STATEWIDE ROUNDABOUT TRAFFIC OPERATIONS ANALYSIS

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ABSTRACT

The state of Wisconsin has been one of the nation's leaders in roundabout installations with over 420 in operation as of 2019. The *Highway Capacity Manual, 6th Edition* (HCM6) was published in 2016 and provided updated roundabout capacity equations. However, the field data used for this study was not from Wisconsin. Further, HCM6 lacks information for critical gap and follow-up headway for 3-lane roundabouts. Collecting and analyzing local traffic operational data from existing roundabouts can provide the state useful planning information regarding future roundabout installations. Given the rapid growth of roundabouts in Wisconsin and the variety of multilane geometric configurations (including 3-lane), there was a need to collect and analyze data specifically from the state to determine if statewide field data concurred with the national publication. New drone technology and advanced vehicle tracking software enabled a total of 37 roundabout approaches at 17 roundabouts to be analyzed for critical gap, follow-up headway, and lane-utilization parameters. In total, this study analyzed critical gap and follow-up headway values for 14 different entry lane/circulating lane scenarios, including 6 scenarios for three lane entries. The objective of the roundabout operations study was to evaluate the critical gaps and follow-up headways observed at roundabouts throughout the state of Wisconsin and compare the results to capacity equations in the HCM6 and the Wisconsin Facilities Development Manual (WI FDM) and to other studies discussed in the literature review.

The study substantially expanded the knowledge base for critical gap and follow-up headways by analyzing various approach lane configurations ranging from a single lane entry with a single circulating lane to a 3-lane entry with dual circulating lanes. Critical gaps and follow-up headways were determined based on observed field data and volume counts at each analyzed roundabout approach. Results of this study show that the majority of the critical gaps and follow-up headways observed were within the data ranges presented in Federal Highway Administration's (FHWA) *Assessment of Roundabout Capacity Models for the Highway Capacity Model* (FHWA-SA-15-070), which is the basis for the HCM6 capacity equations. However, this study determined critical gap and follow-up headways for geometric configurations not published in the WI FDM or the HCM6, such as for 3-lane entry roundabouts.

Critical gaps were determined using two different methodologies (Method 2 and Method 3) based on the Maximum Likelihood Technique which estimates the critical gap based on rejected and accepted gap data. Method 2 only requires a rejected gap whereas Method 3 also requires queued conditions on the approach lane being analyzed. Some Method 2 critical gap estimates were greater than Method 3 estimates and others less than Method 3 estimates. This same phenomenon was reported in the National Cooperative Highway Research Program (NCHRP) Report 572.

Drivers waiting to enter a roundabout may be impacted by exiting vehicles until it is clear that the circulating driver has chosen to exit rather than continue in the circulating lane. Thus, scenarios were analyzed where exiting adjacent vehicles were taken into consideration in the critical gap and follow-up headway estimates. Consideration of exiting vehicles was found to decrease critical gaps and

follow-up headways for all roundabout configurations analyzed. This result was also seen in the University of Wisconsin-Madison Traffic Operations and Safety Laboratory (TOPS Lab) study completed in 2011.

Lastly, the lane utilization of the roundabout approaches in this study was evaluated. However, there was not conclusive evidence of universal lane utilization trends. The lane utilization at roundabout approaches appears to be primarily impacted by local conditions and travel patterns, not the geometry of the roundabout.

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CHAPTER 1: INTRODUCTION

The first modern roundabout was constructed in the United States in 1991 and their number has increased at a fast pace ever since (1). A roundabout is a type of circular intersection, but unlike traffic circles or large rotaries, they have entry yield control. Because roundabouts are still relatively new to the United States, their efficiency is everchanging as drivers learn how to traverse them more effectively. Due to this, traffic professionals' understanding of capacity at roundabouts has changed through the years. The state of Wisconsin has been one of the nation's leaders in roundabout installations. As of 2019, Wisconsin had 420 roundabouts in operation (2). Because roundabouts are more common in Wisconsin than many other states, Wisconsin drivers may be more accustomed to driving them than the average United States driver. Collecting and analyzing traffic operational data from existing roundabouts can provide the state useful planning information regarding future roundabout installations.

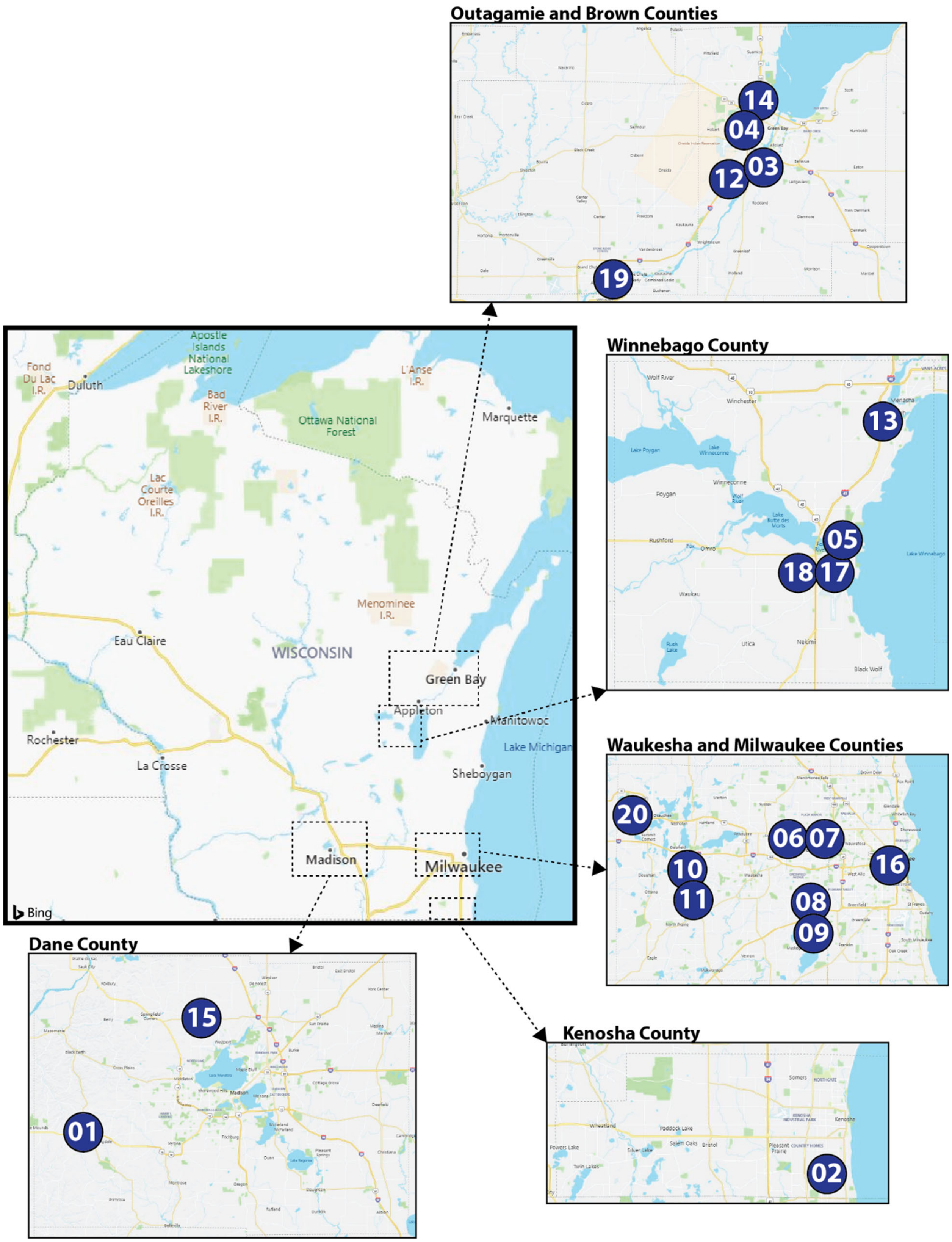
1.1 STUDY OBJECTIVE

The objective of the roundabout operations study is to evaluate the critical gaps and follow-up headways observed at roundabouts throughout the state of Wisconsin and compare them to the results of previous studies, guidance in the Wisconsin Facilities Development Manual (FDM) and in the *Highway Capacity Manual, 6th Edition* (HCM6). Critical gap and follow-up headway are integral in estimating roundabout capacity. If the results of this analysis show that critical gaps and follow-up headways vary from the ranges seen in previous studies, there may be a need to adjust/calibrate parameters used for roundabout capacity estimation in Wisconsin. In addition to evaluating critical gaps and follow-up headways, this study also observed lane utilization in multilane roundabouts to identify if any trends were present.

1.2 RESEARCH SCOPE

A previous capacity study of Wisconsin roundabouts in 2011 evaluated parameters at five roundabout approaches and the HCM6 lacks information on critical gap and follow-up headway information for 3-lane roundabouts. Given the rapid growth of roundabouts in Wisconsin and the wide variety of multilane geometric configurations (including 3-lane), there was a need to collect and analyze data from a larger sample. New drone technology and advanced vehicle tracking software enabled a goal of collecting data at 30 roundabout approaches throughout the state of Wisconsin. Ultimately, efficiencies in the aerial video footage and analysis processes enabled a total of 37 roundabout approaches at 17 roundabouts to be analyzed for critical gap, follow-up headway, and lane-utilization parameters. The sites are shown graphically in Figure 1 following this chapter and names and locations are shown in Table 1 in Chapter 4.

Figure 1. Map of Analyzed Roundabouts.



CHAPTER 2: LITERATURE REVIEW

An extensive literature review was performed to summarize the methods used to estimate critical gap and follow-up headway used in past roundabout capacity studies. Both parameters are key components of roundabout capacity analysis.

A critical gap (sometimes referred to as critical headway in literature, but herein referred to as critical gap), represents the minimum gap, typically measured in time, that an entering driver would utilize to enter the roundabout (3).

Follow-up headway (sometimes referred to as follow-up time in literature, but herein referred to as follow-up headway), represents the difference in time between two successive vehicles entering the roundabout using the same gap, under saturated conditions (3). Saturated conditions for an approach occur when queuing is present in the analyzed approach lane and a continuous discharge of vehicles occurs in an available gap.

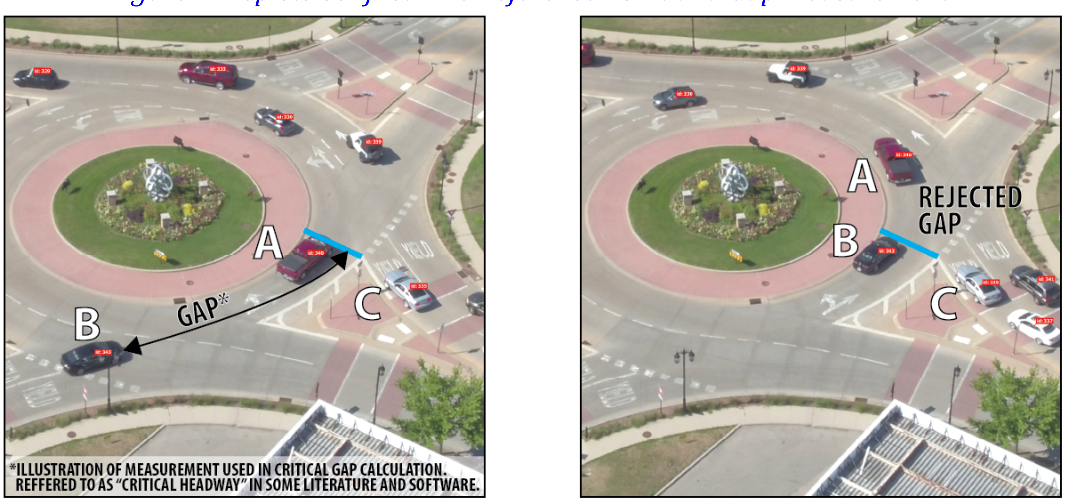
2.1 GAP AND LAG AT ROUNDABOUTS

Gaps and lags are important concepts in critical gap analysis, so their definitions are clarified in the following sections.

2.1.1 Gap Definition

Per the *Highway Capacity Manual, 6th Edition* (HCM6), a gap is the time between two successive circulating vehicles as they pass the same reference point in the roundabout, measured from the same common feature of both vehicles, such as the front bumper (3). For gap analysis, the point chosen as the reference point is the point where circulating vehicles would intersect the entering vehicle's path, commonly referred to as the conflicting line. Figure 2 depicts the location of the conflicting line reference point (blue line) and an example gap between circulating vehicles A & B.

Figure 2. Depicts Conflict Line Reference Point and Gap Measurement.



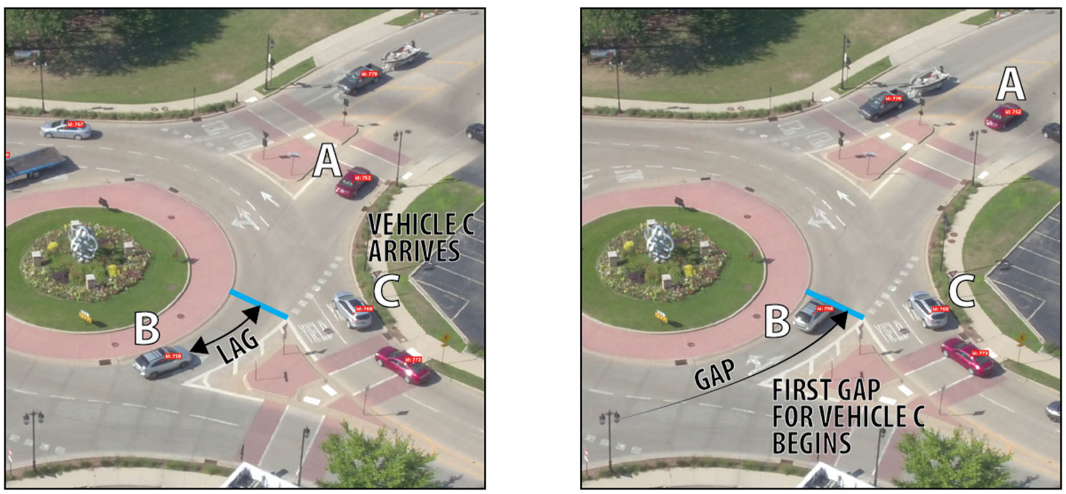
In the case illustrated in Figure 2, vehicle C rejected the gap between vehicles A and B because vehicle C did not enter the roundabout during the gap. If vehicle C would have entered the gap, the length of time between vehicles A and B crossing the conflicting line would have been vehicles C's accepted gap.

2.1.2 Lag Definition

When an entering vehicle arrives at the yield bar, the time from their arrival to the first conflicting vehicle is known as a lag (4). It is important to understand the concept of a lag because drivers that accept lags are excluded from critical gap analysis.

In Figure 3, vehicle C arrived at the yield line after vehicle A crossed the conflicting line, but before vehicle B crosses the conflicting line, so the length of time between vehicle C's arrival and when vehicle B crosses the conflicting line is the lag. If a vehicle enters during this time, the driver did not observe any gaps and entered on a lag and is not used in critical gap analysis.

Figure 3. Depicts Lag Measurement.



2.2 Estimating Critical Gap at Roundabouts

The critical gap is the minimum gap in the conflicting circulating traffic stream that will allow the entry of a vehicle waiting at the roundabout entry approach (3-5, 7). A driver's critical gap cannot be measured directly, since only a driver's accepted and rejected gaps can be measured. However, in theory, a driver's critical gap is less than or equal to their accepted gap and greater than their rejected gaps. This theory assumes that drivers' behaviors are always consistent and rational. The current state-of-practice to estimate critical gap using these assumptions is the Maximum Likelihood Technique. The Maximum Likelihood Technique was used in the previous studies of critical gap discussed later in Section 2.4.

2.3 Estimating Follow-Up Headway at Roundabouts

Per the HCM6, follow-up headway is the time between the departure of one vehicle from the roundabout entry point and the departure of the next vehicle using the same entry point, under queueing conditions (3). Unlike estimating critical headway, the follow-up headway for entering vehicles can be directly measured in the field. Taking a weighted average of all follow-up headway measurements for a particular entry lane/circulating lane combination will provide a follow-up headway value for that specific approach lane type (7).

