DRIVER ADAPTATION TO A NEW TWO-LANE ROUNDABOUT: A NEW PERSPECTIVE USING DRONES

by

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Abstract

The first two-lane roundabout in New Brunswick opened in Fredericton on September 2015. The roundabout development raised significant safety concerns given the unfamiliarity that local drivers had with using two-lane roundabouts. The project provided a unique opportunity to study driver behaviour and how it changed over time as drivers became more familiar with its operation. Video footage was collected at approximately 1-month intervals for a year through the use of an unmanned aerial vehicle (UAV) to extract driver error information. The most commonly observed driver errors by rank were 1. *changing lanes within the roundabout*, 2. *drivers not yielding* to traffic already in roundabout, 3. *improper lane usage*, 4. *stopping within roundabout*, 5. *not giving right-of-way to trucks*, and 6. *left-turns*. The overall rate of driver errors fell by 67% within the first 15 weeks following opening and remained fairly consistent thereafter.

Operational analyses were completed which indicated that the default critical and follow-up headway values used by HCS 2010 underestimate driver behaviour relative to gap-acceptance. New critical and follow-up headway values were developed based on video analysis to better reflect local driver characteristics.

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List of Acronyms

AADT	Annual Average Daily Traffic
AMA	Academy of Model Aeronautics Application
FHWA	Federal Highway Administration
HCM	Highway Capacity Manual
HCS	Highway Capacity Software
LOS	Level of Service
MAAC	Model Aeronautics Association of Canada
NCHRP	National Cooperative Highway Research Program
PDF	Probability Distribution Function
PDO	Property Damage Only
PFI	Potential for Improvement
SPF	Safety Performance Function
TAC	Transportation Association of Canada
UAV	Unmanned Aerial Vehicle

1 INTRODUCTION

The first two-lane roundabout in New Brunswick was proposed in 2013 to create a connection between two of Fredericton's busiest urban collectors (Smythe Street and Bishop Drive). A unique aspect of the roundabout is that it included Route 8, a 4-lane divided provincial arterial highway posted at 90 km/h, shown in Figure 1. Concern was expressed due to the unfamiliarity of drivers with this type of facility and high-speed approaches. The development of this roundabout provided a unique opportunity to study driver behaviour and adaptation since the vast majority of drivers would not have been exposed to this configuration. The intent was to document the types of driver errors and how quickly the error rates change as drivers become familiar with the facility. Underlying safety of the roundabout was investigated with varying levels of proxies including driver errors and collisions.

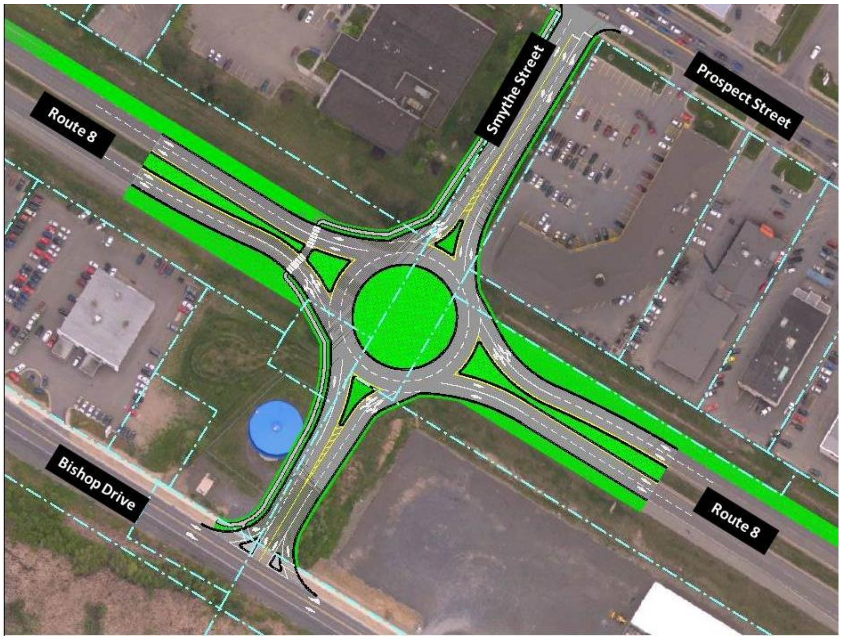


Figure 1: Smythe Street/Route 8 Roundabout [City of Fredericton]

The two-lane roundabout opened in September 2015 and included many safety features to reduce highway driver speeds such as raised medians and central island with landscaping, removal of shoulders, introduction of curbs, reverse curves, oversized guide signs, and low mounted luminaires. An extensive public education campaign was also undertaken by the City of Fredericton to help drivers become more comfortable with how the facility is to be driven.

The use of both an Unmanned Aerial Vehicle (UAV) and a GoPro camera installed on a nearby water tower provided overhead video of drivers as they navigated through the roundabout. The UAV provided such high quality footage that early on it was decided to rely on this collection method solely and abandon the perspective given by the water tower. Using the video footage, driver error was investigated from the opening of the roundabout when drivers were most unfamiliar, continuing throughout a full year to capture the rate at which drivers become accustomed to the facility. Determining what common driving errors were being made within the roundabout and how they change over time indicates how the roundabout performs from a road safety perspective. Results can then be used to modify the current and future design and target driver education programs.

1.1 Problem Statement and Hypotheses

Implementing a two-lane roundabout in an area where two-lane roundabouts previously have not existed is likely to result in excessive driver errors. The subsequent driving errors made may be a natural response to an unfamiliar facility and will decrease as they become more accustomed to the facility, or some errors may be a result of ineffective engineering design. Significant research has been completed on single lane roundabouts, with little research being completed on the safety performance and driver adaptation of two-lane roundabouts.

A sub-problem of this study was to investigate the capacity of the roundabout in the summer of 2016 when traffic increased through the roundabout due to construction on an adjacent collector, Regent Street, in the City of Fredericton. The Smythe Street Roundabout and Regent Street overpass are the sole connectors of uptown Fredericton to greater Fredericton communities. The closing of the Regent Street overpass for maintenance directed significant commuter traffic to the two-lane roundabout, creating an observable saturated condition.

The primary hypotheses investigated by the proposed research are as follows: common driver errors were identifiable and had resulted as a response to the two-lane roundabout, driver errors were highest during the initial roundabout opening, and then decreased as drivers become more familiar with the roundabout. A secondary hypothesis investigated by the research states that observed capacity of this facility was significantly different than default values used in current Level of Service (LOS) software developed on the basis of U.S. and European observation. Critical and follow-up headways are default values used in LOS software which were estimated for the Smythe Street roundabout to then calibrate the LOS model to Eastern Canada.

1.2 Research Goals and Objectives

The primary goal of this research is to better understand driver performance and rate of adaptation to the implementation of a new two-lane roundabout.

The specific objectives of this study required to meet the research goal include:

1. To quantify driver performance over time by:
    i. Observing and quantifying changes in driver error rates over time
    ii. Observing and quantifying levels of near misses based on time-to-collisions predictions generated by vehicle tracking software
    iii. Analyzing reported motor vehicle collisions
2. To quantify facility capacity during periods of over-saturated demand by:
    i. Estimating the critical and follow-up headway accepted by drivers

1.3 Expected Outcomes

The expected results of the research include progress reports on the status of the driver errors within the roundabout to the traffic engineer at the City of Fredericton. The discretion of the traffic engineer can then be used to alter education campaigns or implement design improvements. Programs for future developments similar to the Smythe Street roundabout will benefit from the findings of this research.

There is currently not an example of a two-lane roundabout in New Brunswick; therefore, the research will also aid future jurisdictions in successfully implementing a two-lane roundabout based on the lessons learned surrounding driver unfamiliarity. The Smythe Street/ Route 8 roundabout will serve as an example of dominant driving errors within a two-lane roundabout in an environment with unfamiliar drivers. Common trends in collision or driver types may identify opportunities to improve design or educational materials.

Traffic capacity is an important measurement to predict how many vehicles can traverse a multi-lane roundabout. It also provides the foundation to permit level of service (LOS) analysis used to grade the operational performance of a facility. Given that critical and follow-up headways at two-lane roundabouts are rarely observed in Canada, the Smythe Street/Route 8 roundabout provided a unique opportunity in the summer of 2016 when an adjacent arterial route was closed for rehabilitation. Traffic from Regent Street was redirected to the two-lane roundabout, allowing for capacity observations to be made. It was hypothesized that redirection will increase traffic volumes above predicted peak hour capacities, as well as observed capacity of this facility would be significantly different than default values used in current LOS software developing on the basis of U.S. and European observation. Estimating the critical and follow-up headways accepted by drivers will provide more accurate default values to be used in LOS software analysis in Eastern Canada.

1.4 Scope

The video footage was limited to collecting data using a GoPro camera for 3-hour sample periods and the UAV for 1-hour periods (15 minutes per battery). Only these sized samples were possible due to video memory card constraints.

Critical and follow-up headways can only be estimated if the approach lanes are at or near capacity. The lanes used to estimate critical and follow-up headways were near or at capacity to ensure accurate results. One hour of peak traffic footage was used for critical and follow-up headway estimation due to time constraints for the analysis.

The collision data for the roundabout were received from The City of Fredericton in the form of police reports. New Brunswick collisions are reported if the collision results in property damage in excess of $1,000 or there is a personal injury. For the purpose of this research, reported collisions were assumed to represent all collisions that occurred at the roundabout which is consistent for comparison with established collision rates or Safety Performance Functions.

2 LITERATURE REVIEW

A literature review was conducted to investigate four main areas related to the current study: the safety benefits and common driver errors associated with two-lane roundabouts, the use of Unmanned Aerial Vehicles (UAVs) for traffic monitoring, and the capacity of two-lane roundabouts. Results of the most relevant findings are synthesized in the following sections.

2.1 Safety Benefits of Roundabouts

The safety benefits of roundabouts are well documented and researched. The US Department of Transportation states that roundabouts offer an overall crash frequency reduction due to fewer conflict points and lower speeds associated within roundabouts (FHWA 2000). Compared to traditional intersections, the most severe collisions are eliminated within roundabouts including head-on and side-impact collisions (Weber 2007). There are 32 vehicle conflict points and 24 pedestrian conflict points at a traditional 4-leg intersection, while only 8 vehicle conflicts and 8 pedestrian conflicts are found at a single lane roundabout, shown in Figure 2.1. It is necessary to understand the extensive safety benefits of roundabouts to justify their implementation in Fredericton despite driver unfamiliarity.

In addition to the improvement of safety for motorists, pedestrian safety is improved as well since pedestrians only cross one direction of traffic at a time within the roundabout compared to two directions within a traditional four leg intersection, limiting the distance the pedestrian is exposed to traffic (FHWA 2000; Weber 2007).

