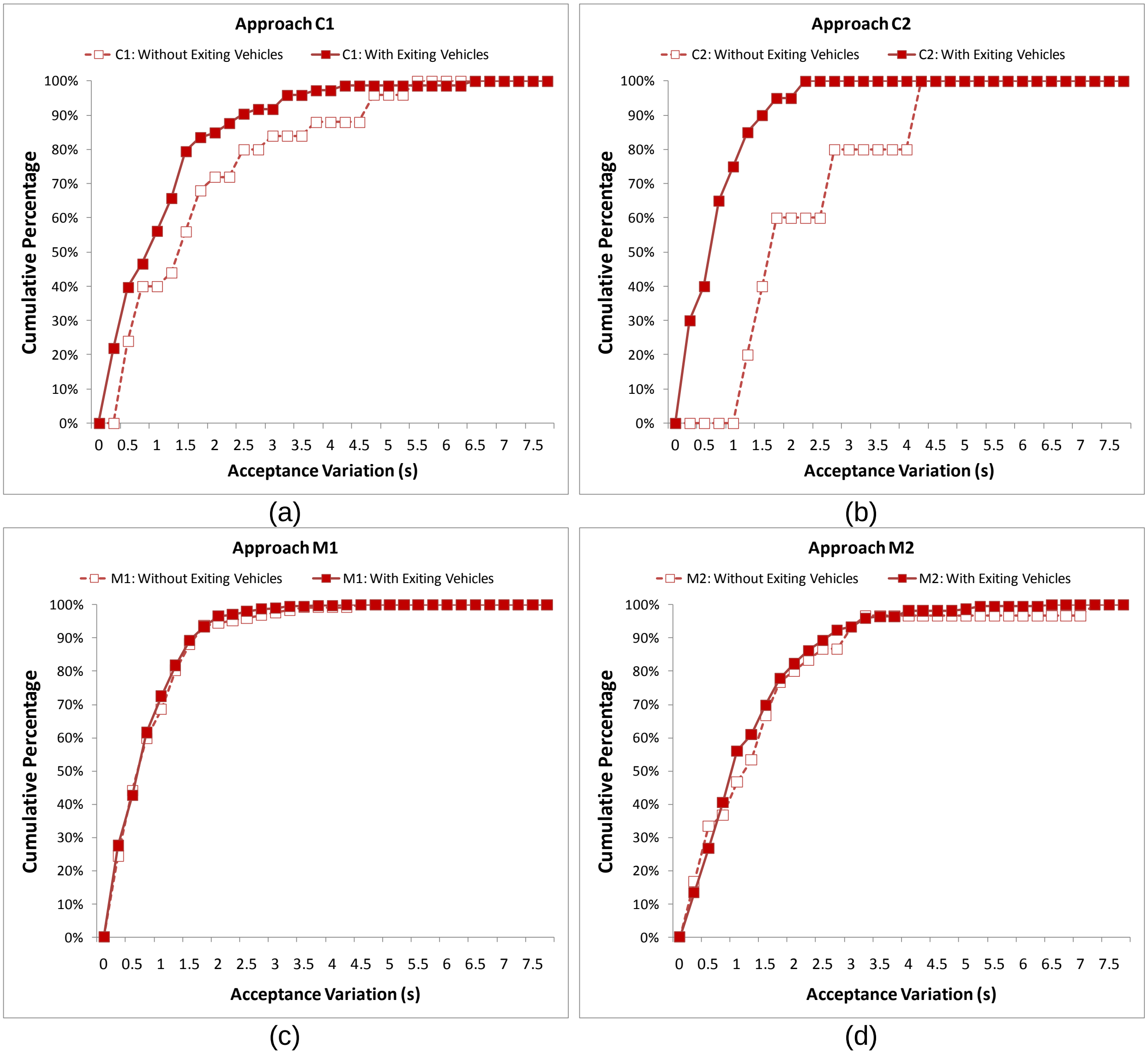


FIGURE 4 Cumulative distributions of acceptance variations: (a) approach S1; (b) approach S2; (c) approach M1; (d) approach M2.

CONCLUSIONS AND RECOMMENDATIONS

With the roundabouts being relatively new to the U.S., there is limited knowledge on the operational characteristics of congested roundabouts. Field data were collected at four approaches of three congested roundabout in Wisconsin. A roundabout was defined as congested if at least one approach had persistent queues. The objectives included investigating critical gap and follow-up headway and how vehicle type, queue length, and exiting vehicles influence those values needed for modeling capacity. In addition driver inconsistency was also studied.

Critical gaps were estimated using the maximum likelihood method assuming a log-normal distribution. The average critical gaps (for all vehicles) computed at the two approaches (M1 and M2) that were most congested, were similar to the lower bound values reported in NCHRP 572, although the standard deviations were considerably lower. Critical gaps observed at C1 and C2 were higher than the average but within the range of values reported by NCHRP

572. Follow-up headways at three approaches (C1, M1, and M2) were similar to values reported in NCHRP 572 study. Follow-up headway at C2 was considerably higher possibly due to limited congestion and presence of an upgrade of four percent on the approach.

Vehicle type was found to have considerable effect on average critical gap and follow-up headway. Similar to other intersection types, trucks had the highest values for both critical gap and follow-up headway followed by passenger cars and motorcycles. Results from two approaches with substantial trucks and motorcycles suggest that average critical gap (when exiting vehicles were not considered) of trucks was about 1.0 seconds higher than that of cars while cars were about 0.3 seconds higher than motorcycles. Average follow-up headway (without considering exiting vehicles) followed a similar trend with trucks greater than cars by 0.7 seconds and cars greater than motorcycles by 0.8 seconds. The differences in critical gaps and follow-up headways between vehicle types reduced when exiting vehicles were considered. Considering the significant difference in average critical gap and follow-up headway between vehicle types, it is strongly recommended that a weighted average of critical gaps/follow-up headways be used in capacity analysis, especially at locations with significant trucks. Data would need to be collected at more sites to validate critical gap and follow-up headway for specific vehicle types.

Considering exiting vehicles was found to reduce average critical gap and follow-up headway significantly. Data showed a decreasing trend in critical gap and follow-up headway (when exiting vehicles are considered) as the number of vehicles queued behind a vehicle increase. The average and range of difference between accepted gap and largest rejected gap for inconsistent drives reduced considerably when exiting vehicles were considered. Further analysis should examine at what level drivers can perceive differences in gaps so that useful data are not lost.

This study illustrates the effects of vehicle type, queue length, and exiting vehicles on critical gap and follow-up headway values. Since critical gap and follow-up headway are the main variables in the capacity model, care should be used in understanding what values should be used.

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