2.4 Previous Critical Gap and Follow-Up Headway Studies at Roundabouts

2.4.1 NCHRP 572

The National Cooperative Highway Research Program (NCHRP) Report 572 was published in 2007 and was the basis for HCM2010 roundabout capacity analysis (4). For critical headway estimation, NCHRP Report 572 used the Maximum Likelihood Technique. Three methodologies were tested:

1. Inclusion of all observations or gap acceptance, including lags;
2. Inclusion of only observations that contain a rejected gap; and
3. Inclusion of only observations where queuing was observed on entry approach and the driver rejected a gap.

In Method 1, lags are considered a rejected gap with a time of zero seconds. This assumption introduces more rejected gaps into the analysis and does not appear as accurate as Methods 2 or 3 for critical gap estimation.

Method 2 includes all observations of rejected gaps while excluding all lag periods from the analysis. Method 2 was the recommended methodology of the study for both single lane and multi-lane approaches.

It was anticipated that Method 3, which only included observations of rejected gaps when queuing conditions were present, would result in lower critical gaps than Method 2. This anticipated result stemmed from the expectation that queued vehicles would more urgently accept gaps. The results however, produced similar results to Method 2, with some critical gaps greater than Method 2 and others less than Method 2. Queued conditions at roundabouts, in NCHRP Report 572, did not conclusively reduce or increase critical gap measurements.

As for follow-up headways, they were estimated by timestamping the entry times of two consecutive vehicles using the same gap or lag. The effects of adjacent exiting vehicles, which can impact a driver's behavior, were not considered in follow-up headway estimates in the NCHRP Report 572.

2.4.2 Wisconsin TOPS Lab Study

The Wisconsin Traffic Operations and Safety Laboratory (TOPS Lab) published a Wisconsin-specific roundabout study in 2011 in accordance with NCHRP Report 572 methodology for its base analysis (5). Specifically, for critical gap estimates in its base analysis, the TOPS Lab study utilized the Maximum Likelihood Technique Method 2 from NCHRP Report 572. The findings of the TOPS Lab study's base analysis showed critical gap and follow-up headway estimates within the data ranges reported by NCHRP Report 572.

In addition to the base analysis, the TOPS Lab study also estimated critical gaps and follow-up headways with the following additional factors considered:

1. Effects of adjacent exiting vehicles;
2. Effects of entering vehicle type; and
3. Effects of queue length on approach lane.

The TOPS Lab study incorporated adjacent exiting vehicles into its critical gap estimates following methodology introduced by Mereszczak et al. (6) and showed that critical gaps and follow-up headways decrease when adjacent exiting vehicles are taken into consideration. The TOPS Lab study mentioned one reason for the reduction in critical gaps is that some of the original gaps will turn into two smaller gaps due to the intervening exiting vehicles. With smaller accepted and rejected gaps, the Maximum Likelihood Technique will estimate a lower critical gap value. As for the decreases observed in follow-up headways, some of the original follow-up headways no longer satisfied the condition of entering the roundabout during the same gap and were excluded. The excluded follow-up headways were typically larger due to the intervening exiting vehicles, so the average of the remaining follow-up headways decreased.

The TOPS Lab study also showed that trucks are expected to have longer critical gaps and follow-up headways than passenger cars and motorcycles. However, although trucks are expected to have longer critical gaps and follow-up headways, their impact on the capacity of roundabouts during peak periods is expected to be minimal, primarily due to low truck percentages expected during these periods. This is seen in the TOPS Lab study results since critical gap and follow-up headway estimates for the full entering sample at all analyzed approaches were all equal to or within 0.1 seconds of the passenger car-only estimates.

The TOPS Lab study found that queue length showed minimal effects on critical gaps and follow-up headways. In the study, queues were categorized into three categories: zero queue, 1 to 4 vehicle queue, and queues 5 vehicles or longer. Differences in critical gaps results for the "zero queue" and "1 to 4 vehicle queue" categories were no larger than 0.1 seconds. Critical gap results for the "5 vehicle or longer" category showed inconclusive trends. Overall, follow-up headway results showed a difference ranging between 0.0 and 0.3 seconds among the three queue length categories.

2.4.3 FHWA-SA-15-070

The Federal Highway Administration's (FHWA) *Assessment of Roundabout Capacity Models for the Highway Capacity Model* (FHWA-SA-15-070), published in 2015, was used as the basis for HCM6 roundabout capacity analysis and is the most recent comprehensive roundabout study to date (7).

For critical gap estimation, FHWA-SA-15-070 used the Maximum Likelihood Technique and Method 3 of NCHRP Report 572, which only evaluated observations that contained a rejected gap and were reduced during periods of known or estimated queuing. Multilane roundabouts were analyzed under the assumption that all conflicting vehicles will influence an entering driver's behavior, so the volumes in all circulating lanes were combined into a single conflicting stream. This is true in some cases but can lead to a more conservative estimate assuming it applies to all entering vehicles.

For follow-up headway estimation, FHWA-SA-15-070 excluded the effects of adjacent exiting vehicles. This was done by only including consecutive entering vehicle events where there were no intervening conflicting circulating vehicles or intervening adjacent exiting vehicles. FHWA-SA-15-070 states that the "resulting follow-up headway measurement is therefore a pure measurement of two consecutive entering vehicles with no intervening real or perceived conflicts."

2.4.4 Highway Capacity Manual 6th Edition

The HCM6 used FHWA-SA-15-070 as the basis for its roundabout capacity models (3). In Chapter 22 of the manual, the HCM6 provides capacity models for the following entry lane/circulating lane scenarios:

- One-lane entries conflicted by one circulating lane;
- Two-lane entries conflicted by one circulating lane;
- One-lane entry conflicted by two circulating lanes;
- Right lane of two-lane entries conflicted by two circulating lanes;
- Left lane of two-lane entries conflicted by two circulating lanes;
- Right lane yielding bypass lane conflicted by one exiting lane; and
- Right lane yielding bypass lane conflicted by two exiting lanes.

The HCM6 recommends local calibration as differences in driver behavior and geometric factors can contribute to variations from the provided capacity models. For calibration, the HCM6 presents the Siegloch model, which is a generalized capacity model shown in Figure 4 below:

Figure 4. Siegloch Capacity Model.

$$c_{pce} = Ae^{(-B*v_c)} \qquad A = \frac{3600}{t_f} \qquad B = \frac{t_c - (t_f/2)}{3600}$$

where

c_{pce} = lane capacity, adjusted for heavy vehicles (pc/hr);
v_c = conflicting flow (pc/hr);
t_f = follow-up headway (s); and
t_c = critical gap (s).

With the Siegloch model, the capacity model can be calibrated to local conditions by using the critical gap (t_c) and the follow-up headway (t_f) parameters of locally observed operations.

CHAPTER 3: STUDY DESIGN

The following chapter summarizes the study design for this project and how it compares to the previous studies mentioned in Chapter 2.

3.1 CRITICAL GAP AND FOLLOW-UP HEADWAY STUDY

The goal of the critical gap and follow-up headway study was to estimate the critical gap values and follow-up headway values at Wisconsin roundabouts and compare them to the values estimated in the aforementioned studies and manuals for each entry lane/circulating lane scenario. The HCM6 provides capacity models for the following entry lane/circulating lane scenarios (3):

- One-lane entries conflicted by one circulating lane (1-1);
- Two-lane entries conflicted by one circulating lane (2-1);
- One-lane entry conflicted by two circulating lanes (1-2);
- Right lane of two-lane entries conflicted by two circulating lanes (R2-2);
- Left lane of two-lane entries conflicted by two circulating lanes (L2-2);
- Right lane yielding bypass lane conflicted by one exiting lane (R-bypass-1); and
- Right lane yielding bypass lane conflicted by two exiting lanes (R-bypass-2).

This study further categorized the two-lane entries conflicted by one circulating lane by estimating values for both the right (R2-1) and left (L2-1) entry lanes separately.

Additionally, this study estimated critical gap and follow-up headway for the following three lane entries roundabout types:

- Right lane of three-lane entries conflicted by one circulating lane (R3-1);
- Center lane of three-lane entries conflicted by one circulating lane (C3-1);
- Left lane of three-lane entries conflicted by one circulating lane (L3-1);
- Right lane of three-lane entries conflicted by two circulating lanes (R3-2);
- Center lane of three-lane entries conflicted by two circulating lanes (C3-2); and
- Left lane of three-lane entries conflicted by two circulating lanes (L3-2).

Figures 5-12 on the following page depict examples of each of the fourteen roundabout configurations analyzed in this study.

Figure 5. Example One-Lane Entry Conflicted by One Circulating Lane (1-1).

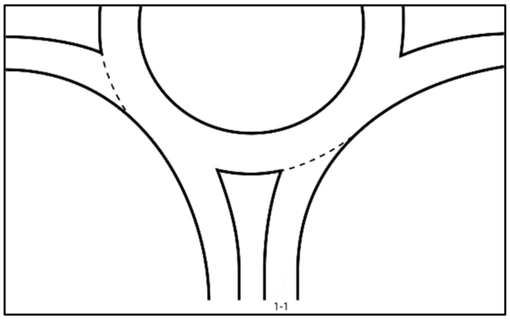


Figure 6. Example One-Lane Entry Conflicted by Two Circulating Lanes (1-2).

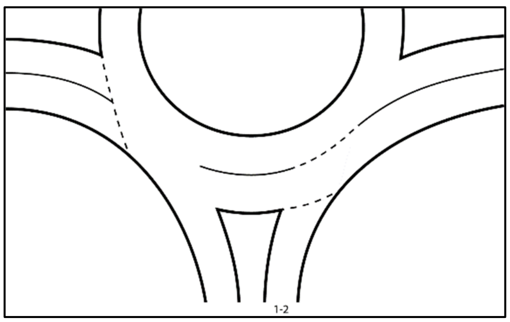


Figure 7. Example Two-Lane Entry Conflicted by One Circulating Lane (L2-1/R2-1).

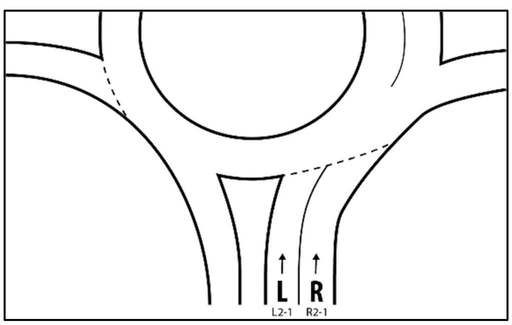


Figure 8. Example Two-Lane Entry Conflicted by Two Circulating Lanes (L2-2/R2-2).

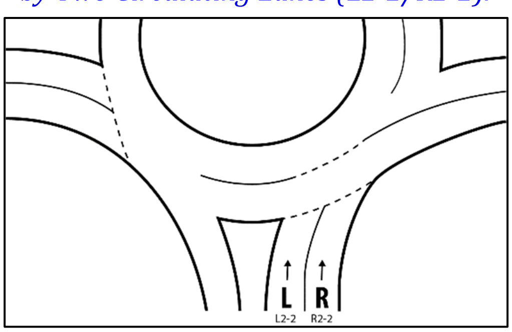


Figure 9. Example Three-Lane Entry Conflicted by One Circulating Lane (L3-1/C3-1/R3-1).

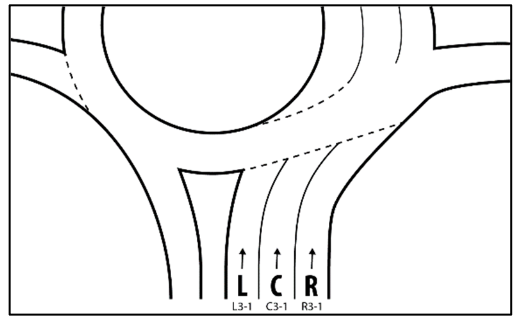


Figure 10. Example Three-Lane Entry Conflicted by Two Circulating Lanes (L3-2/C3-2/R3-2).

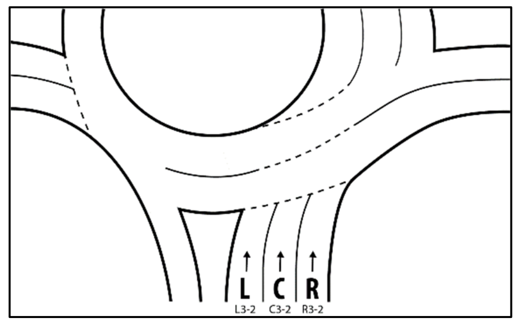


Figure 11. Example Right Yielding Bypass Lane Conflicted by One Exiting Lane (R-bypass-1).

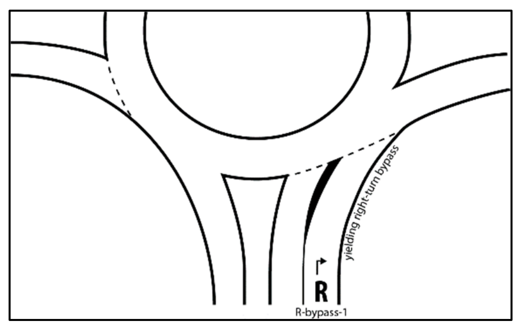
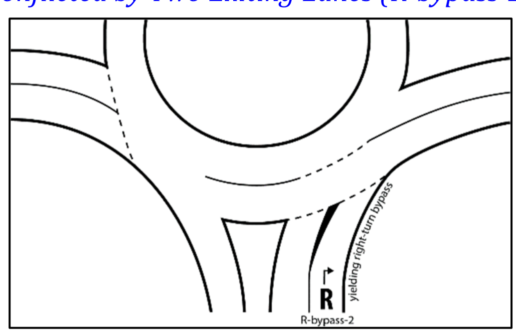


Figure 12. Example Right Yielding Bypass Lane Conflicted by Two Exiting Lanes (R-bypass-2)

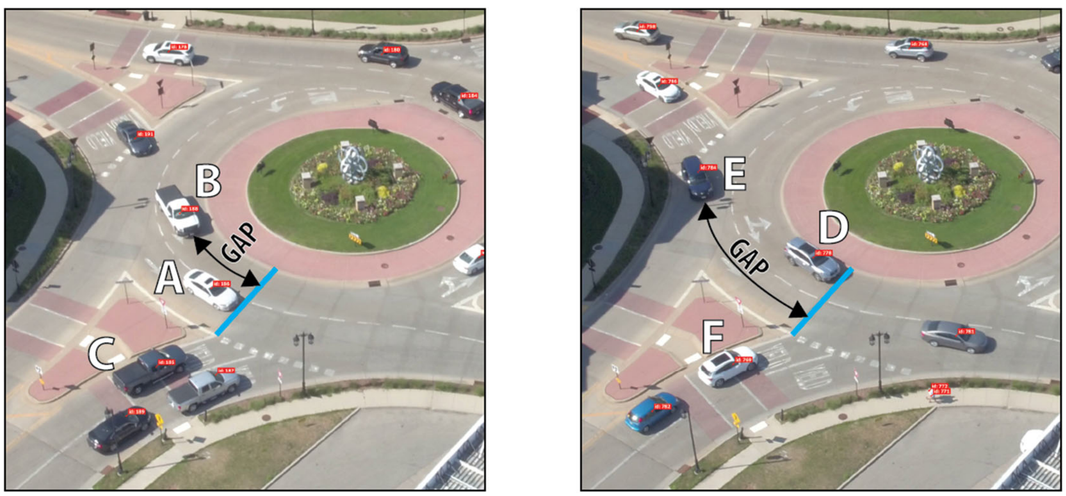


3.2 MEASURING GAPS AT ROUNDABOUTS

A gap is the space or time between two successive circulating vehicles as they pass the conflicting line (3). Measuring gaps and lags at approaches with a single circulating lane is straightforward since the successive circulating vehicles are always in the same lane. Figures 2 & 3 in Chapter 2 depict examples of an approach with a single circulating lane and shows where to timestamp the circulating vehicles to enable the measurement of time between two successive vehicles.