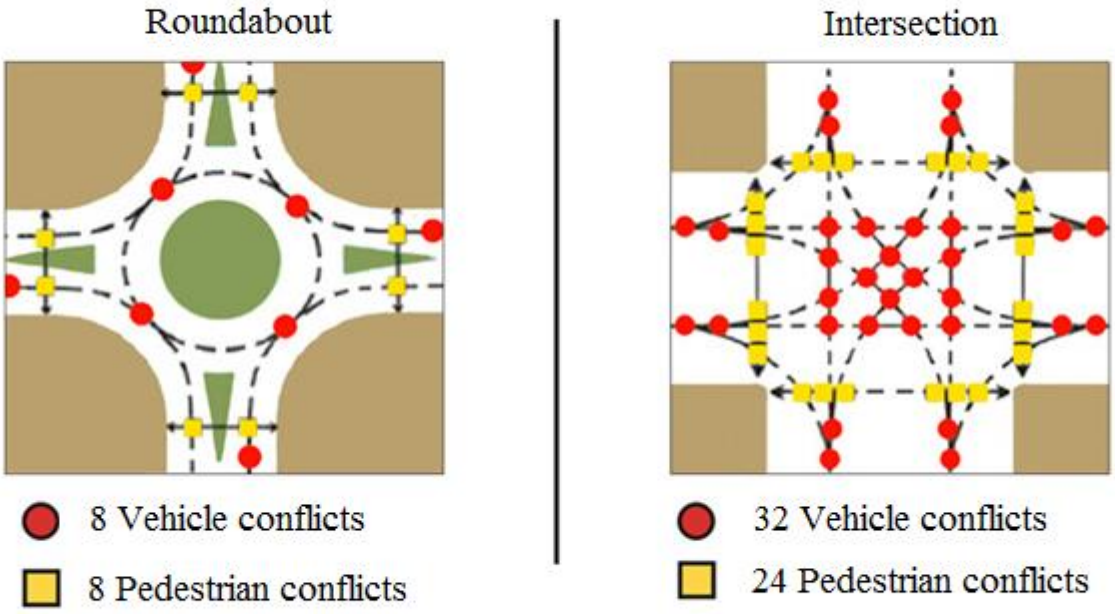


Figure 2.1: Roundabout vs. 4-leg intersection conflict points (Terra Designs 2016)

Conflicts occurring in two-lane roundabouts that do not happen in single-lane roundabouts can be categorized into three types: drivers fail to maintain lane position (Figure 2.2), drivers enter next to an exiting vehicle (Figure 2.3), or drivers turn from the incorrect lane (Figure 2.4) (FHWA 2000).

The collision type may be indicative of driver unfamiliarity, improper traffic control devices, or improper roundabout geometry, or a combination of these (FHWA 2000). Two-lane roundabouts do provide more opportunities for a collision compared to a single-lane roundabout; nonetheless, the overall severity of conflicts is typically less than other intersection alternatives (FHWA 2000).

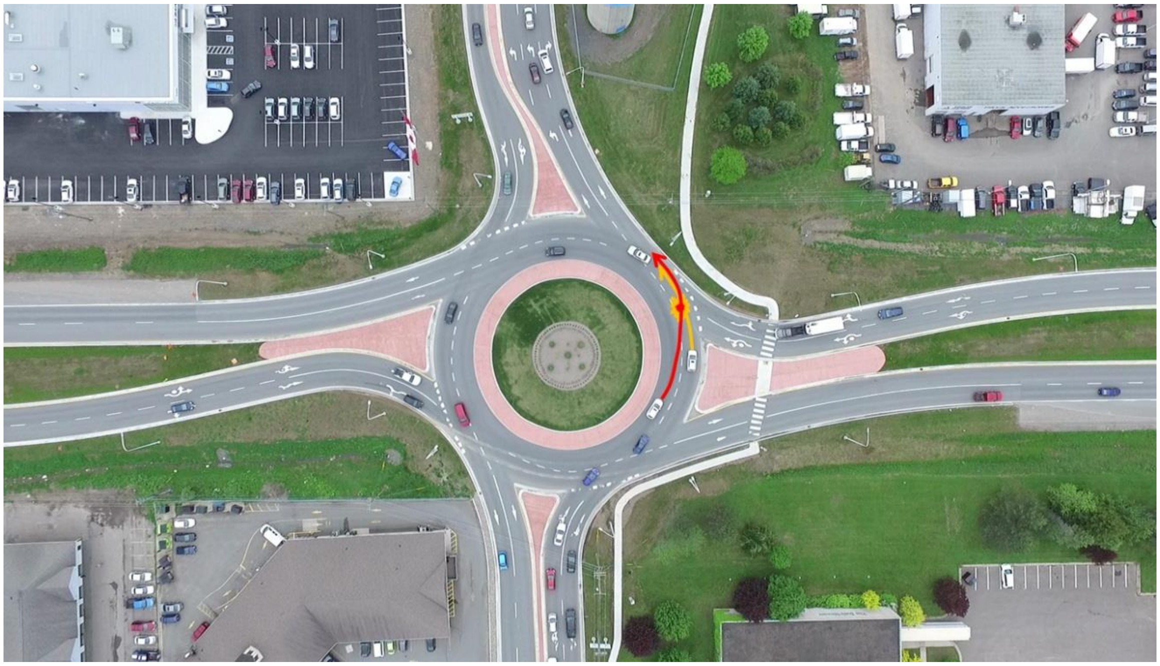


Figure 2.2: Driver fails to maintain lane position

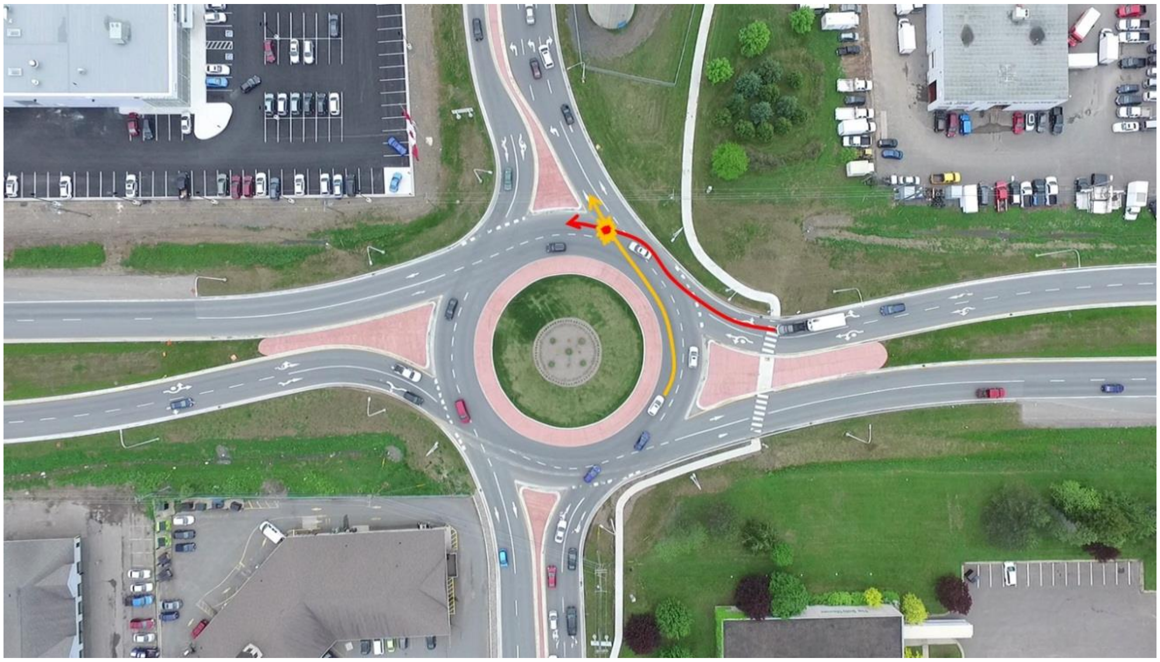


Figure 2.3: Driver enters next to exiting vehicle

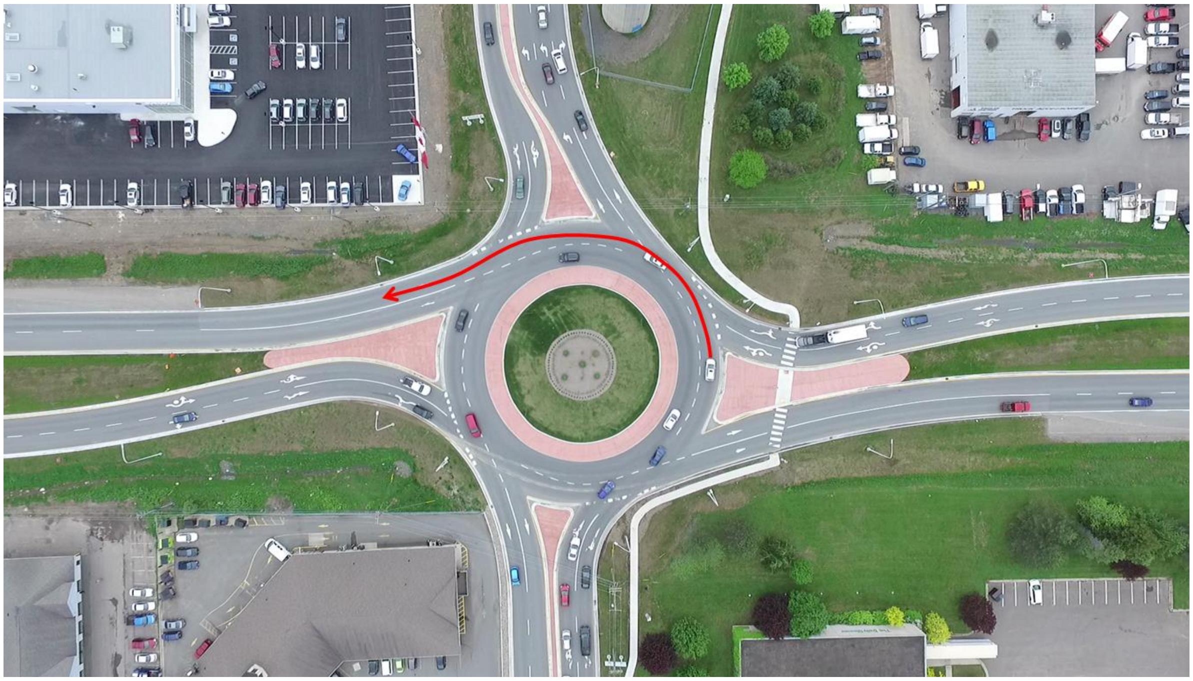


Figure 2.4: Driver turns from incorrect lane

Before-and-after results were collected from 55 sites in the United States where previous intersection treatment (two-way stop, all way stop, or signal control) were converted to roundabouts. An observed reduction of 35% and 76% in total and injury collisions were found, respectively, which was consistent with findings in Australia, France, Germany, Netherlands, and United States (FHWA 2000). A significant safety benefit was found in converting signalized and two-way stop controls to roundabouts, whereas conversions from all-way stop control (typically low-volume) found no apparent safety effect. Collisions causing injury were reduced more than all other crash types combined. A reduction in all collision types was found in rural environments where approach speeds were high (FHWA 2010). Further examples of before-and-after studies which found a reduction in total crashes following roundabout treatment (a distinction was not made between single or two-lane roundabouts) are presented by Damaskou *et al.* (2015) in Table 2.1.