At multilane roundabouts, however, the idea of successive circulating vehicles isn't as clear due to multiple circulating lanes. It is assumed that all conflicting circulating vehicles, whether the driver is entering from the left or right approach lane, have an influence on the entering driver's behavior. Therefore, this study combined the circulating volumes into a single conflicting stream and treated left-lane and right-lane entering vehicles identically. Figure 13 below depicts two combined gap cases where circulating vehicles A & B and vehicles D & E are in different circulating lanes but the time between them crossing the conflicting line is considered a gap in this study.

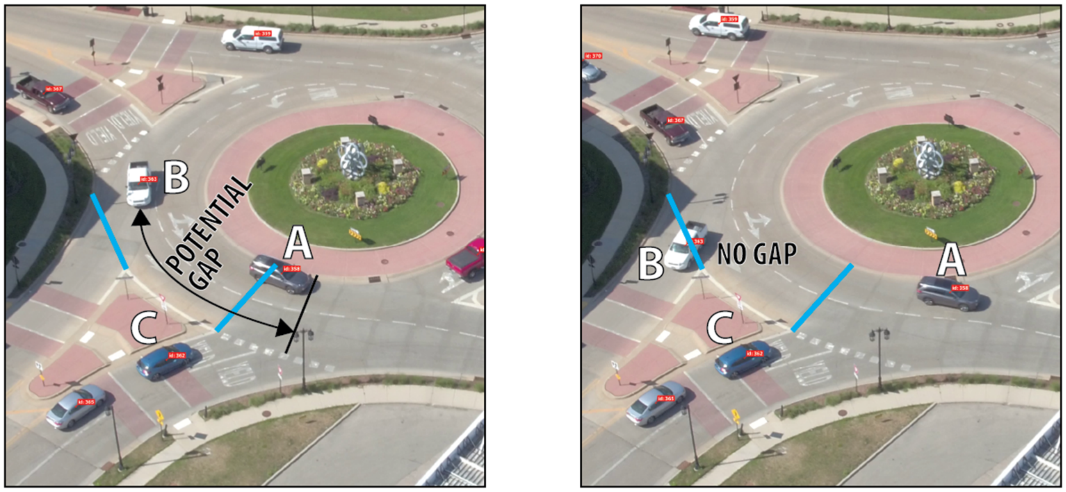
Figure 13. Depicts Combined Gaps in Multilane Roundabouts.



3.2.1 Consideration of Exiting Vehicles

Previous studies have shown that drivers waiting at the yield bar were affected by adjacent exiting vehicles since the driver might be unsure if the circulating vehicle will continue circulating or exit (5, 6). Figure 14 depicts the "potential gap" that entering vehicle C faces when the driver is unsure whether circulating vehicle B is going to exit or continue circulating the roundabout.

Figure 14. Depicts Potential Gap Created by Exiting Vehicle.



In year 2005, Mereszczak et al. conducted a study that investigated the exiting vehicle effect by assuming that the drivers entering the roundabout would be impacted by vehicles that exited the roundabout instead of continuing on the circulatory path across the conflicting line (6). Based on this assumption, Mereszczak et al. introduced "equivalent travel time", which allowed incorporating exiting vehicles into the gap definition. The equivalent travel time is defined as the time that an exiting vehicle would have taken to drive to the conflicting line from the point this vehicle exited, depicted in Figure 15.

Figure 15. Depicts Equivalent Travel Time.

After defining the equivalent travel time, an equation to calculate gap/lag was introduced by Mereszczak et al. (6). The TOPS Lab study (5) simplified the equation and provided concise variable descriptions shown in Figure 16.

Figure 16. Gap Equation with Equivalent Travel Time.

$$t = T_2 - T_1 + \Delta t$$

where

- t = gap or lag (s);
- T_1 = leading vehicle timestamp (s); when T_1 is the timestamp of a conflicting vehicle or an exiting vehicle, t is a gap; when T_1 is the timestamp of an arriving vehicle, t is a lag;
- T_2 = following vehicle timestamp; can be conflicting vehicle or exiting vehicle; and
- Δt = adjustment time; $\Delta t = 0$ when T_2 is an conflicting event; Δt = equivalent travel time when T_2 is an exiting event.

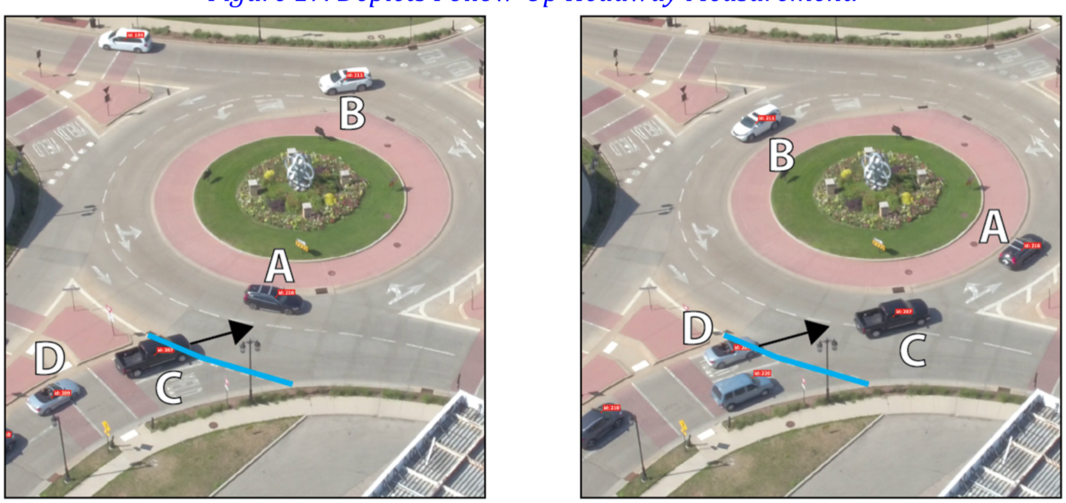
3.2.2 Consideration of Queued Conditions

The NCHRP Report 572 and the TOPS Lab study estimated critical gap using Method 2 of the Maximum Likelihood Technique outlined in the NCHRP Report 572 (4, 5), while FHWA-SA-15-070 estimated critical gap using Method 3 (7). The difference between Methods 2 & 3 is that Method 3 only included observations where queuing was observed on entry approach during vehicle entry and the entering driver rejected a gap, whereas Method 2 only required drivers to reject a gap regardless of queuing conditions (4). In this study, both Method 2 and Method 3 were used to estimate critical gap, which enabled further analysis into the effects of queued conditions on critical gaps.

3.3 Measuring Follow-Up Headway at Roundabouts

Follow-up headway is the time between the departure of one vehicle from the roundabout entry point and the departure of the next vehicle using the same entry point (3). Therefore, follow-up headways were measured for each entry lane separately. Figure 17 depicts an example of a follow-up headway measurement. Vehicle C enters the roundabout followed by vehicle D during the same gap between vehicles A & B.

Figure 17. Depicts Follow-Up Headway Measurement.



3.3.1 Consideration of Exiting Vehicles

The NCHRP Report 572 estimated follow-up headway without consideration of adjacent exiting vehicles whereas the FHWA-SA-15-070 study considered the effects of adjacent exiting vehicles by only including consecutive entering vehicle events where there were no intervening adjacent exiting vehicles (4, 7). The TOPS Lab study reported follow-up headway estimates using both methods (5). This study also estimated follow-up headway values using both methods: with and without considering adjacent exiting vehicles.

3.4 LANE UTILIZATION

This study also presents information collected on lane utilization for the analyzed multilane approaches. The analysis software enabled volume counts on each of the studied approaches. The volume counts were separated by lane and analyzed for trends to see if drivers were favoring a certain lane or lane(s) of multilane roundabout approaches.

CHAPTER 4: DATA CHARACTERISTICS

The following chapter summarizes the roundabout selection process, data collection process, and data reduction process.

4.1 SITE SELECTION

The objective of the roundabout operations study is to evaluate the critical gaps and follow-up headways observed at roundabouts throughout the state of Wisconsin and compare the results to capacity equations in the HCM6 and the Wisconsin Facilities Development Manual (WI FDM) and to the previously mentioned field studies. Lane utilization information was also evaluated at the analyzed multilane approaches. The study was scoped to analyze a maximum of 30 approaches at a maximum of 20 roundabouts. Ultimately, efficiencies in the aerial video footage and analysis processes enabled a total of 37 roundabout approaches at 17 roundabouts to be analyzed. Certain critical gap and follow-up headway calculations require consistent congestion (i.e., a constant queue) to be calculated properly, thus it was important for the study to identify sites that were likely to observe congestion.

TADI used a screening methodology to identify the sites for inclusion in this study. A component of the screening criteria involved evaluating traffic congestion on Google Maps™ during peak weekday periods via the "Typical Traffic" feature to identify sites in which congestion was anticipated. WisDOT provided TADI with a database of 350 roundabout sites in the state of Wisconsin to be considered for analysis at the onset of the study. All 350 of these selected sites were monitored on Google Maps™ and the following screening methodology was applied.

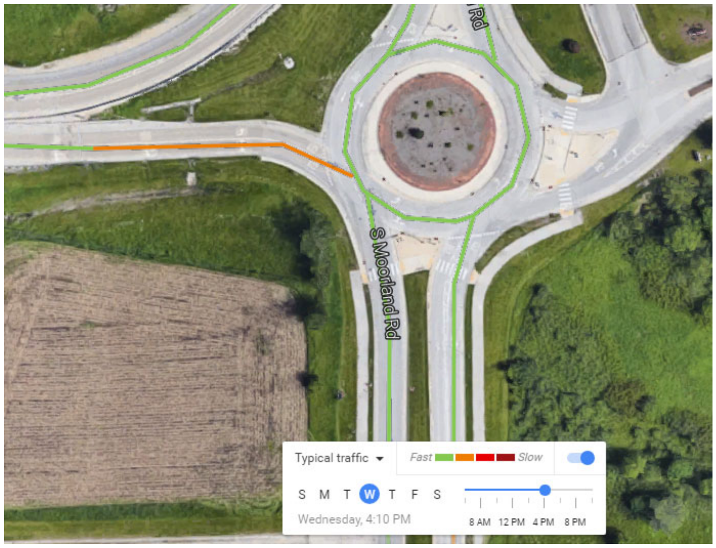
Step 1:
The four roundabouts evaluated in the original study by the TOPS Lab for critical gap and follow-up headway were identified for inclusion in this study.

Step 2:
Roundabouts with consistent orange level congestion or worse on at least one approach for at least one hour, according to Google Maps™ Typical Traffic on a Wednesday were identified. This evaluation was performed on Monday, April 17th, 2017 and Tuesday, April 18th, 2017. Thirty-one roundabouts met Step 2 criteria and adding the four roundabouts from Step 1 provided a total of 35 roundabouts. Figure 18 shows an example of "orange" level of congestion on west leg. The color scales are based on speed of traffic and "green" represents no traffic delays, "orange" represents a medium amount of traffic, and "red" represents traffic delays – the darker the red, the slower the speed of traffic on the road.

Step 3:
Roundabouts that appeared particularly sensitive to school related congestion were removed from the database because data collection was expected to occur in summer months. There were six

roundabouts located in close proximity to a school that were removed. There were 29 roundabouts remaining after Step 3.

Figure 18. Example of Google Maps™ "Orange" Level Congestion.



Step 4:

Lastly, roundabouts that had only one approach that experienced congestion levels that met Step 2's criteria were removed in favor of using roundabouts that had multiple approaches with congestion. Nine roundabouts were removed in Step 4, leaving 20 roundabouts.

The following list of 20 roundabouts, shown in Table 1, were shared with WisDOT and approved for use in the study.

Table 1. Approved Roundabouts.

Site #	Municipality	Intersection
01	Mt. Horeb, WI	STH 78 & STH 92/CTH ID
02	Pleasant Prairie, WI	STH 165 & CTH EZ
03	De Pere, WI	STH 32 & STH 57
04	Green Bay, WI	STH 54/32 & Taylor Street
05	Oshkosh, WI	USH 45 & USH 45/STH 76
06	Brookfield, WI	CTH Y & CTH M
07	Brookfield, WI	CTH M & Brookfield Road
08	New Berlin, WI	IH 43 SB Ramps & CTH O/Moorland Road
09	New Berlin, WI	IH 43 NB Off Ramp & CTH O/Moorland Road
10	Wales, WI	USH 18 & STH 83
11	Genesee, WI	STH 83 & CTH E/DE
12	De Pere, WI	CTH F & Lawrence Drive
13	Neenah, WI	STH 114 & Green Bay Road
14	Howard/Green Bay, WI	STH 29 & Taylor Street
15	Waunakee, WI	STH 19 & STH 113/CTH Q
16	Milwaukee, WI	Canal Street & 25th Street
17	Oshkosh, WI	CTH E/Witzel Avenue & Koeller Street
18	Oshkosh, WI	CTH E/Witzel Avenue & Washburn Street
19	Appleton, WI	College Avenue & Walter Avenue/John Street
20	Oconomowoc, WI	STH 16 & Walnut Street

4.2 Data Collection & Reduction

The data collection and reduction process consisted of recording video at each roundabout from aerial observation, using DataFromSky vehicle tracking software to extract gap and follow-up headway data, reducing the gap data for the Maximum Likelihood Technique, and running analysis to estimate critical gaps and follow-up headways.

4.2.1 Aerial Observation

A drone was used to capture video at all 20 selected roundabouts from approximately 3:00 PM to 6:00 PM, which is when the greatest opportunity for congestion typically occurred. Aerial video recording was selected for this project because software advancements enabled the determination of critical gap, follow-up headway, and lane utilization. Figure 19 below shows an example screenshot from the drone recording at the State Trunk Highway (STH) 16 and Walnut Street (Site #20) roundabout in Oconomowoc, WI.

Figure 19. Example Drone Video Screenshot (Oconomowoc, WI).

4.2.2 DataFromSky Trajectory Processing

DataFromSky is a "cloud-based video analytic platform for deep and fully automated traffic analysis from videos taken by drones or standard cameras" (8). The output from each processed video is an external file containing trajectories, with each trajectory containing detailed information about each object (vehicle, bicycle, pedestrian) in the video. Using the DataFromSky Viewer software, the trajectories can be analyzed and provide data on volume, speed, acceleration/deceleration, headways, gap time, origin/destination, and many more (9).

For this study, the drone video for each roundabout was reviewed to note periods when queueing was present on any of the approaches and only those periods were sent to DataFromSky for processing. In reviewing the video footage, it was determined 18 of the 20 sites were suitable for analysis. Two of the sites, #02 and #11 did not observe consistent queuing on any of their approaches and were excluded from the study. Time periods for the remaining 18 selected roundabouts were sent to DataFromSky for processing. Table 2 shows the dates and times that each of the 18 roundabouts were processed.

Table 2. Processed Roundabouts Dates & Times.