Table 2.1: Average Annual Crash Frequencies Before and After Roundabout

Country	No. of intersections converted to roundabouts	Total Crashes		% reduction in crashes
		Before roundabout	After roundabout	
Netherlands	181	4.9	2.4	51
U.S.A	11	9.3	5.9	37
France	83	1.42	0.31	78
Australia	230	3.9	2.2	41
U.K.	38	9.7	6.2	31

All countries presented by Damaskou *et al.* (2015) experienced a percent reduction in crashes of 31% or greater after converting an intersection to a roundabout.

Roundabouts are often characterized by a reduction in delay when compared to a signalized intersection. This improved delay minimizes the likelihood of aggressive driving and risk-taking. Yielding to vehicles already in the roundabout creates a heightened awareness from the driver (Damaskou *et al.* 2015); furthermore, a driver who receives a green light at a signalized intersection feels empowered to drive aggressively, while a driver facing a yield condition does not (Damaskou *et al.* 2015).

2.2 Common Driver Errors

The Federal Highway Administration (2007) published their findings on the adjustment of driver behaviour to an urban two-lane roundabout in Oregon. Video footage was used to evaluate three aspects: speed variability while approaching the roundabout, lane changes within the roundabout, and late lane changes on the roundabout approach

(Joerger 2007). Speed variability while approaching the roundabout was investigated as traffic lights were previously present, which can cause speed variability (i.e. if the light is green drivers may accelerate to “make it”, or slowdown in anticipation of the coming red light). Joerger (2007) hypothesized the roundabout would decrease the speed variability. The report was kept brief, with specific driver errors outlined including abrupt lane changes within the roundabout in order to continue a (perceived) circulation and avoid exiting, as well as drivers who were observed making a late lane change from the left lane across a solid white line into the right lane as they approached the roundabout (Joerger 2007).

Multiple examples of single-lane and two-lane roundabouts were investigated by Mandavilli *et al.* (2009), who found major crash types of roundabouts included rear-end and sideswipe collisions, both of which can be speculated to be caused by the errors discussed in Oregon by the FHWA. Three quarters of the collisions investigated by Mandavilli *et al.* were property damage only with 14% involving at least one disabling injury (Mandavilli *et al.* 2009). The FHWA stated that the errors associated with the roundabout in Oregon followed a “learning curve” pattern which leveled off approximately six months after the opening of the roundabout (Joerger, 2007). Joerger (2007) used video footage to analyze a particular roundabout, while Mandavilli *et al.* (2009) reviewed 417 collision reports. The latter option can only be used when collision data from many years is available to be reviewed, as this is often not possible, the former option was employed for the current research.

A study by Polders *et al.* (2015) analyzed 399 PDO and injury only collisions on 28 roundabouts (109 crashes occurred at 3 two-lane roundabouts) in Belgium between 2005 and 2010. Police reports provided basic information such as time, place of occurrence, weather conditions, as well as crash type. Collisions were categorized into eight types: run-off-road, collision with central island, wrong-way, rear-end, loss of control, vulnerable road user (pedestrian, cyclists, etc.), entering-circulating, and sideswipe. While collisions with a central island may be considered a run-off-road collision, due to their prominence a specific category was created (Polders *et al.* 2015). Of the eight collision types, four main types (rear-end, collision with central island, entering-circulating, and vulnerable road user) accounted for 75% of the total collisions. Collisions pertaining to the central-island, loss-of-control, and sideswipes were significantly more prominent in a two-lane roundabout compared to a single-lane roundabout. Collisions occurred most commonly while entering the roundabout and while circulating, while the exiting lanes were an uncommon location for a collision. Crash severity was found to be dependent on road user type, with moped riders and cyclists being more likely to be injured in a collision than a passenger vehicle (Polders *et al.* 2015).

A study conducted in 1984 in the U.K. and presented by Damaskou *et al.* (2015) identified geometric variables which correlate to collision frequency and severity within a roundabout. Entry path curvature is the amount of deflection a vehicle exercises when entering the roundabout; minimizing this deflection lessens the likelihood of an entering circulating collision. Entry width increases entering-circulating collisions, but reduces approaching collisions; however, entering-collisions are the more severe of the two.

Significant research has been completed on single lane roundabouts in terms of road safety; however, little has been documented on common driving errors which are characteristic of a two-lane roundabout. Significantly different safety effects have been shown for two-lane roundabouts, given the increased number or conflict points compared to a single lane roundabout (Shadpour 2014), shown in Figure 2.5. Consequently, caution should be taken assuming errors found in single lane roundabouts are representative of errors found in two-lane roundabouts.

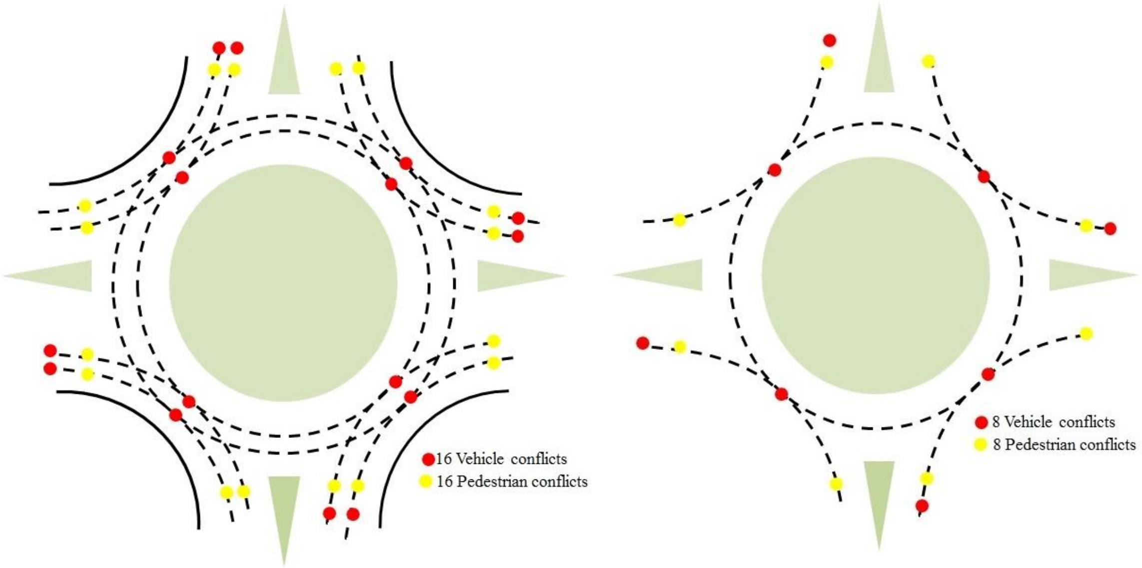


Figure 2.5: Two-lane roundabout vs. single lane roundabout conflict points

An experiment to change roundabout signs and lane markings was undertaken by state engineers in Richfield, Minnesota, with the aspiration to improve safety within the roundabout. The two-lane roundabout sees over 30,000 vehicles per day. The roundabout experienced unusually high collision rates following its opening, with 129 crashes occurring within the roundabout between September 2008 and November 2012 (Hourdos and Richfield 2014). Several hundred hours of video was reviewed prior to any changes to determine the number of driving errors. Video footage was also retrieved after the implemented roundabout changes, as well as a year later for a follow-up.

All relevant collisions (excluding drunk driving, distracted driving, and environmental condition related) were categorized into three types: yield violations, lane change violations, and turn violations. Turning violations were found to be responsible for the most severe crashes; therefore, special concern was given to this particular violation during the study. These turning violations included turning right from the inner lane, turning left from the outer lane, and turning more than 270 degrees (“U-turn”) (Hourdos and Richfield 2014). Most cases of improper lane selection also included a lane change and/or turn violation; therefore, the underlying cause of these violations was improper lane selection (Hourdos and Richfield 2014).

The pavement marking changes made included changing the turn arrows on the approaches from the “fish-hook” style (shown in Figure 2.6) to the standard style, including a dot to represent the roundabout island.

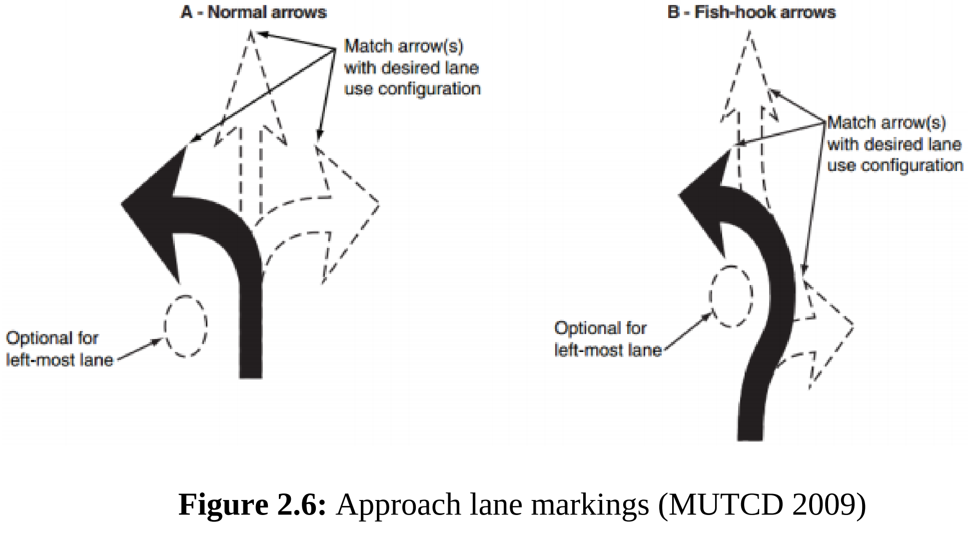


Figure 2.6: Approach lane markings (MUTCD 2009)

Additional turn arrows and lane designation signs were placed 450 metres upstream of the yield line on all legs of the roundabout. Solid lane line markings were extended from 50 feet upstream of the yield line to 250 feet, with solids and skips line markings being replaced with a consistent line gap within the roundabout. Research is inconclusive as to whether arrow or lane marking alternatives provide enhanced safety to a two-lane roundabout.

Hourdos and Richfield (2014) found a reduction in yielding and turning violations of 18% and 48%, respectively, occurred between the before and after data. The most common turning violation was making a left turn from the outer lane, which was categorized as an incorrect lane choice, decreased by 53%. Data were reviewed a year after the improvements, which showed a regression in some of the safety improvements. The 48% reduction in turning violations was consistent with the findings one year later; however, a 60% increase in yielding violations occurred between “after” and “one year after”. A significant effort in ticketing offenders was made at the time of the changes by police enforcement, which likely contributed to a short-term reduction in violations, and then surge in violations one year later, when strict police enforcement was no longer present. Another speculation for the rise in violations could be a result of driver familiarity. Driver familiarity most often aids in preventing driver error within a roundabout; however, there are cases where it is argued that driver familiarity can increase driving error. Referred to as a subset of “fail-to-yield” crashes, a driver in the right lane enters beside traffic circulating inside the roundabout causing a collision. This collision type often increases as drivers become more familiar with the roundabout, resulting in drivers becoming less cautious (Weber 2016).

Roundabouts operate under the principle that vehicles within the roundabout receive priority and the entry traffic must give way (Stuwe 1991). If entering traffic were given priority the roundabout would become locked by those already inside the roundabout (Stuwe 1991). Roundabouts in the West of France were surveyed and 202 total collisions involving personal injury were found to have occurred at 175 roundabouts (Alphand, Noelle & Guichet 1991). Each collision was separated by type and 74 of 202 (37%) were caused by “refusal of priority on entry” (i.e. not yielding to the traffic already inside the roundabout). This type of accident was the highest occurring accident, only followed by loss of control on entry (i.e. mounting the centre island) at 11%.

Notable trends found in driving errors, such as drivers not yielding to traffic already in the roundabout, indicate that corrective action should take place which could include modified public education campaigns or additional signage. Signage in New Brunswick poses a complication as both English and French are required to be used. A sign indicating “Yield to Both Lanes” can be quickly interpreted by an approaching vehicle; however, the presenting two languages may create a visual field that is cluttered and more difficult to process. Drivers not yielding to traffic already in the roundabout is an issue found in other jurisdictions as well. The Waterloo region has experienced the same yield problem, which a human factors specialist identified as a driver cognitive issue (Henderson 2015). A recent survey in Washtenaw County, Michigan, showed that 34% of drivers do not believe that when they are entering in the right lane they have to yield to all circulating traffic (Weber 2016). Total collisions and failure-to-yield collisions have been tracked by the Waterloo Region to track the success of each measure. Prior to any countermeasures, failure-to-yield collisions represented 61% of all collisions. Various countermeasures were undertaken including: relocating yield signs, bigger yield signs, yield tabs which included “yield to oncoming traffic” and “yield to all traffic in all lanes”, all of which were unsuccessful, with failure-to-yield collisions remaining essentially unchanged (Henderson 2015). Text-based “Caution” signs were recently installed, shown in Figure 2.7, which have reduced the proportion of failure-to-yield collisions by 10% to date.

Figure 2.7: Waterloo Region roundabout signage

The Region of Waterloo would have preferred to see a greater reduction in collisions, but believe the “Caution” signs resulted in a positive benefit to the roundabout. Despite this, they have scepticism that the decrease in collisions may be offset by an increase in rear-ends as more people may be yielding, although this has not been verified with data (Henderson 2015).

2.3 Unmanned Aerial Vehicles for Traffic Monitoring

Roadway networks can be difficult to monitor on the ground as they require fixed infrastructure and are labour intensive (Coifman *et al.* 2006). Technology advancements have challenged traditional means of gathering transportation data in favor of more efficient alternatives. The use of Unmanned Aerial Vehicles (UAVs), commonly known as drones, for traffic monitoring is a valuable tool to improve efficiency in data collection. Their use may be preferred for certain applications over inductive loop detectors, radar, and ultra-sound technologies because of low cost and improved mobility (Kanistras *et al*. 2013). UAVs, equipped with a video camera, geo-positioning sensors, and communications hardware to relay the data to the ground, are available on the commercial market. UAVs are able to cover a wide span of area efficiently, with minimal set up time. Many current models are equipped with cellular compatible technology, which allows a cell phone to serve as the control station, feeding live video footage from the drone to the cellular device in real time.

Research has been completed on UAVs at the Ohio State University, where a UAV complete with two cameras flew at an altitude of 150m for two hours, while transmitting video (Coifman *et al.* 2006). Ohio State investigated five applications for the UAV in terms of traffic monitoring: measuring level of service, estimating average annual daily travel, examining intersection operation, measuring original destination, and measuring parking lot utilization (Coifman *et al.* 2006). Ohio State's findings in intersection operations are most relevant to a roundabout analysis, which included analyzing video segments to determine queues, arrival rates, and turning movements (Coifman *et al.* 2006). Using similar methods, common driver errors can be determined as well as capacity for the Route 8/Smythe Street roundabout. Ohio State developed a simplistic computer program based on the queuing data to determine the capacity of the intersection (Coifman *et al.* 2006). In a similar manner, the capacity of the Route 8/Smythe Street roundabout can reasonably be determined as well.

Real time data allows for the mitigation and redirection of traffic should an emergency such as a collision, natural disaster, or humanitarian crisis occur (Lin and Saripalli 2012). Real-time data collection is difficult for a UAV due to the complexity of aerial images (Kanistras *et al*. 2013) and the subsequent reliance on post-data collection analysis. The University of California at Berkeley has developed an algorithm for real-time road detection using a UAV by processing a single image of the target road. The detection process assumes that roads are regions which can be approximated by line segments. The algorithm has been tested on ten thousand images which have been successful, and detection of multiple roads such as intersecting roads was possible in more than 50% of the images (Lin and Saripalli 2012).

Kanistras *et al.* have proposed a similar project where a UAV will collect real-time data to monitor traffic, evaluate and assess traffic patterns, and provide video counts. The vision system has on-board and on the ground processing capabilities which contain algorithms allowing for automatic adjustments to be made to the system.

2.4 Capacity of Roundabouts

The capacity of each entry to the roundabout is defined as “the maximum rate at which vehicles can reasonably be expected to enter the roundabout from an approach during a given time period under prevailing traffic and roadway (geometric) conditions” (Robinson and Rodegerdts 2000). Prevailing conditions indicate that rather than a single constant value, capacity varies as a function of traffic volumes (Akcelik 2005). The capacity is dependent on the entry flow and conflicting flow within a roundabout measured at the yield line, rather than the volume of each turning movement as is the case for a traditional intersection. Site-specific variables should be taken into account during capacity software evaluation. Geometric conditions that affect the entry capacity include approach half width (the narrowest width of the approach road prior to any flaring), entry width, entry angle, and average effective flare length (Robinson and Rodegerdts 2000).

Gap-acceptance parameters including critical and follow-up headways are a human factor which is valuable in determining the entry capacity of a roundabout. Giuffre *et al.* (2016) provide a systematic review of gap-acceptance parameters used worldwide. Capacity accuracy depends on an accurate estimation of critical headway and follow-up headway (Giuffre *et al.* 2016). A summary of this review including critical headway and follow-up headway presented by Giuffre *et al.* (2006) in Table 2.2. The data presented are based on real data at two-lane roundabouts.

Table 2.2: Critical and Follow-up Headway Values for Two-lane Roundabout

Country	Entry Lane	Critical Headway				Follow-up Headway			
		Mean (s)		St. Deviation (s)		Mean (s)		St. Deviation (s)	
		min	max	min	max	min	max	min	max
Canada	-	3.5	6.1	-	-	4.6	5	-	-
Denmark	left	3.9	4.1	-	-	2.6	-	-	-
	right	3.9	4.2	-	-	2.7	-	-	-
US	left	3.7	5.5	0.7	2.6	2.9	5	1	3.9
	right	3.2	4.9	1	3.8	2.8	4.4	0.8	2.3
The Netherlands	left	2.89	3.16	0.04	1.32	2.24	2.26	-	-

Critical and follow-up headways are two parameters which are key in determining the capacity of a facility. Follow-up headways can be measured in the field; however, critical headways cannot be measured directly (Gazarri et *al.* 2013). Two-lane roundabouts are more complicated than single-lane roundabouts in terms of gap theory, as a driver has to perceive a gap in both the inside and outside lane to navigate a safe entry. Some drivers entering from the right lane will yield to both lanes, but others will enter even as a vehicle is circulating in the inside lane if they do not perceive a collision risk (HCM 2010). Gap-acceptance behaviour for the right lane is therefore flawed, and a regression-based model is preferred to account for these factors (HCM 2010). HCM 2010 has recently been replaced by HCM 6th Edition, which has slightly lower follow-up headway estimates, but higher critical headway estimates than its predecessor (HCM 6th Edition 2016).

Many parameters for capacity analysis are approximations made from observed data elsewhere in the world. In Canada, variables used as inputs for capacity software are often based on findings in the USA, Australia, and the U.K. Driver behaviour in the vicinity of large vehicles is of particular interest as it is an approximated variable.

Robinson and Rodegerdts (2000) present three indicators used for performance analysis of a roundabout: degree of saturation, delay, and queue length. Degree of saturation is the demand volume to capacity ratio at the roundabout entry. Robinson and Rodegerdts (2000) cite Austroads (1993) when presenting the acceptable degree of saturation. The acceptable degree of saturation for an entry lane should be less than 0.85, as an exceedence of this range will cause roundabout users to experience an unacceptable delay.

The Transportation Research Board (2007) recommends an empirical regression model based on recent analysis of U.S. field data to determine the capacity of a two-lane circulatory roadway. The capacity of a two-lane entry into a two-lane circulatory roadway is described as:

$$c_{crit} = 1130 \exp(-0.007 \times v_c) \qquad \text{[Eq.2.1]}$$

where

c_{crit} = capacity of the critical lane (pcu/h)

v_c = conflicting flow (pcu/h)

The recommended control delay model is described as:

$$d = \frac{3600}{c} + 900T\left[\frac{v}{c} - 1 + \sqrt{\left(\frac{v}{c} - 1\right)^2} + \frac{\left(\frac{3600}{c}\right)\frac{v}{c}}{450T}\right] \qquad \text{[Eq.2.2]}$$

where

d = average control delay (s/veh)

c = capacity of subject lane (veh/h)

T = time period (T = 0.25 for a 15-min analysis)

v = flow in subject lane (veh/h)

The control delay experienced by drivers is a common traffic analysis tool to investigate capacity of an intersection, both signalized and unsignalized. The control delay experienced in a roundabout includes the delays experienced while travelling through the roundabout in addition to all acceleration and deceleration delays, as well as stopped delay (Akcelik 2005). Geometric delay is the delay experienced by a vehicle negotiating the roundabout in the absence of any other vehicles (Akcelik 2005). Geometric delay in LOS calculations as HCM defines LOS solely on control delay (NCHRP 2007).