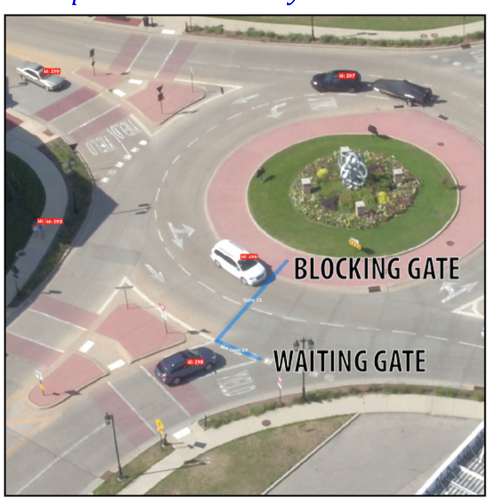
Site #	Municipality	Intersection	Date	Actual Time Start	Actual Time End
01	Mt. Horeb, WI	STH 78 & STH 92/CTH ID	4/16/2019	3:28:23 PM	5:49:20 PM
03	De Pere, WI	STH 32 & STH 57	5/15/2019	3:30:00 PM*	6:00:00 PM*
04	Green Bay, WI	STH 54/32 & Taylor Street	5/16/2019	3:38:57 PM	5:46:03 PM
05	Oshkosh, WI	USH 45 & USH 45/STH 76	5/28/2019	3:08:27 PM	5:32:50 PM
06	Brookfield, WI	CTH Y & CTH M	5/7/2019	3:42:15 PM	5:56:04 PM
07	Brookfield, WI	CTH M & Brookfield Road	6/4/2019	4:06:35 PM	6:00:23 PM
08	New Berlin, WI	IH 43 SB Ramps & CTH O/Moorland Road	5/21/2019	2:50:32 PM	5:58:06 PM
09	New Berlin, WI	IH 43 NB Off Ramp & CTH O/Moorland Road	6/18/2019	2:58:55 PM	6:00:16 PM
10	Wales, WI	USH 18 & STH 83	6/26/2019	3:00:17 PM	6:00:17 PM
12	De Pere, WI	CTH F & Lawrence Drive	5/29/2019	3:31:51 PM	5:24:09 PM
13	Neenah, WI	STH 114 & Green Bay Road	7/30/2019	2:59:24 PM	5:45:58 PM
14	Howard/Green Bay, WI	STH 29 & Taylor Street	5/30/2019	3:47:30 PM	5:40:07 PM
15	Waunakee, WI	STH 19 & STH 113/CTH Q	7/2/2019	3:41:07 PM	5:55:56 PM
16	Milwaukee, WI	Canal Street & 25th Street	7/31/2019	3:31:11 PM	5:49:08 PM
17	Oshkosh, WI	CTH E/Witzel Avenue & Koeller Street	7/9/2019	3:09:20 PM	6:00:36 PM
18	Oshkosh, WI	CTH E/Witzel Avenue & Washburn Street	7/16/2019	3:43:41 PM	5:53:34 PM
19	Appleton, WI	College Avenue & Walter Avenue/John Street	6/5/2019	3:31:18 PM	5:47:15 PM
20	Oconomowoc, WI	STH 16 & Walnut Street	8/1/2019	3:51:26 PM	6:06:52 PM

*approximate start/end times

4.2.3 DataFromSky Viewer to Extract Gap and Follow-Up Headway Data

With the returned output trajectory files, each video was further processed using the DataFromSky Viewer software to extract the gap and follow-up headway data (10). Within the software, a waiting gate was placed at the entry lane yield line and a blocking gate was placed at the circulating conflicting line, as shown in Figure 20. These are paired in the software into a measurement node.

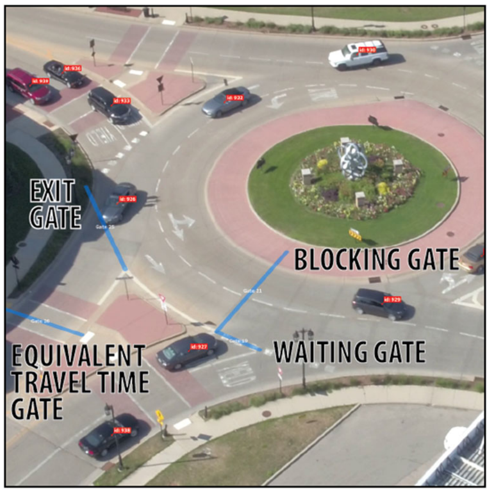
Figure 20. Depicts DataFromSky Viewer Gate Positions.



The DataFromSky Viewer software detects when a vehicle is stopped at the waiting gate and then detects when circulating vehicles cross the blocking gate. The software outputs the length in milliseconds (ms) of the initial lag for the waiting vehicle. If the waiting vehicle rejects the lag, the software outputs the length (ms) of any rejected gaps and the accepted gap when they enter the roundabout. The software computes and outputs these values for every vehicle that stops at the waiting gate. If multiple vehicles enter within the same lag or gap, the software will output a time to follow value (ms), which is the follow-up headway time for that specific following vehicle (10).

To account for exiting vehicles, two additional gates were placed as shown in Figure 21. The exit gate is an additional blocking gate added to the same measurement node as the first waiting gate/blocking gate pair. With the additional blocking gate added to the measurement node, the DataFromSky Viewer software could consider blocking events at both blocking gates if a vehicle was waiting at the waiting gate.

Figure 21. Depicts DataFromSky View Exit Gate Positions.



The equivalent travel time gate was placed at a location where the travel time between the exit gate and the equivalent travel time gate was approximately equal to the equivalent travel time, as shown in Figure 15 in Section 3.2.1. The equivalent travel time was added to the gap time in accordance to the equation in Figure 16 in Section 3.2.1 for critical gap estimates taking adjacent exiting vehicles into consideration.

4.2.4 Reducing Gap Data for Maximum Likelihood Technique

The data output from the DataFromSky Viewer software contained each gap event on a separate line and needed to be reduced so that the Maximum Likelihood Method could be applied. For example, in cases where a waiting vehicle rejected multiple gaps, information from each rejected gap was on a separate line of data. Since the Maximum Likelihood Technique only requires a driver's accepted gap time and largest rejected gap time, the first step in the data reduction was to remove the lines of data for multiple rejected gaps, leaving the data for a vehicle's accepted gap and largest rejected gap. Table 3 shows an example of a table after the first step of data reduction was applied.

Table 3. Sample First Step of Data Reduction.

First Waiting Vehicle ID	Accepted Gap [s]	Largest Rejected Gap [s]
207	4.713	1.919
229	5.589	3.378
296	6.131	3.629
309	11.720	2.711
361	31.240	4.755
390	5.047	3.712
...	...	...
4483	3.462	1.668

The Maximum Likelihood Technique was performed using the spreadsheet procedure summarized in Troutbeck's *Estimating the Mean Critical Gap* (11). In the paper, Troutbeck outlines how to use Microsoft Excel® and the SOLVER add-on tool to perform the iterative technique for determining critical gaps. Following Troutbeck's method, a table was populated as shown in Table 4.

Table 4. Sample Data for Maximum Likelihood Technique.

	A	B	C	D
1	Driver	Accepted gap	Largest rejected gap	Ln[F(a)-F(r)]
2	1	4.713	1.919	-0.5404
3	2	5.589	3.378	-0.3592
4	3	6.131	3.629	-0.3411
5	4	11.72	2.711	-0.0191
6	5	31.24	4.755	-0.9088
7	6	5.047	3.712	-0.7540
...	...	...	...	...
63	62	3.462	1.668	-1.9448
64	Sum			-39.3708
65	Mean critical gap			4.6138
66	Standard deviation of critical gap			1.1323
67	Mean of log of critical gap			1.4998
68	Standard deviation of log of critical gap			0.2418

Formulas were entered in cells D64, D67, and D68 as Troutbeck recommends, which assumed a lognormal distribution of critical gaps (11). To complete the Maximum Likelihood table, initial estimated values for the mean critical gap and standard deviation of critical gap were input into cells D65 and D66, respectively.

4.2.5 Critical Gap and Follow-Up Headway Analysis

Table 5 displays a summary of the roundabout lane approaches that were analyzed in the DataFromSky Viewer software and part of critical gap and follow-up headway analysis. Site #18 was excluded from analysis despite being processed by DataFromSky because the drone was too far from the roundabout and trajectories for entering vehicles and circulating overlapped.

Table 5. Roundabout Approaches Analyzed.

Site #	Municipality	Intersection	Leg	Lane	Entry Lanes	Conflicting Circulating Lanes
01	Mt. Horeb, WI	STH 78 & STH 92/CTH ID	EB	Single	1	1
			NB	Single	1	1
			WB	Left	2	1
			WB	Right	2	1
03	De Pere, WI	STH 32 & STH 57	EB	Left	2	1
			EB	Right	yield bypass	1
			NB	Left	2	1
			NB	Right	2	1
04	Green Bay, WI	STH 54/32 & Taylor Street	EB	Left	2	2
			EB	Right	2	2
			SB	Left	2	2
			SB	Right	2	2
			WB	Left	2	2
			WB	Right	2	2
05	Oshkosh, WI	USH 45 & USH 45/STH 76	EB	Left	2	2
			EB	Right	2	2
			SB	Left	2	2
			SB	Right	2	2
06	Brookfield, WI	CTH Y & CTH M	EB	Single	1	2
			SB	Left	2	1
			SB	Right	2	1
			WB	Single	1	2
07	Brookfield, WI	CTH M & Brookfield Road	EB	Single	1	1
			NB	Single	1	1
			SB	Single	1	1
			WB	Single	1	1
08	New Berlin, WI	IH 43 SB Ramps & CTH O/Moorland Road	SB	Center	3	1
			SB	Left	3	1
			SB	Right	3	1
			WB	Left	2	2
			WB	Right	yield bypass	2
09	New Berlin, WI	IH 43 NB Off Ramp & CTH O/Moorland Road	NB	Left	2	2
			NB	Right	2	2
			WB	Single	1	2
10	Wales, WI	USH 18 & STH 83	EB	Left	2	2
			EB	Right	2	2
			SB	Left	2	2
			SB	Right	2	2
12	De Pere, WI	CTH F & Lawrence Drive	NB	Left	2	2
			NB	Right	2	2
13	Neenah, WI	STH 114 & Green Bay Road	EB	Left	2	2
			EB	Right	2	2
14	Howard/Green Bay, WI	STH 29 & Taylor Street	EB	Left	2	2
			EB	Right	2	2
			NB	Center	3	2
			NB	Left	3	2
			NB	Right	3	2

Site #	Municipality	Intersection	Leg	Lane	Entry Lanes	Conflicting Circulating Lanes
15	Waunakee, WI	STH 19 & STH 113/CTH Q	NB	Left	2	2
			NB	Right	2	2
			WB	Left	2	2
			WB	Right	2	2
16	Milwaukee, WI	Canal Street & 25th Street	EB	Left	2	1
			SB	Single	1	2
17	Oshkosh, WI	CTH E/Witzel Avenue & Koeller Street	SB	Left	2	2
			SB	Right	2	2
19	Appleton, WI	College Avenue & Walter Avenue/John Street	EB	Left	2	1
			EB	Right	2	1
			NB	Left	2	2
			NB	Right	2	2
			WB	Left	2	2
			WB	Right	2	2
20	Oconomowoc, WI	STH 16 & Walnut Street	NB	Left	2	2
			NB	Right	yield bypass	2
			WB	Left	2	2
			WB	Right	2	2

To estimate mean critical gap for each roundabout lane approach, the Maximum Likelihood table (Table 4) was analyzed using the SOLVER routine (11). The SOLVER routine attempts to maximize the sum (cell D64 in Table 4) while iterating through different values for mean critical gap and standard deviation of critical gap (cells D65 & D66 in Table 4). Once the SOLVER routine was complete, a critical gap value for that particular roundabout lane approach was estimated.

To determine a solution, initial guesses for the mean critical gap and standard deviation of critical gap are necessary using the methodology followed in this study and outlined by Troutbeck (11). In this study, initial guesses of 4.00s for mean critical gap and 1.00s for standard deviation were used. If a solution was not determinable from the initial guess, up to two subsequent guesses were attempted. If the initial guess or subsequent guesses did not result in a solution following the SOLVER routine, the approach results were not used in this study.

Note that the eastbound and westbound approaches at site #4 are three-lane approaches. The lanes denoted as right lanes in Table 5 for that site are actually the center lanes, just classified as right lanes for analysis. The actual right lanes are low-volume, yield bypass lanes separated from the center lane by a large island and didn't produce critical gap results in the SOLVER analysis. Because of those characteristics, it was deemed appropriate to classify the center lane as right lane for critical gap and follow-up headway analysis.

Follow-up headway did not require SOLVER analysis and was directly measured by the DataFromSky Viewer software (10). A sample average and standard deviation of follow-up headway was calculated for each roundabout lane approach.

Once critical gap and follow-up headway values were estimated for all roundabout approach lanes analyzed, the values were compiled into weighted averages for each entry lane/circulating lane scenario outlined in Section 3.1 of this report.

CHAPTER 5: RESULTS AND ANALYSES

5.1 CRITICAL GAP RESULTS

Critical gaps were estimated as outlined in Chapter 4 of this report and summary results for each roundabout configuration are shown in Table 6. Results for Maximum Likelihood Technique Methods 2 and 3 are shown side-by-side. Critical gap results for each individual site are found in the Appendix A organized by roundabout configuration.

Table 6. Summary Results for Critical Gap in Roundabouts.

	Method 2*			Method 3*			
Configuration	Site Sample Size	Range (s)	Weighted Average (s)	Site Sample Size	Range (s)	Weighted Average (s)	Difference
1-1	6	4.4 - 5.1	4.6	6	4.5 - 5.0	4.7	-0.1
R2-1	3	4.3 - 5.0	4.4	1	4.4 - 4.4	4.4	0.0
L2-1	6	3.9 - 5.3	4.7	4	4.5 - 5.4	4.7	0.0
1-2	4	4.0 - 5.4	4.7	4	4.2 - 5.5	4.8	-0.1
R2-2	17	3.6 - 5.2	4.3	17	3.7 - 5.1	4.3	0.0
L2-2	18	4.2 - 5.3	4.5	18	4.4 - 5.5	4.6	-0.1
R-bypass-1	1	3.9 - 3.9	3.9	1	4.0 - 4.0	4.0	-0.1
R-bypass-2	2	4.2 - 4.6	4.4	1	4.8 - 4.8	4.8	-0.4
R3-1	1	4.2 - 4.2	4.2	1	4.4 - 4.4	4.4	-0.2
C3-1	1	4.5 - 4.5	4.5	1	4.4 - 4.4	4.4	0.1
L3-1	1	4.5 - 4.5	4.5	1	4.6 - 4.6	4.6	-0.1
R3-2	1	4.3 - 4.3	4.3	1	4.6 - 4.6	4.6	-0.3
C3-2	1	4.3 - 4.3	4.3	1	4.4 - 4.4	4.4	-0.1
L3-2	1	4.5 - 4.5	4.5	0	---	---	---

*Method 2 requires only rejected gap. Method 3 requires rejected gap AND waiting queue.

Overall, Method 2 and Method 3 produced similar results, which is what was found in NCHRP Report 572 (4) when comparing the two methods. The critical gap weighted averages for Method 2 ranged from 3.9 seconds to 4.7 seconds, while they ranged from 4.0 seconds to 4.8 seconds for Method 3. All Method 3 results were equal to or had slightly longer estimated critical gaps than Method 2, with the exception of the C3-1 configuration. However, the average difference between Method 2 and Method 3 estimates was only -0.1 seconds. The R-bypass-1 configuration had the smallest estimated critical gap for both Method 2 and Method 3. The largest estimated critical gaps for Method 2 were for the L2-1 and 1-2 configurations, while Method 3's largest estimated critical gaps were for the 1-2 and R-bypass-2 configurations.

5.1.1 Effect of Considering Exiting Vehicles

Table 7 shows the critical gap comparison when adjacent exiting vehicles are considered. Again, Maximum Likelihood Technique Methods 2 and 3 results are shown side-by-side. In all cases, critical gap estimates decreased with adjacent exiting vehicles considered.

Table 7. Critical Gap Comparison Considering Adjacent Exiting Vehicles.