Queue length is valuable in determining if the geometric design meets the demand needs of a facility. The 95th-percentile queue length indicates that 95% of the time the queue length is at or below this amount. The 95th-percentile queue for a given lane on an approach is determined using Equation 2.3:

$$Q_{95} = 900T\left[\left(x - 1^2 + \frac{\left(\frac{3,600}{c}\right)x}{150T}\right)\right]\left(\frac{c}{3,600}\right) \qquad \text{[Eq. 2.3]}$$

where

Q_{95} = 95th-percentile queue (veh)

x = volume-to-capacity ratio of the subject lane

c = capacity of the subject lane (veh/h)

T = time period (T = 1 for a 1-hr analysis)

To determine the entry flow and circulating flow the volume of each turning movement at each approach is required. The volumes should be collected for both the morning and evening peak periods. Vehicle type should be categorized as the size of vehicle is impactful to capacity, with conversion factors used to create passenger car equivalents (pce) for the vehicle count (Robinson and Rodegerdts 2000).

2.5 Estimating Critical and Follow-up Headways

Local values for critical and follow-up headways dictate capacity in a roundabout. A critical headway is defined as the minimum time interval in the major-street traffic stream that allows intersection entry for one minor-street vehicle (HCM 2010). A follow-up headway is defined as the time between the departure of one vehicle from the minor street and the departure of the next vehicle using the same gap under a condition of continuous queuing (HCM 2010). In the case of roundabouts, the approaches act as the minor street, and the circulating vehicles inside the roundabout function as the major street. Drivers will determine what critical and follow-up headways they feel comfortable with and will enter the roundabout accordingly.

Follow-up headways can be observed in-situ. Critical headways cannot be measured directly in the field as they are stochastically distributed (Wu 2012); only rejected and accepted gaps can be observed. A variety of estimation theories exist to determine the critical headway, all of which use the rejected and accepted gaps observed. Raff's method is the first method and is favoured for its ease of use. Raff's method states that the number of rejected headways larger than the critical headway is equal to the number of accepted headways smaller than the critical headway (Guo 2011). The critical headway occurs when the cumulative probability of acceptance and the cumulative probability of rejection intersect. This model is still used today due to its simplicity;

however, it includes shortcomings. Criticisms have been made that Raff’s method lacks a basis of theoretical principles. Furthermore, the critical headway determined by Raff’s method is the median value not the mean value (Guo 2011). The mean value exceeds the median value for lognormal-distributed critical headways; therefore, Raff’s method may underestimate the critical headway, resulting in an overestimation of the corresponding capacity (Wu 2012).

Other procedures including Troutbeck’s have their shortcomings as well. Troutbeck bases its theory on the Maximum Likelihood technique. The presumption required by Troutbeck’s model is that the maximum rejected gap must be smaller than the corresponding accepted gap for a vehicle for the data pair to be used (Wu 2012). Each observed vehicle may have multiple rejected gaps which provide valuable insight into driver behaviour; however, Troutbeck uses only the maximum rejected gap. This limitation unfortunately results in disqualifying a large portion of the data, with a large data set being required to stabilize the results provided by Troutbeck (Wu 2012).

A new method for determining the critical headway is presented by Wu (2006) based on the equilibrium of probabilities. Wu presents previous methods including Raff and Troutbeck, establishing their limitations and model assumptions. His model is then presented as an alternative which is based on a solid theoretical background, independent of any model assumptions, and takes into account all observed gaps (Wu 2006). Probability distribution functions (PDFs) were estimated through both the new model presented by Wu (2006) and Troutbeck for the same data set. Results for the mean values of the critical headway proved to be similar for both models (2006).

3 METHODOLOGY

This study involved the analysis of driver errors and the rate at which they change over time following the introduction of an unfamiliar facility. A secondary aspect to the research was to quantify facility capacity. The following sections present an overview of the methodology used for data collection and analyses of driving errors and safety, in addition to the methodology for investigating capacity during periods of over-saturated demand.

3.1 Data Collection

3.1.1 Video Footage

Data collection for the Route 8/Smythe Street roundabout began in September 2015 and continued to September 2016, resulting in the accumulation of a full year of data. A water tower near the roundabout presented a unique vantage point to capture video footage. A GoPro camera was installed on the water tower by city workers (ground level photo is shown in Figure 3.1), capturing approximately two hours of oblique footage in both September and October 2015.

Figure 3.1: Ground level water tower view

Video footage from the water tower required permission from the City of Fredericton, which included the understanding that no video equipment could be permanently attached to the water tower or cause any damage. A tripod mount was used to magnetically secure the GoPro to the edge of the water tower. A typical frame capture is shown in Figure 3.2.

Figure 3.2: GoPro frame capture

An unmanned aerial vehicle model DJI Phantom 3 Professional (Figure 3.3) was also flown for a one-hour period in conjunction with GoPro footage during the months of September and October 2015. Upon reviewing the footage, it was determined that quality of footage captured by the UAV was of significantly higher quality compared to that of the mounted water tower camera. Furthermore, the image provides a perfectly centered aerial image (rather than orthogonal) which provides the ability to monitor vehicle off-tracking throughout the roundabout. A typical frame capture is shown in Figure 3.3.

Figure 3.3: Aerial view of roundabout captured by drone from 150m

The rectangular-shaped frame of the footage was selected intentionally to allow a greater view of the Route 8 approaches. This allows for queuing to be shown for the purpose of capacity investigations, as well as speed investigations as vehicles transition from a rural two-lane divided highway into an urban two-lane roundabout.

Since the UAV also requires no installation, it was decided that the UAV would thereafter become the sole means of data collection for the remainder of the project. Data were collected once a month by the drone for a duration of approximately one hour at non-peak hours throughout the year to normalize for potentially aggressive driving during peak periods. The drone battery life was the limiting factor as each battery held approximately 15 minutes of charge, requiring four batteries to collect an hour of data. The UAV type used is shown in Figure 3.4.

Figure 3.4: DJI Phantom 3 Professional
[www.bhphotovideo.com]

3.1.2 Unmanned Aerial Vehicle Approval

Transport Canada is the governing body in Canada that is responsible for the regulation of UAVs in Canadian Airspace. An application was required as it was not possible for this project to “stay at least 30 metres away from people, animals, buildings, structures, and vehicles not involved in the operation”, which is required for an unmanned aerial vehicle of 2kg or less. Transport Canada states that there are two main types of applications, a Compliant Operation Application and a Restricted Operator Application, which has three sub methodologies: Complex Application, Simplified Application, and a Model Aeronautics Association of Canada/Academy of Model Aeronautics Application (MAAC/AMA). For the application of this project a Restricted Operator – Simplified Application was appropriate after discussion with the Atlantic Regional Civil Aviation Inspector.

A Restricted Operator Application is described by Transport Canada (2014) as:

> "Restricted Operator Application: These certificate applicants are either unable or unwilling to meet the criteria to become a Compliant Operator or compliance with these criteria is not required based on the scope and complexity of the operation. Again, these operators will be granted fewer privileges than those extended to Compliant Operators."

A Simplified Application is described by Transport Canada (2014) as:

> "Simplified Application: Applies to small UAVs, operated within Visual Line of Sight (VLOS) where the scope of operation is limited. See specific eligibility requirements and the SFOC application process in Section 11 of this Staff Instruction (SI)."

The Restricted Operator – Simplified Application format required information describing:

1. Applicant Main Contact
2. Operation Manager Main Contact
3. Operation Manager Flight Contact
4. Operation Type and Purpose
5. Operation Dates
6. UAV Specifications
7. Security Plan
8. Emergency Plan
9. Ground Supervisor Contact
10. Flight Plan
11. Pilot Qualifications
12. Inspections and Operations

The 14-page application was filed on May 11, 2015, with approval granted from Transport Canada on June 12, 2015. A renewal was filed in January 2016 for the blanket coverage of the remainder of the project (until September 2016), which was also approved.

3.1.3 Collision Data

Motor vehicle collision data at the roundabout location were collected by the Fredericton police department at the time of the collision. The collision data were received from The City in the form of police reports from the opening of the roundabout in September 2015 through to September 2016. In New Brunswick, collisions are reported if it results in property damage exceeding $1,000, or there is a personal injury. For the purpose of this research, reported collisions were assumed to represent all collisions that have occurred at the roundabout which is consistent for comparison with known collision rates or Safety Performance Functions.

3.1.4 Critical and Follow-up Headway Data

Accepted and rejected headways were recorded for all vehicles in the northbound and southbound approaches, as these approaches were observed to be operating at or near capacity. Figure 3.15 depicts the areas where time stamps were collected, using the northbound approach as illustration. For each approach lane analyzed, the time at which a vehicle came to a stop and entered the roundabout at line 2, shown in Figure 3.5, was recorded. The time when circulating vehicles in either the inside or outside lane crossed line 1 was also recorded. Using these three recordings, the accepted and rejected gaps by each entering driver was recorded. The follow-up headway was also recorded when two consecutive vehicles entered at line 2 using the same gap in circulating traffic, provided there were queuing conditions.

Figure 3.5: Follow-up headway data collection

3.2 Analyses

3.2.1 Manual Review of Errors

Data from the video footage were manually transcribed to identify types of driving errors made and how they change as drivers became more familiar with the roundabout. The errors counted were organized into six categories: changing lanes within the roundabout (Figure 3.6), not yielding to traffic already in the roundabout (Figure 3.7), stopping within the roundabout to allow approaching vehicles to enter (Figure 3.8), left-turn into roundabout (wrong-way) (Figure 3.9), passenger vehicles not giving right-of-way to trucks (Figure 3.10), and improper lane usage (i.e. using the approaching right lane to turn left, or using the approaching left lane to turn right) (Figure 3.11). In each Figure (3.6-3.11) the vehicle at fault is depicted with a red arrow.

If more than one error was made by a driver, the error more likely to cause a collision was counted. This method was used as the goal is not to solely count errors, but rather to measure error rates (errors per passenger vehicle). If a single passenger vehicle is counted twice (for multiple errors), this results in an incorrect estimate of the number of passenger vehicles making errors. Multiple errors were found only in cases where vehicles changed lanes within the roundabout, while also selecting the improper lane for their destination. In this case, selecting the improper lane was deemed more likely to cause a collision; therefore, this was the error counted.

Vehicles and truck counts were also completed manually to normalize the observed errors. Footage that was taken on the same day from both the drone and the GoPro that resulted in varying error values were averaged.