Configuration	Method 2* (No Exiting Veh. Consideration) Weighted Average (s)	Method 2* (With Exiting Veh. Consideration) Weighted Average (s)	Difference	Method 3* (No Exiting Veh. Consideration) Weighted Average (s)	Method 3* (With Exiting Veh. Consideration) Weighted Average (s)	Difference
1-1	4.6	3.8	-0.8	4.7	3.9	-0.8
R2-1	4.4	3.8	-0.6	4.4	3.9	-0.5
L2-1	4.7	3.9	-0.8	4.7	4.0	-0.7
1-2	4.7	4.2	-0.5	4.8	4.3	-0.5
R2-2	4.3	3.8	-0.5	4.3	3.9	-0.4
L2-2	4.5	3.9	-0.6	4.6	4.0	-0.6
R-bypass-1	3.9	3.7	-0.2	4.0	3.8	-0.2
R-bypass-2	4.4	4.2	-0.2	4.8	4.1	-0.7
R3-1	4.2	4.0	-0.2	4.4	4.1	-0.3
C3-1	4.5	4.0	-0.5	4.4	4.1	-0.3
L3-1	4.5	4.0	-0.5	4.6	4.0	-0.6
R3-2	4.3	3.8	-0.5	4.6	4.0	-0.6
C3-2	4.3	3.9	-0.4	4.4	4.0	-0.4
L3-2	4.5	3.8	-0.7	---	---	---

*Method 2 requires only rejected gap. Method 3 requires rejected gap AND waiting queue.

Critical gap estimates decreased for all roundabout configurations when considering exiting vehicles for both Method 2 and Method 3. On average, the critical gap estimates decreased by approximately 0.5 seconds for each method when considering exiting vehicles. The decrease ranged from 0.2 seconds to 0.8 seconds for each method. For Method 2, the largest difference in critical gap estimate was for the 1-1 and L2-1 configurations, with results showing a decrease of 0.8 seconds. For Method 3, the largest difference in critical gap was for the 1-1 configuration, with results also showing a decrease of 0.8 seconds.

5.2 Follow-Up Headway Results

Follow-up headways were estimated as outlined in Chapter 4 of this report and summary results are shown in Table 8. Results for without and with exiting vehicle consideration are shown side-by-side in each table. Follow-up headway results for each individual site are found in the Appendix A organized by roundabout configuration. In all cases, follow-up headway estimates decreased with adjacent exiting vehicles considered.

All follow-up headways estimated when considering exiting vehicles were lower than without considering them. The average decrease in estimates between the two methods was 0.2 seconds. The follow-up headway weighted averages when not considering exiting vehicles ranged from 2.4 seconds to 3.0 seconds, while they ranged from 2.3 seconds to 2.8 seconds with exiting vehicles considered. For follow-up headway estimates without considering exiting vehicles, the R-bypass-1 configuration had the smallest estimated value, while the 1-1 configuration had the largest. For follow-up headway estimates with considering exiting vehicles, the R-bypass-1 and L3-1 configurations had the smallest estimated value, while the R-bypass-2 configuration had the largest. Note that the R-bypass-2 configuration was the least affected by exiting vehicles as that configuration only decreased by 0.02 seconds with exiting vehicles considered.

Table 8. Summary Results for Follow-Up Headway in Roundabouts.

	No Exiting Vehicle Consideration			*With Exiting Vehicle Consideration*			
Configuration	Site Sample Size	Range (s)	Weighted Average (s)	Site Sample Size	Range (s)	Weighted Average (s)	Difference
1-1	6	2.8 - 3.3	3.0	6	2.5 - 2.9	2.6	-0.4
R2-1	4	2.5 - 3.3	2.8	4	2.4 - 3.6	2.5	-0.3
L2-1	6	2.5 - 3.2	2.8	6	2.2 - 2.8	2.5	-0.3
1-2	4	2.6 - 3.0	2.8	4	2.4 - 2.7	2.6	-0.2
R2-2	17	2.4 - 3.2	2.8	17	2.3 - 3.0	2.6	-0.2
L2-2	19	2.3 - 3.2	2.8	18	2.3 - 2.8	2.6	-0.2
R-bypass-1	1	2.5 - 2.5	2.4	1	2.4 - 2.4	2.3	-0.1
R-bypass-2	2	2.6 - 3.2	2.8	1	2.8 - 2.8	2.8	0.0
R3-1	1	2.6 - 2.6	2.6	1	2.4 - 2.4	2.4	-0.2
C3-1	1	2.8 - 2.8	2.8	1	2.6 - 2.6	2.6	-0.2
L3-1	1	2.7 - 2.7	2.6	1	2.3 - 2.3	2.3	-0.3
R3-2	1	2.6 - 2.6	2.6	1	2.5 - 2.5	2.5	-0.1
C3-2	1	2.6 - 2.6	2.6	1	2.4 - 2.4	2.4	-0.2
L3-2	0	---	---	0	---	---	---

5.3 Comparison to Past Studies' Findings

The following sections compares this study's estimated critical gap and follow-up headway values to values estimated in past studies.

5.3.1 Comparison to Wisconsin TOPS Lab Study Findings

Critical gap values estimated in the TOPS Lab study were obtained using a method similar to Maximum Likelihood Technique Method 2, so only values estimated in this study using Method 2 were compared (5). Critical gap and follow-up headway values estimated in the TOPS Lab study were obtained both with and without considering exiting vehicles, so values estimated both ways in this study were compared (5). Values estimated in the TOPS Lab study were categorized into the proper roundabout configuration for each approach to better make a comparison to this study's values. Table 9 shows the critical gap comparisons and Table 10 shows the follow-up headway comparisons. Since only the L2-1 configuration had more than one analyzed approach lane in the TOPS Lab study, ranges for values estimated in that study are not shown in the tables.

For critical gap and follow-up headway estimates, the same trend was seen in this study as the TOPS Lab study where estimates with considering exiting vehicles were smaller than without considering them. The roundabout configuration with the greatest difference in estimated critical gap between the two studies is the R2-1 configuration, but that configuration had one of the closest follow-up headway comparisons. Overall, all comparisons are within ±1 second, but vary among the roundabout configurations for how close the estimates compare.

Table 9. Critical Gap Comparison to Wisconsin TOPS Lab Study Findings.

	No Exiting Vehicle Consideration			*With Exiting Vehicle Consideration*		
	TADI Method 2*	TOPS Lab	Difference	TADI Method 2*	TOPS Lab	Difference
Configuration	Weighted Average (s)			Weighted Average (s)		
1-1	4.6	4.8	-0.2	3.8	3.8	0.0
R2-1	4.4	3.4	1.0	3.8	3.0	0.8
L2-1	4.7	4.1	0.6	3.9	3.4	0.5
1-2	4.7	5.5	-0.8	4.2	4.6	-0.4
R2-2	4.3	4.4	-0.1	3.8	4.1	-0.3
L2-2	4.5	4.8	-0.3	3.9	4.4	-0.5
R-bypass-1	3.9	3.8	0.1	3.7	3.5	0.2
R-bypass-2	4.4	---	---	4.2	---	---
R3-1	4.2	---	---	4.0	---	---
C3-1	4.5	---	---	4.0	---	---
L3-1	4.5	---	---	4.0	---	---
R3-2	4.3	---	---	3.8	---	---
C3-2	4.3	---	---	3.9	---	---
L3-2	4.5	---	---	3.8	---	---

*Method 2 requires only rejected gap.

Table 10. Follow-Up Headway Comparison to Wisconsin TOPS Lab Study Findings.

	No Exiting Vehicle Consideration			*With Exiting Vehicle Consideration*		
	TADI	TOPS Lab	Difference	TADI	TOPS Lab	Difference
Configuration	Weighted Average (s)			Weighted Average (s)		
1-1	3.0	3.8	-0.8	2.6	3.1	-0.5
R2-1	2.8	3.0	-0.2	2.5	2.6	-0.1
L2-1	2.8	2.9	-0.1	2.5	2.3	0.2
1-2	2.8	2.6	0.2	2.6	2.3	0.3
R2-2	2.8	2.2	0.6	2.6	2.2	0.4
L2-2	2.8	2.5	0.3	2.6	2.1	0.5
R-bypass-1	2.4	2.8	-0.4	2.3	2.2	0.1
R-bypass-2	2.8	---	---	2.8	---	---
R3-1	2.6	---	---	2.4	---	---
C3-1	2.8	---	---	2.6	---	---
L3-1	2.6	---	---	2.3	---	---
R3-2	2.6	---	---	2.5	---	---
C3-2	2.6	---	---	2.4	---	---
L3-2	---	---	---	---	---	---

Four approaches were analyzed in both this study and the TOPS Lab study. The results of the direct comparisons for the four approaches are shown in Table 11 for the critical gap comparison and Table 12 for the follow-up headway comparison.

The roundabout approach with the greatest difference in critical gap is the right-lane of the northbound approach of STH 32 at STH 57. This lane is an R2-1 configuration, which is the configuration with the largest difference between the two studies as noted previously. Overall, for critical gap the comparisons were different by similar amounts with no exiting vehicle consideration and with exiting vehicle consideration, while for follow-up headway the differences were smaller when taking exiting vehicles into consideration.

Table 11. Critical Gap Direct Comparison to Common TOPS Lab Approaches.

		No Exiting Vehicle Consideration			*With Exiting Vehicle Consideration*		
		TADI Method 2*	TOPS Lab	Difference	TADI Method 2*	TOPS Lab	Difference
	Configuration	Weighted Average (s)			Weighted Average (s)		
SB Canal Street at 25th Street (Site #16)	1-2	5.4	5.5	-0.1	4.8	4.6	0.2
WB STH 78 at STH92/CTH ID (Site #01)**	1-1	5.1	4.8	0.3	4.1	3.8	0.3
NB STH 57 at STH 32 (Site #03)	R2-1	4.3	3.4	0.9	3.9	3.0	0.9
	L2-1	4.7	4.1	0.6	3.9	3.3	0.6
EB STH 32 at STH 57 (Site #03)	R-bypass-1	3.9	3.8	0.1	3.7	3.5	0.2
	L2-1	4.6	4.2	0.4	3.9	3.7	0.2

*Method 2 requires only rejected gap. **WB STH 78, but NB approach at roundabout.

Table 12. Follow-Up Headway Direct Comparison to Common TOPS Lab Approaches.

		No Exiting Vehicle Consideration			*With Exiting Vehicle Consideration*		
		TADI Method 2*	TOPS Lab	Difference	TADI Method 2*	TOPS Lab	Difference
	Configuration	Weighted Average (s)			Weighted Average (s)		
SB Canal Street at 25th Street (Site #16)	1-2	2.7	2.6	0.1	2.5	2.3	0.2
WB STH 78 at STH92/CTH ID (Site #01)**	1-1	3.1	3.8	-0.7	2.9	3.1	-0.2
NB STH 57 at STH 32 (Site #03)	R2-1	2.8	3.0	-0.2	2.4	2.6	-0.2
	L2-1	3.0	3.1	-0.1	2.5	2.5	0.0
EB STH 32 at STH 57 (Site #03)	R-bypass-1	2.4	2.8	-0.4	2.3	2.2	0.1
	L2-1	2.6	2.8	-0.2	2.2	2.2	0.0

**WB STH 78, but NB approach at roundabout.

5.3.2 Comparison to FHWA-SA-15-070 Study Findings

Critical gap values estimated in the FHWA-SA-15-070 study were obtained using Maximum Likelihood Technique Method 3 and without considering adjacent exiting vehicles, so only values estimated in this study using Method 3 and without considering adjacent exiting vehicles were compared (7). Follow-up headway values estimated in the FHWA-SA-15-070 study were obtained only with considering exiting vehicles, so only values estimated in that manner in this study were compared (7). Values estimated in the FHWA-SA-15-070 study were categorized into the proper roundabout configuration for each approach to better make a comparison to this study's values. Table 13 shows the critical gap comparisons and Table 14 shows the follow-up headway comparisons.

As shown in Table 13, critical gaps for all comparable configurations are within ranges presented in FHWA-SA-15-070 except for the 1-2 configuration. However, this study's critical gap estimate for the 1-2 configuration was only 0.1 seconds below the lower threshold of the FHWA-SA-15-070 range.

Table 13. Critical Gap Comparison to FHWA-SA-15-070 Study Findings.

No Exiting Vehicle Consideration

	TADI Method 3*		FHWA-SA-15-070		Difference
Configuration	Weighted Average (s)	Range (s)	Weighted Average (s)	Range (s)	
1-1	4.7	4.5 - 5.0	4.7	3.3 - 6.5	0.0
R2-1	4.4	4.4 - 4.4	4.3	3.8 - 6.1	0.1
L2-1	4.7	4.5 - 5.4	4.6	4.1 - 6.6	0.1
1-2	4.8	4.2 - 5.5	5.2	4.9 - 5.3	-0.4
R2-2	4.3	3.7 - 5.1	4.9	3.8 - 12.9	-0.6
L2-2	4.6	4.4 - 5.5	5.5	4.0 - 13.2	-0.9
R-bypass-1	4.0	4.0 - 4.0	---	---	---
R-bypass-2	4.8	4.8 - 4.8	---	---	---
R3-1	4.4	4.4 - 4.4	---	---	---
C3-1	4.4	4.4 - 4.4	---	---	---
L3-1	4.6	4.6 - 4.6	---	---	---
R3-2	4.6	4.6 - 4.6	---	---	---
C3-2	4.4	4.4 - 4.4	---	---	---
L3-2	---	---	---	---	---

*Method 3 requires rejected gap AND waiting queue.

As shown in Table 14, follow-up headways for all comparable configurations are within ranges presented in FHWA-SA-15-070 except for the 1-2 configuration. This study's follow-up headway estimate for the 1-2 configuration was 0.1 seconds above the upper threshold of the FHWA-SA-15-070 range. However, the FHWA-SA-15-070 study only had two follow-up headway sites for the 1-2 configuration, so the range presented for the 1-2 configuration is small since both sites found similar values.

Table 14. Follow-Up Headway Comparison to FHWA-SA-15-070 Study Findings.

With Exiting Vehicle Consideration

	TADI		FHWA-SA-15-070		Difference
Configuration	Weighted Average (s)	Range (s)	Weighted Average (s)	Range (s)	
1-1	2.6	2.5 - 2.9	2.6	1.7 - 3.0	0.0
R2-1	2.5	2.4 - 3.6	2.3	2.0 - 2.8	0.2
L2-1	2.5	2.2 - 2.8	2.1	1.5 - 2.9	0.4
1-2	2.6	2.4 - 2.7	2.5	2.5 - 2.5	0.1
R2-2	2.6	2.3 - 3.0	2.5	2.0 - 4.1	0.1
L2-2	2.6	2.3 - 2.8	2.7	1.6 - 3.7	-0.1
R-bypass-1	2.3	2.4 - 2.4	---	---	---
R-bypass-2	2.8	2.8 - 2.8	---	---	---
R3-1	2.4	2.4 - 2.4	---	---	---
C3-1	2.6	2.6 - 2.6	---	---	---
L3-1	2.3	2.3 - 2.3	---	---	---
R3-2	2.5	2.5 - 2.5	---	---	---
C3-2	2.4	2.4 - 2.4	---	---	---
L3-2	---	---	---	---	---

5.3.3 Comparison to HCM6 and WI FDM Capacity Models

Values for critical gap and follow-up headway were derived from the HCM6 (3) and WI FDM (12) capacity models using the Siegloch model, which is discussed in Section 2.4.4 of this report. Table 15 shows the critical gap comparisons and Table 16 shows the follow-up headway comparisons.

Table 15. Critical Gap Comparison to HCM6 and WI FDM Capacity Models.

	No Exiting Vehicle Consideration		*With Exiting Vehicles Consideration*			
	TADI Method 2*	TADI Method 3*	TADI Method 2*	TADI Method 3*	HCM 6th Edition	Wisconsin FDM
Configuration	Weighted Average (s)		Weighted Average (s)		Derived from Siegloch Model	
1-1	4.6	4.7	3.8	3.9	5.0	4.2
R2-1	4.4	4.4	3.8	3.9	4.5	4.2
L2-1	4.7	4.7	3.9	4.0	4.5	4.2
1-2	4.7	4.8	4.2	4.3	4.3	4.0
R2-2	4.3	4.3	3.8	3.9	4.3	4.0
L2-2	4.5	4.6	3.9	4.0	4.6	4.0
R-bypass-1	3.9	4.0	3.7	3.8	5.0	4.2
R-bypass-2	4.4	4.8	4.2	4.1	4.3	4.0
R3-1	4.2	4.4	4.0	4.1	---	4.2
C3-1	4.5	4.4	4.0	4.1	---	4.2
L3-1	4.5	4.6	4.0	4.0	---	4.2
R3-2	4.3	4.6	3.8	4.0	---	4.0
C3-2	4.3	4.4	3.9	4.0	---	4.0
L3-2	4.5	---	3.8	---	---	4.0

*Method 2 requires only rejected gap. Method 3 requires rejected gap AND waiting queue.