Figure 3.6: Changing lanes within roundabout

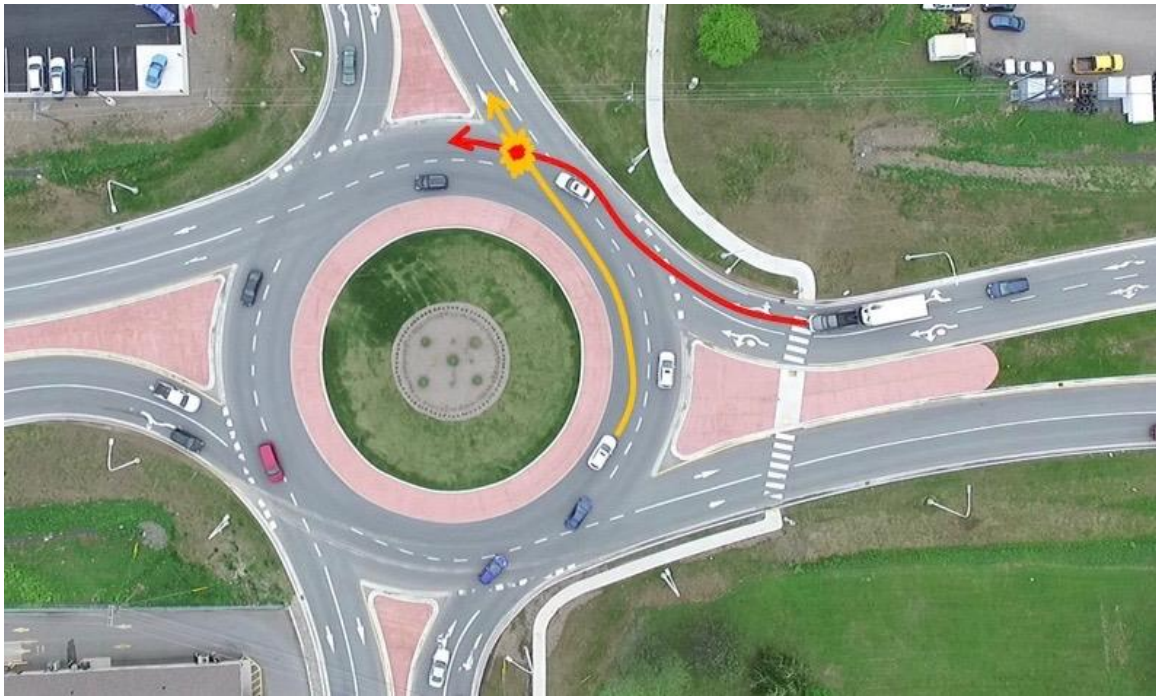


Figure 3.7: Not yielding to traffic already in roundabout

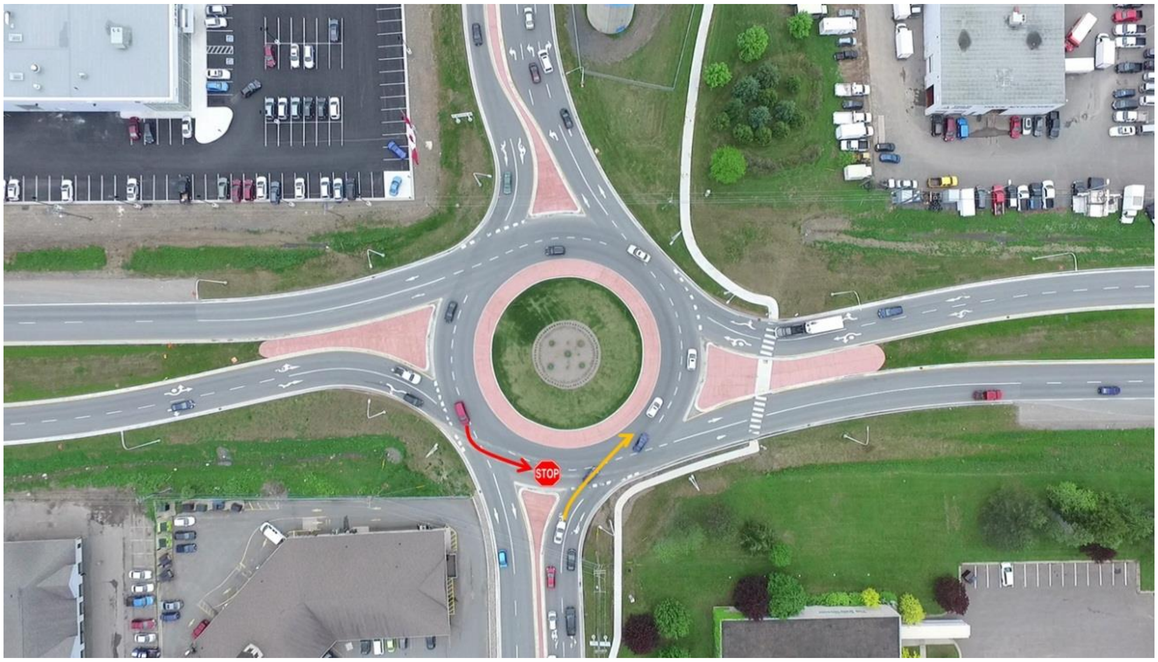


Figure 3.8: Stopping within roundabout

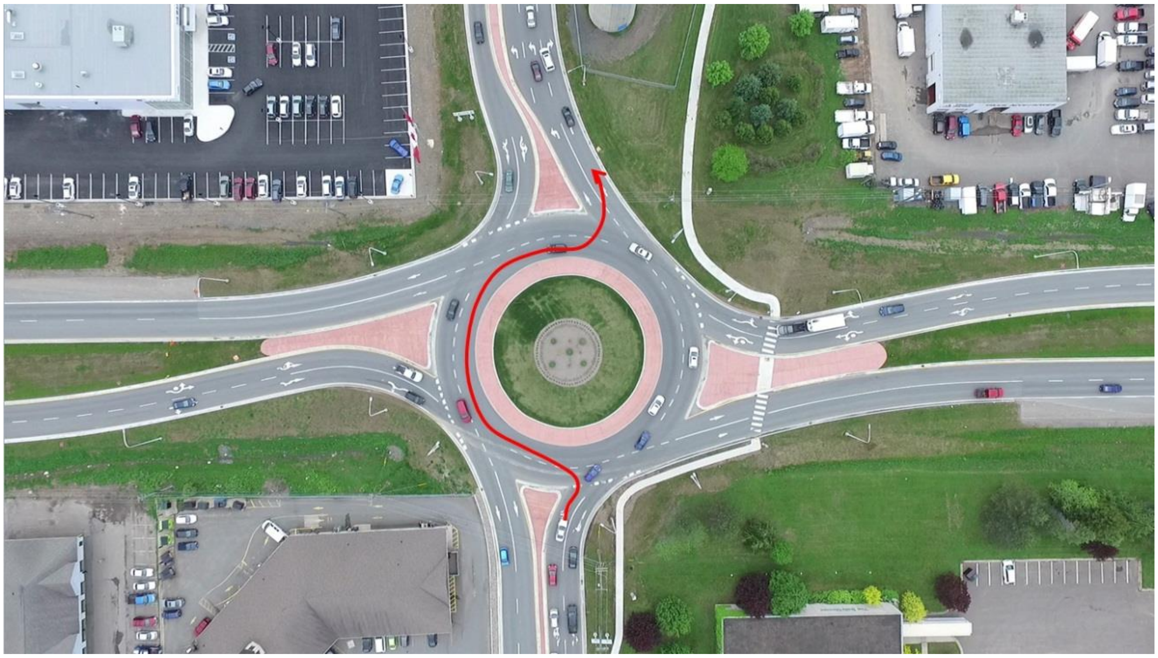


Figure 3.9: Left-turn into roundabout (wrong-way)

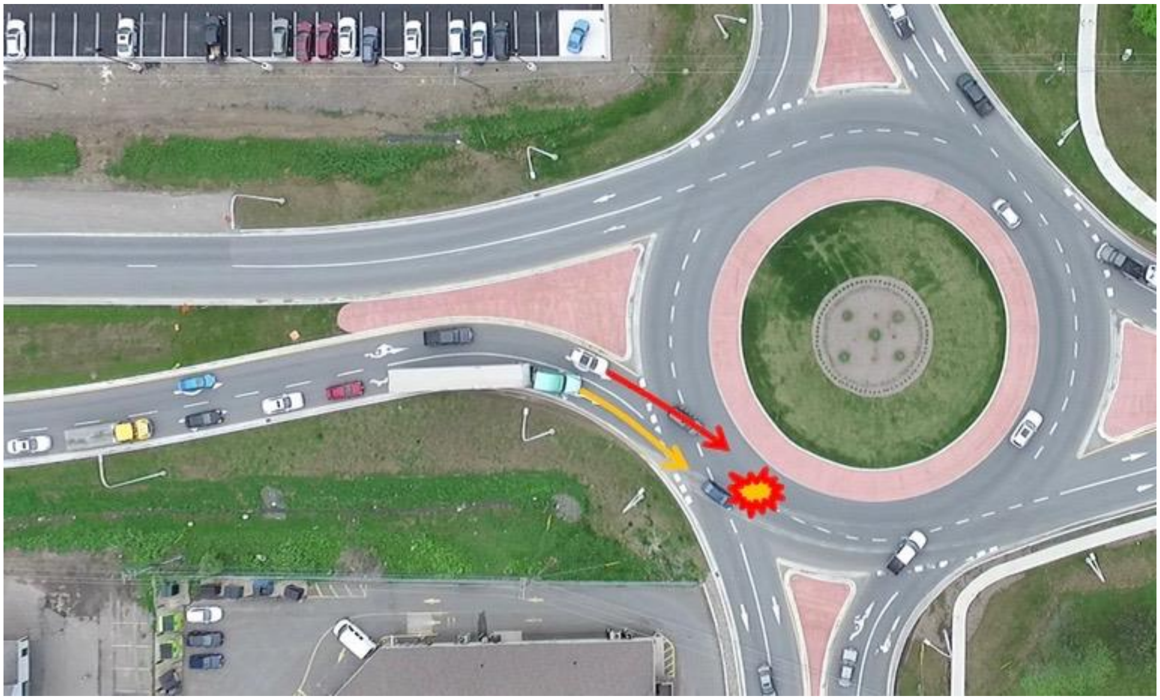


Figure 3.10: Failure to yield ROW to trucks

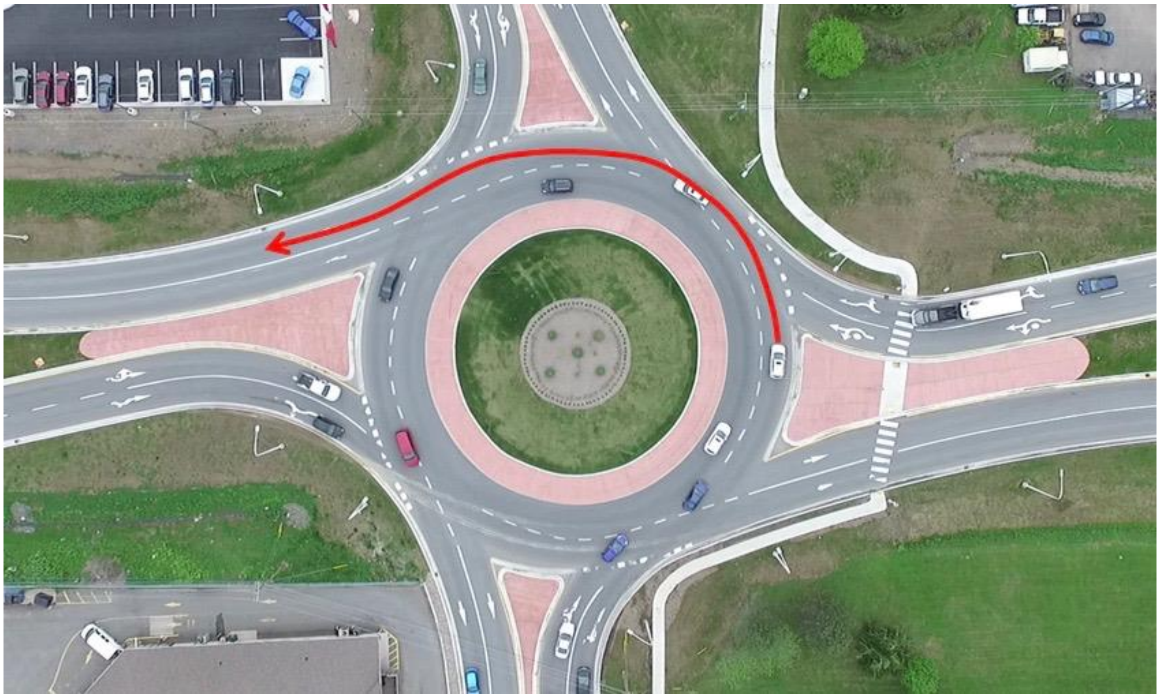


Figure 3.11: Improper lane selection

3.2.2 Collision Analysis

Important factors indicated by collision reports included cause of collision, collision configuration, driver age and driver address. Collision descriptions provided in the report often indicate the cause of the collision; otherwise the cause of collision can be inferred from the collision configuration. The cause of collision is valuable as it can reflect the driving error(s) at fault. Driver age is an important factor as seniors may be predisposed to driving error. Educational campaigns were used to familiarize local drivers with the roundabout before opening; however, tourists would not have been captured by this campaign, and as a result may be entirely unfamiliar with the roundabout and its rules. These factors were counted and analyzed to determine collision trends and their respective causes.

Motor vehicle collision reports were also analyzed to determine a collision rate that was compared to a safety performance function to determine if the roundabout is performing better or worse than expected from a safety perspective. The Region of Waterloo presents an empirical collision prediction model which uses the AADT for all movements to estimate the total daily conflicts (TDC) at each approach for roundabouts (Region of Waterloo 2014). The total annual collisions are determined by:

$$Estimated\ Annual\ Collisions = (0.0004 \times Total\ Daily\ Conflicts) + 1.8122 \qquad \text{[Eq. 3.1]}$$

The total daily conflicts for the eastbound (EB) approach, by way of illustration, can be described as:

$$\begin{aligned}\mathit{EB\ Conflicting\ Volume} = {} & \mathit{min(EBL, SBT) + min(EBL, SBL) + min(EBL, NBL)} + \\ & \mathit{min(EBL, NBT) + min(EBL, WBL) + min(EBL, WBT), + min(EBT, SBL)}, + \\ & \mathit{min(EBT, SBT), + min(EBT, NBL) + min(EBT, NBT) + min(EBT, NBR)} + \\ & \mathit{min(EBR, SBT)}\end{aligned}$$

[Eq. 3.2]

The number of injury collisions is considered to be 10% of the total estimated annual collisions (Region of Waterloo 2014). The SPF values determined can then be compared to the observed collision rate and any difference would represent a potential for improvement (PFI) for the Smythe Street roundabout.

3.2.3 Capacity in Oversaturated Conditions

Miovision traffic counts were completed by Crandall Engineering during the month of June, 2016. The counts were reviewed to isolate the peak hour of traffic, to use as a timeline to gather drone footage of the roundabout in oversaturated conditions associated with the work zone detour. The peak hour was determined to occur between both 4:30pm-5:30pm and 4:45pm-5:45pm. The drone was deployed at 4:40pm and the 55 minutes of video footage was proportionally increased to represent 60 minutes of footage, and analyzed to extract the appropriate data to determine the capacity of the facility.

The original intent was to observe the roundabout during a period of over-saturated demand to quantify the facility capacity. Upon review of the footage, it was clear that the roundabout was not simultaneously over-saturated on all approaches as anticipated. Instead, volume counts from the footage were evaluated through HCS 2010 software for predictions relative to volume/capacity ratios (v/s) and LOS.

HCS 2010 states that the required data for a capacity analysis includes:

1. Number of configuration of lanes on each approach
2. Demand volume for each entering vehicular movement and each pedestrian crossing during the peak hour, and a peak hour factor
3. Percentage of heavy vehicles
4. Volume distribution across lanes for two-lane entries
5. Length of analysis period

The HCM 2010 software uses the inputs listed above to generate a v/c ratio, approach delay, 95th percentile, and approach LOS for each lane, as well as an overall intersection LOS. The software's technical approach is detailed in this section. Standard practice for determining capacity is described in Chapter 21 of the HCM 2010 manual and was followed for the analysis.

An empirical regression model based on U.S. field data was used to determine the capacity of the two-lane entry to a two-lane circulating roadway:

$$c_{crit} = 1130\ exp(-0.007 \times v_c) \qquad \text{[Eq. 3.3]}$$

where

c_{crit}= capacity of the critical lane (pcu/h)

v_c = conflicting flow (pcu/h)

Level of service cannot be directly experienced by the driver; therefore, average control delay experienced by the driver is used as a proxy to reflect LOS. Equation 2.2 (Transportation Research Board, 2007) presented in the literature review section was used to determine the control delay of the facility:

$$d = \frac{3600}{c} + 900T\left[\frac{v}{c} - 1 + \sqrt{\left(\frac{v}{c} - 1\right)^2 + \frac{\left(\frac{3600}{c}\right)\frac{v}{c}}{450T}}\right] \qquad \text{[Eq. 3.4]}$$

where

d = average control delay (s/veh)

c = capacity of subject lane (veh/h)

T = time period (T = 0.25 for a 15-min analysis)

v = flow in subject lane (veh/h)

The HCM 2010 capacity model is an exponential regression model with parameter estimates based on gap acceptance theory (Gazarri *et al.* 2013). Local driver behaviour such as critical and follow-up headways significantly impact gap acceptance models; and therefore significantly impact capacity.

3.2.4 Estimating Critical and Follow-up Headways

The hour of footage recorded for the capacity analysis was used to determine the critical and follow-up headways. The east and westbound lanes were not at or near capacity (constant queuing); however, the north and southbound approach lanes were found to be at capacity. Both the right and left lane for the north and southbound lanes were analyzed separately.

3.2.4.1 Raff's Method

The accepted and rejected gaps were grouped in intervals of 0.3 seconds to determine a cumulative probability of acceptance for each interval. Likewise, a cumulative probability of rejection was also determined. Raff's method states that the number of rejected gaps larger than the critical headway is equal to the number of accepted gaps smaller than the critical headway (Guo 2011), described as:

$$1 - F_r(t) = F_a(t) \qquad \text{[Eq. 3.5]}$$

where

$F_r(t)$ is the cumulative proportion of rejected headways

$F_a(t)$ is the cumulative proportion of accepted headways

The point then found from the intersection of the cumulative probability of acceptance and the cumulative probability of rejection was determined to be the critical headway.

Raff's method is commonly used in engineering practice as it can be performed quickly with minimal in-depth analysis. Wu's method was used in conjunction with Raff's method as it has a more robust analytical approach. In engineering practice, constraints on human resources and budget may prevent a robust approach such as Wu's from being used, when a less involved method such as Raff's is available. Comparing both methods may be valuable to transportation engineers undertaking a similar analysis, should the comparison yield similar results.

3.2.4.2 Wu's Method

The accepted and rejected headways used for Raff's method were also applied to Wu's method. Each headway was categorized as accepted ("*a*") or rejected ("*r*") and sorted in ascending order. An additional column was used to calculate the accumulative frequencies of each headway, n_{rj}/n_{aj} (for a given row j, if "*a*" was selected, $n_{aj} = n_{aj} + 1$, otherwise $n_{aj} = n_{aj}$ with $n_{a0}=0$). If "*r*" was selected, , $n_{rj} = n_{rj} + 1$, otherwise $n_{rj} = n_{rj}$ with $n_{r0}=0$.

Probability density functions (PDFs) for the accepted (F_a) and rejected headways (F_r) were determined by Equation 3.6 and 3.7 presented by Wu (2006).

$$F_j(r) = n_{rj}/n_{r,max} \qquad \text{[Eq. 3.6]}$$

$$F_j(a) = n_{aj}/n_{a,max} \qquad \text{[Eq. 3.7]}$$

where n_{rj} = the accumulative frequencies of the rejected headways for a given row, j

n_{aj} = the accumulative frequencies of the accepted headways for a given row, j

$n_{r,max}$ = number of all rejected headways

$n_{a,max}$ = number of all accepted headways

The accepted and rejected PDFs were then used to yield the PDF of the estimated critical headway, $F_{tc}(t_j)$, through Equation 3.8 presented by Wu (2006).

$$F_{tc}(t_j) = \frac{F_a(t_j)}{F_a(t_j)+1-F_r(t_j)} \qquad \text{[Eq. 3.8]}$$

where $F_{tc}(t_j)$ = the PDF of the estimated critical headway for a given row, j

$F_a(t_j) = F_j(a)$ and $F_r(t_j) = F_j(r)$ for a given row, j, and a given headway, t

The frequencies of the estimated critical headway, $p_{tc}(t_j)$ and the class mean, $t_{d,j}$, were determined using Equations 3.9 and 3.10. The frequencies of the estimated critical headway and the class mean are of particular importance as their product equals the average critical headway.

$$p_{tc}(t_j) = F_{tc}(t_j) - F_{tc}(t_{j-1}) \qquad \text{[Eq. 3.9]}$$

$$t_{d,j} = \frac{(t_j + t_{j-1})}{2} \qquad \text{[Eq. 3.10]}$$

where t_j is the observed accepted or rejected headway (seconds)

The average value of the estimated critical headway can then be determined using Equation 3.11.

$$t_{c,average} = \sum p_{tc}(t_j) \times t_{d,j} \qquad \text{[Eq. 3.11]}$$

Table 4.7 and 4.8 of Section 4.4.2 include a selection of right and left lane headway data to illustrate the methodology of Wu’s analysis.