For the eight comparable configurations between this study and HCM6, values estimated in this study with no exiting vehicle consideration using Method 2 or Method 3 varied as to whether they were larger or smaller than their HCM6 counterpart, but values estimated in this study with exiting vehicle consideration using Method 2 or Method 3 were lower for all eight comparable configurations.

WI FDM critical headways are recommended to be 4.2 seconds for a single circulating lane and 4.0 seconds for two or more circulating lanes, regardless of the entry approach lane being analyzed. Values estimated in this study with no exiting vehicle consideration using Method 2 or Method 3 were larger than WI FDM values for a large majority of the configurations. Similar to the HCM6 comparison, values estimated in this study with exiting vehicle consideration using Method 2 or Method 3 were lower for a large majority of the configurations.

As shown in Table 16, follow-up headway results from this study estimated with no exiting vehicle consideration are generally closer to the WI FDM values, while results estimated with exiting vehicle consideration are generally closer to the HCM6 values. Note that the WI FDM recommends using 2.8 second follow-up headways for all roundabout configurations.

Table 16. Follow-Up Headway Comparison to HCM6 and WI FDM Capacity Models.

	TADI No Exiting Veh. Consideration	TADI With Exiting Veh. Consideration	HCM 6th Edition	Wisconsin FDM
Configuration	Weighted Average (s)		Derived from Siegloch Model	
1-1	3.0	2.6	2.6	2.8
R2-1	2.8	2.5	2.5	2.8
L2-1	2.8	2.5	2.5	2.8
1-2	2.8	2.6	2.5	2.8
R2-2	2.8	2.6	2.5	2.8
L2-2	2.8	2.6	2.7	2.8
R-bypass-1	2.4	2.3	2.6	2.8
R-bypass-2	2.8	2.8	2.5	2.8
R3-1	2.6	2.4	---	2.8
C3-1	2.8	2.6	---	2.8
L3-1	2.6	2.3	---	2.8
R3-2	2.6	2.5	---	2.8
C3-2	2.6	2.4	---	2.8
L3-2	---	---	---	2.8

5.4 Lane Utilization Results

Lane utilization results for the analyzed approaches are shown in Table 17. Based on the data, there isn't conclusive evidence of universal lane utilization trends at the analyzed roundabouts, though it does appear in the small sample size of 3-lane approaches, that the center-lane was favored by entering vehicles compared to the right or left lanes. The lane utilization at a roundabout approach appears to be primarily impacted by local conditions and travel patterns.

Table 17. Lane Utilization Results.

	Sample Size	Range of Lane Utilizations Left Lane	Center Lane	Right Lane
2-Lane	23	27% - 78%	---	23% - 73%
3-Lane	4	08% - 42%	33% - 51%	10% - 41%

	Sample Size	Average Lane Utilizations Left Lane	Center Lane	Right Lane
2-Lane	23	49%	---	51%
3-Lane	4	31%	45%	24%

A table containing lane utilization results for each individual roundabout approach can be found in Appendix B.

Chapter 6: Summary

The HCM6 recommends local calibration as differences in driver behavior and geometric factors can contribute to variations from the provided capacity models (3). For calibration, the HCM6 presents the Siegloch model, which is a generalized capacity model shown in Figure 4 in Section 2.4.4. With this model, the capacity model can be calibrated to local conditions by using the critical gap and the follow-up headway parameters of locally observed operations. To aid in policy decisions regarding roundabout capacity parameters, the results of the analysis in this study are organized into Table 18, which presents the critical gap and follow-up headway estimates sorted by circulating lane configuration, and Table 19, which presents the critical gap and follow-up headway estimates sorted by entry lane configuration. In each table, the number in parenthesis next to the critical gap or follow-up headway estimate represents the sample size of approach lanes analyzed in this study.

Table 18. Critical Gap and Follow-Up Headway Estimates Sorted by Circulating Lane Configuration.

		No Exiting Vehicle Consideration				*With Exiting Vehicle Consideration*				*No Exiting Vehicle Consideration*		*With Exiting Vehicle Consideration*	
		Critical Gap (Sample Size)				**Critical Gap (Sample Size)**				**Follow-Up Headway (Sample Size)**			
		Method 2*		Method 3*		Method 2*		Method 3*					
SINGLE CIRCULA-TING LANE	1-1	4.6	(6)	4.7	(6)	3.8	(6)	3.9	(6)	3.0	(6)	2.6	(6)
	L2-1	4.7	(6)	4.7	(4)	3.9	(6)	4.0	(6)	2.8	(6)	2.5	(6)
	R2-1	4.4	(3)	4.4	(1)	3.8	(4)	3.9	(2)	2.8	(4)	2.5	(4)
	L3-1	4.5	(1)	4.6	(1)	4.0	(1)	4.0	(1)	2.6	(1)	2.3	(1)
	C3-1	4.5	(1)	4.4	(1)	4.0	(1)	4.1	(1)	2.8	(1)	2.6	(1)
	R3-1	4.2	(1)	4.4	(1)	4.0	(1)	4.1	(1)	2.6	(1)	2.4	(1)
	R-bypass-1	3.9	(1)	4.0	(1)	3.7	(1)	3.8	(1)	2.4	(1)	2.3	(1)
Summary	***Average (Sum)***	***4.4***	***(19)***	***4.5***	***(15)***	***3.9***	***(20)***	***4.0***	***(18)***	***2.7***	***(20)***	***2.5***	***(20)***
DUAL CIRCULA-TING LANE	1-2	4.7	(4)	4.8	(4)	4.2	(4)	4.3	(4)	2.8	(4)	2.6	(4)
	L2-2	4.5	(18)	4.6	(18)	3.9	(18)	4.0	(18)	2.8	(19)	2.6	(18)
	R2-2	4.3	(17)	4.3	(17)	3.8	(17)	3.9	(17)	2.8	(17)	2.6	(17)
	L3-2	4.5	(1)	---	(0)	3.8	(1)	---	(0)	---	(0)	---	(0)
	C3-2	4.3	(1)	4.4	(1)	3.9	(1)	4.0	(1)	2.6	(1)	2.4	(1)
	R3-2	4.3	(1)	4.6	(1)	3.8	(1)	4.0	(1)	2.6	(1)	2.5	(1)
	R-bypass-2	4.4	(2)	4.8	(1)	4.2	(1)	4.1	(1)	2.8	(2)	2.8	(1)
Summary	***Average (Sum)***	***4.4***	***(44)***	***4.6***	***(42)***	***4.0***	***(43)***	***4.1***	***(42)***	***2.7***	***(44)***	***2.6***	***(42)***

*Method 2 requires only rejected gap. Method 3 requires rejected gap AND waiting queue.

( ) = sample size of approach lanes analyzed

Table 19. Critical Gap and Follow-Up Headway Estimates Sorted by Entry Lane Configuration.

		No Exiting Vehicle Consideration				*With Exiting Vehicle Consideration*				*No Exiting Vehicle Consideration*		*With Exiting Vehicle Consideration*	
		Critical Gap (Sample Size)				**Critical Gap (Sample Size)**				**Follow-Up Headway (Sample Size)**			
	Configuration	Method 2*		Method 3*		Method 2*		Method 3*					
SINGLE LANE ENTRY	1-1	4.6	(6)	4.7	(6)	3.8	(6)	3.9	(6)	3.0	(6)	2.6	(6)
	1-2	4.7	(4)	4.8	(4)	4.2	(4)	4.3	(4)	2.8	(4)	2.6	(4)
Summary	*Average (Sum)*	***4.7***	***(10)***	***4.7***	***(10)***	***4.0***	***(10)***	***4.1***	***(10)***	***2.9***	***(10)***	***2.6***	***(10)***
DUAL LANE ENTRY	L2-1	4.7	(6)	4.7	(4)	3.9	(6)	4.0	(6)	2.8	(6)	2.5	(6)
	L2-2	4.5	(18)	4.6	(18)	3.9	(18)	4.0	(18)	2.8	(19)	2.6	(18)
	Average (Sum)	***4.6***	***(24)***	***4.7***	***(22)***	***3.9***	***(24)***	***4.0***	***(24)***	***2.8***	***(25)***	***2.5***	***(24)***
	R2-1	4.4	(3)	4.4	(1)	3.8	(4)	3.9	(2)	2.8	(4)	2.5	(4)
	R2-2	4.3	(17)	4.3	(17)	3.8	(17)	3.9	(17)	2.8	(17)	2.6	(17)
	Average (Sum)	***4.3***	***(20)***	***4.4***	***(18)***	***3.8***	***(21)***	***3.9***	***(19)***	***2.8***	***(21)***	***2.6***	***(21)***
Summary	2-1	4.6	(9)	4.5	(5)	3.9	(10)	3.9	(8)	2.8	(10)	2.5	(10)
	2-2	4.4	(35)	4.5	(35)	3.9	(35)	4.0	(35)	2.8	(36)	2.6	(35)
	Average (Sum)	***4.5***	***(44)***	***4.5***	***(40)***	***3.9***	***(45)***	***4.0***	***(43)***	***2.8***	***(46)***	***2.5***	***(45)***
TRIPLE LANE ENTRY	L3-1	4.5	(1)	4.6	(1)	4.0	(1)	4.0	(1)	2.6	(1)	2.3	(1)
	L3-2	4.5	(1)	---	(0)	3.8	(1)	---	(0)	---	(0)	---	(0)
	Average (Sum)	***4.5***	***(2)***	*---*	***(1)***	***3.9***	***(2)***	*---*	***(1)***	*---*	***(1)***	*---*	***(1)***
	C3-1	4.5	(1)	4.4	(1)	4.0	(1)	4.1	(1)	2.8	(1)	2.6	(1)
	C3-2	4.3	(1)	4.4	(1)	3.9	(1)	4.0	(1)	2.6	(1)	2.4	(1)
	Average (Sum)	***4.4***	***(2)***	***4.4***	***(2)***	***4.0***	***(2)***	***4.1***	***(2)***	***2.7***	***(2)***	***2.5***	***(2)***
	R3-1	4.2	(1)	4.4	(1)	4.0	(1)	4.1	(1)	2.6	(1)	2.4	(1)
	R3-2	4.3	(1)	4.6	(1)	3.8	(1)	4.0	(1)	2.6	(1)	2.5	(1)
	Average (Sum)	***4.2***	***(2)***	***4.5***	***(2)***	***3.9***	***(2)***	***4.0***	***(2)***	***2.6***	***(2)***	***2.4***	***(2)***
Summary	3-1	4.4	(3)	4.5	(3)	4.0	(3)	4.1	(3)	2.7	(3)	2.4	(3)
	3-2	4.4	(3)	4.5	(2)	3.9	(3)	4.0	(2)	2.6	(2)	2.4	(2)
	Average (Sum)	***4.4***	***(6)***	***4.5***	***(5)***	***4.0***	***(6)***	***4.0***	***(5)***	***2.7***	***(5)***	***2.4***	***(5)***
BYPASS LANE ENTRY	R-bypass-1	3.9	(1)	4.0	(1)	3.7	(1)	3.8	(1)	2.4	(1)	2.3	(1)
	R-bypass-2	4.4	(2)	4.8	(1)	4.2	(1)	4.1	(1)	2.8	(2)	2.8	(1)
Summary	*Average (Sum)*	***4.1***	***(3)***	***4.4***	***(2)***	***3.9***	***(2)***	***4.0***	***(2)***	***2.6***	***(3)***	***2.6***	***(2)***

*Method 2 requires only rejected gap. Method 3 requires rejected gap AND waiting queue.

( ) = sample size of approach lanes analyzed

CHAPTER 7: CONCLUSIONS

The objective of the roundabout operations study is to evaluate the critical gap, follow-up headway, and lane utilization observed at roundabouts throughout the state of Wisconsin. The study analyzed 37 approaches at 17 roundabouts. Each approach lane analyzed was categorized based on the seven capacity models presented in HCM6, but also contained seven additional geometric configurations for a total of 14 categories. Critical gaps and follow-up headways were estimated based on field data from aerial observation and analyzed using the DataFromSky Viewer software. The data was analyzed using multiple techniques to make applicable comparisons to the previous TOPS Lab and FHWA-SA-15-070 studies and to the HCM6 and WI FDM capacity models.

To aid in policy decisions regarding roundabout capacity parameters, the results of the analysis in this study are organized into two tables shown in Chapter 6 Summary: one which presents the critical gap and follow-up headway estimates sorted by circulating lane configuration, and one which presents the critical gap and follow-up headway estimates sorted by entry lane configuration.

It is recommended that WisDOT consider basing policy on the critical gaps in the "no exiting vehicle consideration" category using Method 3 (which requires a queue to be present). This scenario is consistent with the basis for the HCM6 capacity equations and has the most conservative results. While exiting vehicles do impact critical gap, the current HCM6 capacity equations do not have an input for exiting vehicles, thus it is recommended that the results in the "no exiting vehicle consideration" category be used for policy decisions.

For follow-up headway policy decisions, it is recommended that the "with exiting vehicle consideration" category be used for the basis of policy decisions. This is recommended because only observations including consecutive entering vehicle events where there were no intervening conflicting circulating vehicles or intervening adjacent exiting vehicles were used in analysis. This method provides a pure follow-up headway measurement with no intervening real or perceived conflicts.

Lane utilization for multi-lane approaches was also evaluated in this study. However, there were no conclusive results regarding a preference of lane choice based on the geometry of the roundabout. Local conditions and travel patterns appear to be the most influential factors regarding lane utilization at multi-lane roundabouts.

In conclusion, this study expanded the knowledge base of parameters critical to estimating roundabout capacity, mainly critical gap (i.e., critical headway) and follow-up headway for various geometric configurations. For most geometric configurations, critical gaps were found to be higher than currently used in the WI FDM and follow-up headways were lower. To identify the impacts these parameters would have on overall roundabout capacity and level-of-service calculations, further analysis is suggested.

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APPENDIX A

CRITICAL GAP AND FOLLOW-UP HEADWAY RESULTS

One-lane entries conflicted by one circulating lane (1-1)

Critical gap without consideration of exiting vehicles

Site #	Configuration	Method 2*			Method 3*		
		Number of Observations, n	Mean	Std. Dev.	Number of Observations, n	Mean	Std. Dev.
01-EB	1-1	133	4.917	0.878	107	5.010	0.810
01-NB	1-1	101	5.061	1.254	52	5.039	1.108
07-EB	1-1	62	4.614	1.132	53	4.758	1.083
07-NB	1-1	142	4.397	0.879	112	4.473	0.766
07-SB	1-1	172	4.530	1.127	150	4.569	1.088
07-WB	1-1	141	4.505	1.019	131	4.534	1.037
Total/Weighted Avg.		751	4.647	1.033	605	4.679	0.970

*Method 2 requires only rejected gap. Method 3 requires rejected gap AND waiting queue.

Critical gap with consideration of exiting vehicles

Site #	Configuration	Method 2*			Method 3*		
		Number of Observations, n	Mean	Std. Dev.	Number of Observations, n	Mean	Std. Dev.
01-EB	1-1	201	4.165	0.684	141	4.263	0.743
01-NB	1-1	116	4.056	0.811	51	4.107	0.734
07-EB	1-1	95	3.964	0.572	67	3.986	0.593
07-NB	1-1	164	3.693	0.667	119	3.795	0.674
07-SB	1-1	210	3.492	0.608	159	3.550	0.613
07-WB	1-1	171	3.694	0.954	139	3.722	0.721
Total/Weighted Avg.		957	3.819	0.717	676	3.863	0.680

*Method 2 requires only rejected gap. Method 3 requires rejected gap AND waiting queue.

Follow-up headway with and without consideration of exiting vehicles

Site #	Configuration	No Exiting Veh. Consideration			With Exiting Veh. Consideration		
		Number of Observations, n	Mean	Std. Dev.	Number of Observations, n	Mean	Std. Dev.
01-EB	1-1	95	2.821	0.714	48	2.585	0.558
01-NB	1-1	37	3.083	0.937	23	2.943	0.985
07-EB	1-1	52	2.867	0.760	19	2.531	0.476
07-NB	1-1	74	2.890	0.833	22	2.468	0.611
07-SB	1-1	100	3.310	0.878	25	2.743	0.746
07-WB	1-1	111	3.085	0.880	41	2.643	0.607
Total/Weighted Avg.		469	3.024	0.830	178	2.647	0.649

Right lane of two-lane entries conflicted by one circulating lane (R2-1)

Critical gap without consideration of exiting vehicles

Site #	Configuration	Method 2*			Method 3*		
		Number of Observations, n	Mean	Std. Dev.	Number of Observations, n	Mean	Std. Dev.
01-WB	R2-1	20	5.022	0.978	---	---	---
03-NB	R2-1	324	4.342	0.782	315	4.359	0.789
06-SB	R2-1	29	4.362	1.236	---	---	---
Total/Weighted Avg.		373	4.380	0.828	315	4.359	0.789

*Method 2 requires only rejected gap. Method 3 requires rejected gap AND waiting queue.

Critical gap with consideration of exiting vehicles

Site #	Configuration	Method 2*			Method 3*		
		Number of Observations, n	Mean	Std. Dev.	Number of Observations, n	Mean	Std. Dev.
01-WB	R2-1	41	3.942	0.612	7	4.179	0.734
03-NB	R2-1	270	3.869	0.597	251	3.882	0.610
06-SB	R2-1	34	3.208	0.195	---	---	---
19-EB	R2-1	17	4.273	0.469	---	---	---
Total/Weighted Avg.		362	3.834	0.555	258	3.890	0.614

*Method 2 requires only rejected gap. Method 3 requires rejected gap AND waiting queue.

Follow-up headway with and without consideration of exiting vehicles

Site #	Configuration	No Exiting Veh. Consideration			With Exiting Veh. Consideration		
		Number of Observations, n	Mean	Std. Dev.	Number of Observations, n	Mean	Std. Dev.
01-WB	R2-1	7	3.337	0.552	3	3.643	0.518
03-NB	R2-1	186	2.759	0.731	34	2.438	0.475
06-SB	R2-1	5	2.519	0.503	4	2.638	0.493
19-EB	R2-1	14	2.735	0.622	5	2.536	0.399
Total/Weighted Avg.		212	2.770	0.712	46	2.544	0.471

Left lane of two-lane entries conflicted by one circulating lane (L2-1)

Critical gap without consideration of exiting vehicles

Site #	Configuration	Method 2*			Method 3*		
		Number of Observations, n	Mean	Std. Dev.	Number of Observations, n	Mean	Std. Dev.
01-WB	L2-1	92	5.271	1.223	60	5.409	1.308
03-EB	L2-1	167	4.567	0.685	134	4.539	0.685
03-NB	L2-1	378	4.705	0.885	372	4.709	0.890
06-SB	L2-1	73	4.488	0.915	42	4.535	0.819
16-EB	L2-1	17	3.937	1.581	---	---	---
19-EB	L2-1	28	5.191	0.644	---	---	---
Total/Weighted Avg.		755	4.723	0.891	608	4.729	0.881

*Method 2 requires only rejected gap. Method 3 requires rejected gap AND waiting queue.

Critical gap with consideration of exiting vehicles

Site #	Configuration	Method 2*			Method 3*		
		Number of Observations, n	Mean	Std. Dev.	Number of Observations, n	Mean	Std. Dev.
01-WB	L2-1	140	3.945	0.663	77	4.068	0.639
03-EB	L2-1	204	3.861	0.603	141	3.941	0.526
03-NB	L2-1	295	3.934	0.710	278	3.957	0.716
06-SB	L2-1	103	3.614	0.685	50	3.714	0.811
16-EB	L2-1	24	3.981	1.378	5	4.314	1.169
19-EB	L2-1	45	4.111	0.513	20	4.258	0.625
Total/Weighted Avg.		811	3.888	0.681	571	3.960	0.668

*Method 2 requires only rejected gap. Method 3 requires rejected gap AND waiting queue.

Follow-up headway with and without consideration of exiting vehicles

Site #	Configuration	No Exiting Veh. Consideration			With Exiting Veh. Consideration		
		Number of Observations, n	Mean	Std. Dev.	Number of Observations, n	Mean	Std. Dev.
01-WB	L2-1	54	3.212	0.900	28	2.775	0.566
03-EB	L2-1	145	2.578	0.525	30	2.236	0.388
03-NB	L2-1	186	3.026	0.820	38	2.514	0.672
06-SB	L2-1	40	2.497	0.626	24	2.311	0.469
16-EB	L2-1	5	3.070	0.539	2	2.670	0.708
19-EB	L2-1	31	2.785	0.820	11	2.533	0.683
Total/Weighted Avg.		461	2.845	0.717	133	2.473	0.551

One-lane entry conflicted by two circulating lanes (1-2)

Critical gap without consideration of exiting vehicles

Site #	Configuration	Method 2*			Method 3*		
		Number of Observations, n	Mean	Std. Dev.	Number of Observations, n	Mean	Std. Dev.
06-EB	1-2	77	4.007	1.030	42	4.240	1.084
06-WB	1-2	143	4.666	1.066	114	4.781	1.107
09-WB	1-2	200	4.456	1.290	125	4.460	1.334
16-SB	1-2	138	5.362	1.869	105	5.498	1.909
Total/Weighted Avg.		558	4.672	1.340	386	4.813	1.396

*Method 2 requires only rejected gap. Method 3 requires rejected gap AND waiting queue.

Critical gap with consideration of exiting vehicles

Site #	Configuration	Method 2*			Method 3*		
		Number of Observations, n	Mean	Std. Dev.	Number of Observations, n	Mean	Std. Dev.
06-EB	1-2	87	3.505	0.786	46	3.622	0.741
06-WB	1-2	145	3.699	0.824	107	3.864	0.909
09-WB	1-2	184	4.442	1.128	119	4.348	1.065
16-SB	1-2	146	4.788	1.290	110	4.916	1.287
Total/Weighted Avg.		562	4.195	1.039	382	4.289	1.046

*Method 2 requires only rejected gap. Method 3 requires rejected gap AND waiting queue.

Follow-up headway with and without consideration of exiting vehicles

Site #	Configuration	No Exiting Veh. Consideration			With Exiting Veh. Consideration		
		Number of Observations, n	Mean	Std. Dev.	Number of Observations, n	Mean	Std. Dev.
06-EB	1-2	30	2.587	0.594	19	2.393	0.536
06-WB	1-2	86	2.981	0.827	50	2.710	0.712
09-WB	1-2	44	2.627	0.662	34	2.591	0.606
16-SB	1-2	100	2.685	0.810	79	2.531	0.710
Total/Weighted Avg.		260	2.762	0.766	182	2.577	0.673

Right lane of two-lane entries conflicted by two circulating lanes (R2-2)

Critical gap without consideration of exiting vehicles

Site #	Configuration	Method 2* Number of Observations, n	Method 2* Mean	Method 2* Std. Dev.	Method 3* Number of Observations, n	Method 3* Mean	Method 3* Std. Dev.
04-EB	R2-2	34	4.745	1.161	23	4.672	1.243
04-SB	R2-2	162	3.584	0.605	90	3.708	0.597
04-WB	R2-2	90	4.191	0.591	74	4.250	0.663
05-EB	R2-2	107	4.340	0.881	58	4.478	0.911
05-SB	R2-2	131	4.476	0.643	99	4.571	0.665
09-NB	R2-2	54	4.471	0.728	45	4.615	0.448
10-EB	R2-2	204	3.901	0.956	138	4.031	0.949
10-SB	R2-2	202	4.340	0.846	167	4.369	0.841
12-NB	R2-2	185	4.275	0.879	166	4.318	0.774
13-EB	R2-2	102	4.290	0.755	69	4.346	0.829
14-EB	R2-2	35	4.377	0.738	17	4.619	0.913
15-NB	R2-2	179	4.152	0.983	106	4.255	0.840
15-WB	R2-2	102	4.560	1.244	57	4.617	1.294
17-SB	R2-2	69	4.350	0.734	29	4.472	0.509
19-NB	R2-2	147	4.525	1.066	89	4.619	1.040
19-WB	R2-2	63	4.302	0.952	41	4.327	1.068
20-WB	R2-2	28	5.175	1.209	22	5.087	1.213
Total/Weighted Avg.		1894	4.253	0.868	1290	4.342	0.840

*Method 2 requires only rejected gap. Method 3 requires rejected gap AND waiting queue.

Critical gap with consideration of exiting vehicles

Site #	Configuration	Method 2* Number of Observations, n	Method 2* Mean	Method 2* Std. Dev.	Method 3* Number of Observations, n	Method 3* Mean	Method 3* Std. Dev.
04-EB	R2-2	48	4.270	0.448	22	4.272	0.562
04-SB	R2-2	154	3.311	0.495	86	3.384	0.533
04-WB	R2-2	130	3.893	0.611	84	3.961	0.626
05-EB	R2-2	124	3.553	0.631	59	3.694	0.632
05-SB	R2-2	167	3.592	0.723	101	3.685	0.765
09-NB	R2-2	79	4.317	0.606	60	4.404	0.678
10-EB	R2-2	214	3.693	0.694	130	3.783	0.670
10-SB	R2-2	218	3.817	0.667	171	3.856	0.701
12-NB	R2-2	184	4.026	0.831	164	4.093	0.749
13-EB	R2-2	136	3.733	0.589	77	3.750	0.485
14-EB	R2-2	54	4.100	0.712	21	4.282	0.932
15-NB	R2-2	185	3.800	0.697	103	3.933	0.651
15-WB	R2-2	132	3.393	0.579	60	3.541	0.632
17-SB	R2-2	72	3.898	0.559	28	4.062	0.469
19-NB	R2-2	149	4.499	0.720	79	4.595	0.697
19-WB	R2-2	93	4.329	0.747	57	4.522	0.824
20-WB	R2-2	55	4.219	0.667	27	4.491	0.717
Total/Weighted Avg.		2194	3.843	0.660	1329	3.948	0.671

*Method 2 requires only rejected gap. Method 3 requires rejected gap AND waiting queue.

Follow-up headway with and without consideration of exiting vehicles

Site #	Configuration	No Exiting Veh. Consideration: Number of Observations, n	Mean	Std. Dev.	With Exiting Veh. Consideration: Number of Observations, n	Mean	Std. Dev.
04-EB	R2-2	23	2.661	0.794	3	2.369	0.385
04-SB	R2-2	41	2.709	0.628	22	2.638	0.462
04-WB	R2-2	69	2.768	0.597	21	2.595	0.544
05-EB	R2-2	35	2.861	0.811	9	2.595	0.693
05-SB	R2-2	88	3.126	0.791	32	2.802	0.729
09-NB	R2-2	60	2.442	0.605	29	2.262	0.482
10-EB	R2-2	68	2.590	0.623	31	2.535	0.642
10-SB	R2-2	129	2.994	0.865	55	2.694	0.694
12-NB	R2-2	119	2.703	0.604	95	2.662	0.587
13-EB	R2-2	74	2.681	0.639	22	2.370	0.432
14-EB	R2-2	16	2.763	0.760	6	2.607	0.742
15-NB	R2-2	56	2.841	0.748	32	2.652	0.735
15-WB	R2-2	43	3.157	0.744	15	2.997	0.514
17-SB	R2-2	14	2.738	0.871	9	2.725	0.875
19-NB	R2-2	59	2.609	0.685	32	2.337	0.505
19-WB	R2-2	51	2.590	0.615	25	2.417	0.456
20-WB	R2-2	25	2.946	0.970	10	2.377	0.519
Total/Weighted Avg.		970	2.788	0.708	448	2.587	0.594

Left lane of two-lane entries conflicted by two circulating lanes (L2-2)

Critical gap without consideration of exiting vehicles

Site #	Configuration	Method 2* Number of Observations, n	Method 2* Mean	Method 2* Std. Dev.	Method 3* Number of Observations, n	Method 3* Mean	Method 3* Std. Dev.
04-EB	L2-2	44	4.722	1.053	22	4.958	1.057
04-SB	L2-2	211	4.172	0.855	137	4.388	0.842
04-WB	L2-2	86	4.457	0.590	58	4.505	0.542
05-EB	L2-2	184	4.547	0.857	116	4.525	0.760
05-SB	L2-2	179	4.789	1.133	125	4.992	1.287
08-WB	L2-2	261	4.515	1.015	209	4.627	1.110
09-NB	L2-2	69	5.262	0.768	42	5.136	0.693
10-EB	L2-2	254	4.189	1.017	145	4.455	1.138
10-SB	L2-2	179	4.492	0.933	138	4.532	0.952
12-NB	L2-2	117	4.437	0.875	65	4.688	0.966
13-EB	L2-2	137	4.445	0.679	93	4.503	0.733
14-EB	L2-2	83	4.460	0.860	55	4.699	0.770
15-NB	L2-2	191	4.515	0.826	142	4.577	0.859
15-WB	L2-2	150	4.570	1.110	113	4.658	1.191
17-SB	L2-2	113	4.613	0.727	34	4.879	0.731
19-NB	L2-2	82	4.836	0.758	28	4.662	0.717
19-WB	L2-2	69	4.642	0.812	29	4.947	0.868
20-NB	L2-2	64	5.107	1.243	33	5.458	1.273
Total/Weighted Avg.		2473	4.523	0.911	1584	4.642	0.959

*Method 2 requires only rejected gap. Method 3 requires rejected gap AND waiting queue.

Critical gap with consideration of exiting vehicles

Site #	Configuration	Method 2* Number of Observations, n	Method 2* Mean	Method 2* Std. Dev.	Method 3* Number of Observations, n	Method 3* Mean	Method 3* Std. Dev.
04-EB	L2-2	64	4.296	0.834	26	4.500	0.727
04-SB	L2-2	207	3.607	0.587	130	3.727	0.489
04-WB	L2-2	110	3.844	0.660	55	4.039	0.731
05-EB	L2-2	183	3.735	0.762	106	3.741	0.691
05-SB	L2-2	206	3.581	0.716	118	3.730	0.784
09-NB	L2-2	99	4.211	0.571	42	4.390	0.581
10-EB	L2-2	254	3.783	0.580	141	4.117	1.123
10-SB	L2-2	204	3.828	0.715	147	3.876	0.725
12-NB	L2-2	121	4.108	0.869	61	4.474	0.965
13-EB	L2-2	149	3.567	0.571	82	3.673	0.697
14-EB	L2-2	99	4.198	0.725	53	4.316	0.806
15-NB	L2-2	192	4.017	0.713	132	4.100	0.724
15-WB	L2-2	162	3.501	0.571	113	3.651	0.565
17-SB	L2-2	120	4.186	0.766	35	4.344	0.997
19-NB	L2-2	91	4.493	0.794	26	4.748	0.858
19-WB	L2-2	90	4.288	0.799	30	4.810	0.960
20-NB	L2-2	67	4.479	1.043	30	5.076	0.959
20-WB	L2-2	44	4.117	0.495	18	4.161	0.536
Total/Weighted Avg.		2462	3.893	0.692	1345	4.014	0.759

*Method 2 requires only rejected gap. Method 3 requires rejected gap AND waiting queue.

Follow-up headway with and without consideration of exiting vehicles

Site #	Configuration	No Exiting Veh. Consideration			With Exiting Veh. Consideration		
		Number of Observations, n	Mean	Std. Dev.	Number of Observations, n	Mean	Std. Dev.
04-EB	L2-2	29	2.371	0.406	9	2.298	0.450
04-SB	L2-2	52	2.882	0.716	26	2.755	0.718
04-WB	L2-2	50	2.767	0.546	18	2.604	0.477
05-EB	L2-2	58	3.085	0.797	19	2.762	0.732
05-SB	L2-2	100	3.202	0.869	29	2.796	0.709
08-WB	L2-2	144	2.335	0.617	---	---	---
09-NB	L2-2	44	2.723	0.908	18	2.292	0.396
10-EB	L2-2	67	2.855	0.667	24	2.635	0.567
10-SB	L2-2	99	2.895	0.812	45	2.549	0.706
12-NB	L2-2	44	2.627	0.578	36	2.628	0.584
13-EB	L2-2	85	2.687	0.629	19	2.283	0.509
14-EB	L2-2	52	2.748	0.680	21	2.435	0.520
15-NB	L2-2	65	2.998	0.848	38	2.822	0.757
15-WB	L2-2	70	3.057	0.859	24	2.551	0.638
17-SB	L2-2	15	2.847	0.784	10	2.577	0.383
19-NB	L2-2	19	2.476	0.553	12	2.384	0.507
19-WB	L2-2	27	2.700	0.715	12	2.381	0.487
20-NB	L2-2	21	2.788	0.680	15	2.653	0.433
20-WB	L2-2	15	2.886	0.651	8	2.695	0.805
Total/Weighted Avg.		1056	2.794	0.718	383	2.595	0.608

Right lane yielding bypass lane conflicted by one exiting lane (R-bypass-1)

Critical gap without consideration of exiting vehicles

Site #	Configuration	Method 2*			Method 3*		
		Number of Observations, n	Mean	Std. Dev.	Number of Observations, n	Mean	Std. Dev.
03-EB	R-bypass-1	42	3.933	0.831	37	4.045	0.817
Total/Weighted Avg.		42	3.933	0.831	37	4.045	0.817

*Method 2 requires only rejected gap. Method 3 requires rejected gap AND waiting queue.

Critical gap with consideration of exiting vehicles

Site #	Configuration	Method 2*			Method 3*		
		Number of Observations, n	Mean	Std. Dev.	Number of Observations, n	Mean	Std. Dev.
03-EB	R-bypass-1	71	3.703	0.520	56	3.810	0.453
Total/Weighted Avg.		71	3.703	0.520	56	3.810	0.453

*Method 2 requires only rejected gap. Method 3 requires rejected gap AND waiting queue.

Follow-up headway with and without consideration of exiting vehicles

Site #	Configuration	No Exiting Veh. Consideration			With Exiting Veh. Consideration		
		Number of Observations, n	Mean	Std. Dev.	Number of Observations, n	Mean	Std. Dev.
03-EB	R-bypass-1	65	2.447	0.701	21	2.345	0.522
Total/Weighted Avg.		65	2.447	0.701	21	2.345	0.522

Right lane yielding bypass lane conflicted by two exiting lanes (R-bypass-2)

Critical gap without consideration of exiting vehicles

Site #	Configuration	Method 2* Number of Observations, n	Method 2* Mean	Method 2* Std. Dev.	Method 3* Number of Observations, n	Method 3* Mean	Method 3* Std. Dev.
08-WB	R-bypass-2	74	4.214	0.916	---	---	---
20-NB	R-bypass-2	46	4.603	0.996	12	4.793	0.918
Total/Weighted Avg.		120	4.363	0.947	12	4.793	0.918

*Method 2 requires only rejected gap. Method 3 requires rejected gap AND waiting queue.

Critical gap with consideration of exiting vehicles

Site #	Configuration	Method 2* Number of Observations, n	Method 2* Mean	Method 2* Std. Dev.	Method 3* Number of Observations, n	Method 3* Mean	Method 3* Std. Dev.
20-NB	R-bypass-2	43	4.154	0.855	11	4.097	0.911
Total/Weighted Avg.		43	4.154	0.855	11	4.097	0.911

*Method 2 requires only rejected gap. Method 3 requires rejected gap AND waiting queue.

Follow-up headway with and without consideration of exiting vehicles

Site #	Configuration	No Exiting Veh. Consideration Number of Observations, n	No Exiting Veh. Consideration Mean	No Exiting Veh. Consideration Std. Dev.	With Exiting Veh. Consideration Number of Observations, n	With Exiting Veh. Consideration Mean	With Exiting Veh. Consideration Std. Dev.
08-WB	R-bypass-2	15	2.547	0.307	---	---	---
20-NB	R-bypass-2	10	3.166	0.728	2	2.774	1.032
Total/Weighted Avg.		25	2.794	0.475	2	2.774	1.032

Right lane of three-lane entries conflicted by one circulating lane (R3-1)

Critical gap without consideration of exiting vehicles

Site #	Configuration	Method 2*			Method 3*		
		Number of Observations, n	Mean	Std. Dev.	Number of Observations, n	Mean	Std. Dev.
08-SB	R3-1	101	4.161	1.065	70	4.373	1.157
Total/Weighted Avg.		101	4.161	1.065	70	4.373	1.157

*Method 2 requires only rejected gap. Method 3 requires rejected gap AND waiting queue.

Critical gap with consideration of exiting vehicles

Site #	Configuration	Method 2*			Method 3*		
		Number of Observations, n	Mean	Std. Dev.	Number of Observations, n	Mean	Std. Dev.
08-SB	R3-1	131	4.022	0.673	68	4.099	0.735
Total/Weighted Avg.		131	4.022	0.673	68	4.099	0.735

*Method 2 requires only rejected gap. Method 3 requires rejected gap AND waiting queue.

Follow-up headway with and without consideration of exiting vehicles

Site #	Configuration	No Exiting Veh. Consideration			With Exiting Veh. Consideration		
		Number of Observations, n	Mean	Std. Dev.	Number of Observations, n	Mean	Std. Dev.
08-SB	R3-1	62	2.614	0.732	24	2.358	0.349
Total/Weighted Avg.		62	2.614	0.732	24	2.358	0.349

Center lane of three-lane entries conflicted by one circulating lane (C3-1)

Critical gap without consideration of exiting vehicles

Site #	Configuration	Method 2*			Method 3*		
		Number of Observations, n	Mean	Std. Dev.	Number of Observations, n	Mean	Std. Dev.
08-SB	C3-1	172	4.460	0.814	125	4.432	0.723
Total/Weighted Avg.		172	4.460	0.814	125	4.432	0.723

*Method 2 requires only rejected gap. Method 3 requires rejected gap AND waiting queue.

Critical gap with consideration of exiting vehicles

Site #	Configuration	Method 2*			Method 3*		
		Number of Observations, n	Mean	Std. Dev.	Number of Observations, n	Mean	Std. Dev.
08-SB	C3-1	206	4.046	0.644	136	4.135	0.643
Total/Weighted Avg.		206	4.046	0.644	136	4.135	0.643

*Method 2 requires only rejected gap. Method 3 requires rejected gap AND waiting queue.

Follow-up headway with and without consideration of exiting vehicles

Site #	Configuration	No Exiting Veh. Consideration			With Exiting Veh. Consideration		
		Number of Observations, n	Mean	Std. Dev.	Number of Observations, n	Mean	Std. Dev.
08-SB	C3-1	99	2.810	0.766	33	2.575	0.632
Total/Weighted Avg.		99	2.810	0.766	33	2.575	0.632

Left lane of three-lane entries conflicted by one circulating lane (L3-1)

Critical gap without consideration of exiting vehicles

Site #	Configuration	Method 2*: Number of Observations, n	Method 2*: Mean	Method 2*: Std. Dev.	Method 3*: Number of Observations, n	Method 3*: Mean	Method 3*: Std. Dev.
08-SB	L3-1	230	4.503	0.941	182	4.551	0.928
Total/Weighted Avg.		230	4.503	0.941	182	4.551	0.928

*Method 2 requires only rejected gap. Method 3 requires rejected gap AND waiting queue.

Critical gap with consideration of exiting vehicles

Site #	Configuration	Method 2*: Number of Observations, n	Method 2*: Mean	Method 2*: Std. Dev.	Method 3*: Number of Observations, n	Method 3*: Mean	Method 3*: Std. Dev.
08-SB	L3-1	246	4.004	0.664	178	3.998	0.671
Total/Weighted Avg.		246	4.004	0.664	178	3.998	0.671

*Method 2 requires only rejected gap. Method 3 requires rejected gap AND waiting queue.

Follow-up headway with and without consideration of exiting vehicles

Site #	Configuration	No Exiting Veh. Consideration: Number of Observations, n	No Exiting Veh. Consideration: Mean	No Exiting Veh. Consideration: Std. Dev.	With Exiting Veh. Consideration: Number of Observations, n	With Exiting Veh. Consideration: Mean	With Exiting Veh. Consideration: Std. Dev.
08-SB	L3-1	132	2.647	0.770	44	2.344	0.667
Total/Weighted Avg.		132	2.647	0.770	44	2.344	0.667

Right lane of three-lane entries conflicted by two circulating lanes (R3-2)

Critical gap without consideration of exiting vehicles

Site #	Configuration	Method 2* Number of Observations, n	Method 2* Mean	Method 2* Std. Dev.	Method 3* Number of Observations, n	Method 3* Mean	Method 3* Std. Dev.
14-NB	R3-2	89	4.327	1.274	46	4.640	1.361
Total/Weighted Avg.		89	4.327	1.274	46	4.640	1.361

*Method 2 requires only rejected gap. Method 3 requires rejected gap AND waiting queue.

Critical gap with consideration of exiting vehicles

Site #	Configuration	Method 2* Number of Observations, n	Method 2* Mean	Method 2* Std. Dev.	Method 3* Number of Observations, n	Method 3* Mean	Method 3* Std. Dev.
14-NB	R3-2	95	3.843	0.807	49	3.981	0.733
Total/Weighted Avg.		95	3.843	0.807	49	3.981	0.733

*Method 2 requires only rejected gap. Method 3 requires rejected gap AND waiting queue.

Follow-up headway with and without consideration of exiting vehicles

Site #	Configuration	No Exiting Veh. Consideration Number of Observations, n	No Exiting Veh. Consideration Mean	No Exiting Veh. Consideration Std. Dev.	With Exiting Veh. Consideration Number of Observations, n	With Exiting Veh. Consideration Mean	With Exiting Veh. Consideration Std. Dev.
14-NB	R3-2	27	2.609	0.527	13	2.490	0.447
Total/Weighted Avg.		27	2.609	0.527	13	2.490	0.447

Center lane of three-lane entries conflicted by two circulating lanes (C3-2)

Critical gap without consideration of exiting vehicles

Site #	Configuration	Method 2* Number of Observations, n	Method 2* Mean	Method 2* Std. Dev.	Method 3* Number of Observations, n	Method 3* Mean	Method 3* Std. Dev.
14-NB	C3-2	147	4.335	0.620	93	4.373	0.604
Total/Weighted Avg.		147	4.335	0.620	93	4.373	0.604

*Method 2 requires only rejected gap. Method 3 requires rejected gap AND waiting queue.

Critical gap with consideration of exiting vehicles

Site #	Configuration	Method 2* Number of Observations, n	Method 2* Mean	Method 2* Std. Dev.	Method 3* Number of Observations, n	Method 3* Mean	Method 3* Std. Dev.
14-NB	C3-2	154	3.938	0.616	91	3.997	0.552
Total/Weighted Avg.		154	3.938	0.616	91	3.997	0.552

*Method 2 requires only rejected gap. Method 3 requires rejected gap AND waiting queue.

Follow-up headway with and without consideration of exiting vehicles

Site #	Configuration	No Exiting Veh. Consideration Number of Observations, n	No Exiting Veh. Consideration Mean	No Exiting Veh. Consideration Std. Dev.	With Exiting Veh. Consideration Number of Observations, n	With Exiting Veh. Consideration Mean	With Exiting Veh. Consideration Std. Dev.
14-NB	C3-2	53	2.617	0.590	29	2.382	0.553
Total/Weighted Avg.		53	2.617	0.590	29	2.382	0.553

Left lane of three-lane entries conflicted by two circulating lanes (L3-2)

Critical gap without consideration of exiting vehicles

Site #	Configuration	Method 2*			Method 3*		
		Number of Observations, n	Mean	Std. Dev.	Number of Observations, n	Mean	Std. Dev.
14-NB	L3-2	29	4.523	0.478	---	---	---
Total/Weighted Avg.		29	4.523	0.478	0	0.000	0.000

*Method 2 requires only rejected gap. Method 3 requires rejected gap AND waiting queue.

Critical gap with consideration of exiting vehicles

Site #	Configuration	Method 2*			Method 3*		
		Number of Observations, n	Mean	Std. Dev.	Number of Observations, n	Mean	Std. Dev.
14-NB	L3-2	31	3.847	0.752	---	---	---
Total/Weighted Avg.		31	3.847	0.752	0	0.000	0.000

*Method 2 requires only rejected gap. Method 3 requires rejected gap AND waiting queue.

Follow-up headway with and without consideration of exiting vehicles

Site #	Configuration	No Exiting Veh. Consideration			With Exiting Veh. Consideration		
		Number of Observations, n	Mean	Std. Dev.	Number of Observations, n	Mean	Std. Dev.
---	---	---	---	---	---	---	---
Total/Weighted Avg.		---	---	---	---	---	---

APPENDIX B

LANE UTILIZATION DATA FOR ANALYZED APPROACHES

Site #	Peak Hour	NB-L	NB-C	NB-R	SB-L	SB-C	SB-R	EB-L	EB-C	EB-R	WB-L	WB-C	WB-R
01	4:30-5:30pm		*255*						*510*		465	---	135
03	4:45-5:45pm	425	---	485				840	---	1,030			
04	4:15-5:15pm				290	---	305	515	560	160	515	615	120
05	3:45-4:45pm				490	---	430	295	---	255			
06	4:30-5:30pm				365	---	150		*420*			*535*	
07	4:45-5:45pm		*535*			*575*			*640*			*755*	
08	4:30-5:30pm				535	510	495				450	---	155
09	4:30-5:30pm	535	---	740								*120*	
10	4:30-5:30pm				450	---	550	300	---	400			
12	4:00-5:00pm	410	---	670									
13	4:15-5:15pm							555	---	625			
14	4:30-5:30pm	55	335	270				535	---	355			
15	4:45-5:45pm	355	---	415							395	---	365
16	4:30-5:30pm					*480*		215	---	190			
17	4:30-5:30pm				135	---	200						
19	4:15-5:15pm	140	---	385				585	---	705	230	---	390
20	4:30-5:30pm	170	---	155							245	---	635

01	4:30-5:30pm		*100%*						*100%*		78%	---	23%
03	4:45-5:45pm	47%	---	53%				45%	---	55%			
04	4:15-5:15pm				49%	---	51%	42%	45%	13%	41%	49%	10%
05	3:45-4:45pm				53%	---	47%	54%	---	46%			
06	4:30-5:30pm				71%	---	29%		*100%*			*100%*	
07	4:45-5:45pm		*100%*			*100%*			*100%*			*100%*	
08	4:30-5:30pm				35%	33%	32%				74%	---	26%
09	4:30-5:30pm	42%	---	58%								*100%*	
10	4:30-5:30pm				45%	---	55%	43%	---	57%			
12	4:00-5:00pm	38%	---	62%									
13	4:15-5:15pm							47%	---	53%			
14	4:30-5:30pm	8%	51%	41%				60%	---	40%			
15	4:45-5:45pm	46%	---	54%							52%	---	48%
16	4:30-5:30pm					*100%*		53%	---	47%			
17	4:30-5:30pm				40%	---	60%						
19	4:15-5:15pm	27%	---	73%				45%	---	55%	37%	---	63%
20	4:30-5:30pm	52%	---	48%							28%	---	72%

*merged and italicized indicates single lane approach; "---" indicates lane doesn't exist; gray fill indicates approach not analyzed in gap/headway analysis