4 ANALYSIS AND RESULTS

The following sections synthesize the analysis and results from three areas of the research: observed vehicle errors, collision analysis, and facility capacity during periods of oversaturated demand.

4.1 Observed Vehicle Errors

The error observation period was intended to be undertaken from September 2015 to September 2016, resulting in a full year of data; however, construction began on a major uptown connection in the south side of Fredericton in June 2016. The construction influenced drivers to redirect their route to the Smythe Street roundabout, who otherwise may have avoided the roundabout. The disturbance caused by the construction altered the “normal” environment in which driver behaviour was being observed; therefore, vehicle errors were not observed during the construction period which ended in early September 2016. Error observations were therefore made from September 2015 to September 2016, bar June, July, and August.

Driver error data are synthesized in Table 4.1; the date of flight is indicated as well as observation type (drone vs. GoPro on Water Tower).

Table 4.1: Driving Error Rates (September 2015 - September 2016)

	Changing Lanes Within Roundabout	Not Yielding to Traffic Already in Roundabout	Stopping Within Roundabout to Allow Approach Vehicles to Enter	Left-turn into Roundabout	Passenger Vehicles not Giving ROW to Trucks	Improper Lane Usage	**Total Errors**	Total Vehicle Count	Truck Count
	Per 1,000 Entering Vehicles								
Sept 23 Wed (Drone)	53.5	7.0	2.7	1.1	1.1	5.0	83.3	2995	40
Sept 23 Wed (Tower)	83.6	8.6	0.8	0.4	0.0	2.8		2465	64
Oct 4 Sun (Drone)	69.6	10.7	0.0	0.0	0.0	5.4	85.7	2241	7
Oct 28 Wed (Tower)	47.1	7.1	0.5	0.0	0.0	4.2	58.9	4077	87
Nov 4 Wed (Drone)	40.0	5.6	0.6	0.0	0.0	3.9	50.1	1798	25
Nov 26 Thurs (Drone)	30.9	4.4	0.0	0.0	0.0	2.4	37.7	2065	21
Jan 7 Thurs (Drone)	18.6	7.2	0.5	0.0	0.5	0.5	27.3	2097	31
Feb 4 Thurs (Drone)	26.3	6.3	1.1	0.0	0.0	2.1	35.8	1900	29
March 14 Mon (Drone)	14.6	4.2	0.0	0.0	0.0	2.4	21.2	2123	32
April 14 Thurs (Drone)	17.4	2.9	1.0	0.0	0.0	1.0	22.3	2074	17
May 13 Fri (Drone)	18.4	0.5	1.0	0.0	0.0	6.0	25.9	1844	15
Sept 30 2016 (Drone)	12.7	3.3	1.1	0.0	0.6	3.3	21.0	1817	14

Errors peaked at the onset, during the first month of opening, which was to be expected as drivers were the most unfamiliar. All driver error types have declined since the roundabout's opening. Figure 4.1 depicts the data presented in Table 4.1, indicating total driver error reduction throughout the observation period. The total number of errors fell approximately 74% during the 52 week observation period since the roundabout first opened.

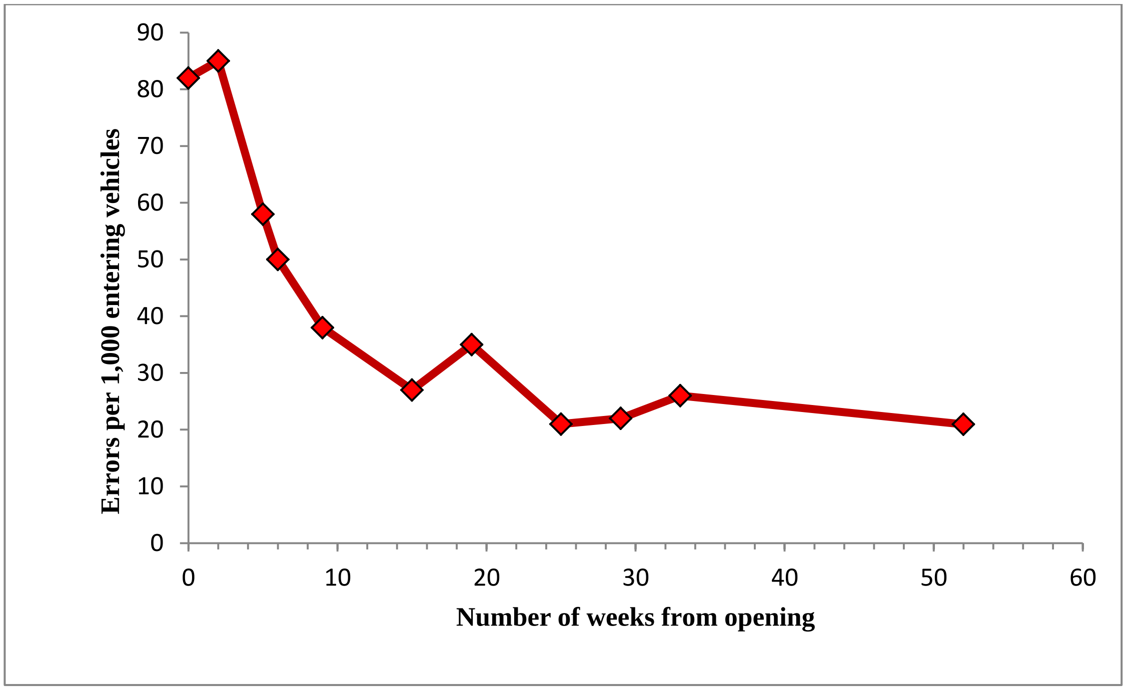


Figure 4.1: Total driver errors

An unusual spike can be seen in the second data collection point (week 2, corresponding to early October) in Figures 4.1, 4.2, and 4.3. This spike may be attributed to the day of collection which was a Sunday. It is quite possible that this early Sunday period saw a disproportionate percentage of cautious first-time users of the two-lane roundabout. Following this experience, all further data were collected at similar times during mid-week.

The findings found in Oregon by The Federal Highway Administration (2007) indicated that the driver errors associated with an urban two-lane roundabout followed a "learning curve" pattern which levelled off approximately six months after opening. Figure 4.1 confirms this pattern, with total driver errors levelling off at approximately 24 weeks (six months).

Hourdos and Richfield (2014) speculated why driver error saw a 60% increase a year after safety implementations were put in place. They suspected that the rise in violations could be a result of driver familiarity. As drivers become more comfortable with the facility they will become less cautious (Weber 2016), resulting in heightened driver error. The data presented in Figure 4.1 indicates that over the 52 week observation period, driving errors were not found to increase as drivers became more comfortable with the facility, in fact the opposite was observed. The percent reduction of each error and the percent total of each error for the entirety of the research are presented in Table 4.2.

Table 4.2: Percent Error Reduction and Percent of Total Errors

	% Reduction (September 2015 – 2016)	% of Total Errors (September/16)
Changing lanes within roundabout	81	60
Not yielding to traffic already in roundabout	59	16
Improper lane usage	15	16
Stopping within roundabout	39	5
Not giving ROW to trucks	0	3
Left-turn (wrong way)	100	0

Total Error	**74**	**100**

Figure 4.2 presents drivers who made the error of changing lanes within the roundabout. Changing lanes within the roundabout was initially observed at 68.6 (the average of 53.5 and 83.6) errors per 1,000 entering vehicles and as of September 2016 it had declined to 12.7 as shown in Table 4.1, an 81% reduction. The roundabout lane line being broken (which would typically indicate a lane change is allowed) may be an attributing factor to vehicles making lane changes within the roundabout. There is a discrepancy on pavement marking guidelines for two-lane roundabouts; TAC indicates that pavement markings should be dashed, whereas, other jurisdictions such as British Columbia indicate a solid line should be used. The error data appears to support that a solid line might be preferred to improve safety.

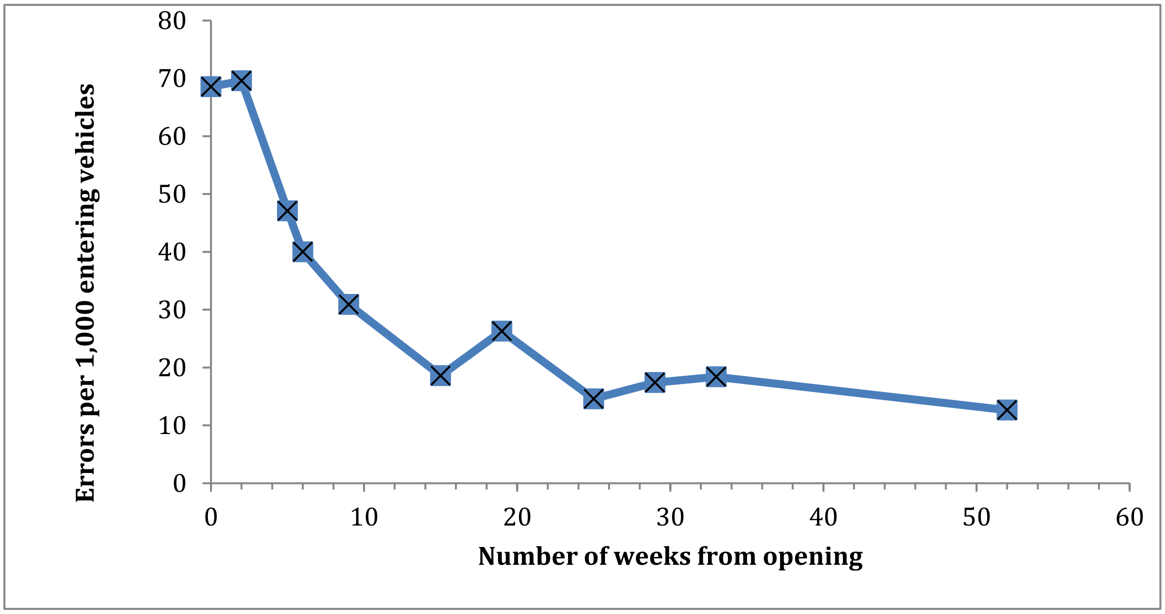


Figure 4.2: Driver errors: changing lanes within roundabout

It was common for a single driver to make both a lane change within the roundabout, as well as select the improper lane for their desired destination. The more dangerous error of these two is selecting the improper lane; therefore, it was the error counted when both errors were present. Figure 4.3 presents improper lane usage and yielding errors made by drivers. Vehicles not yielding to those already inside of the roundabout and improper lane usage saw 7.8 (the average of 7.0 and 8.6) and 3.9 (the average of 5.0 and 2.8) per 1,000 entering vehicles in September 2015, respectively, which had decreased to 3.3 for both as of September 2016.

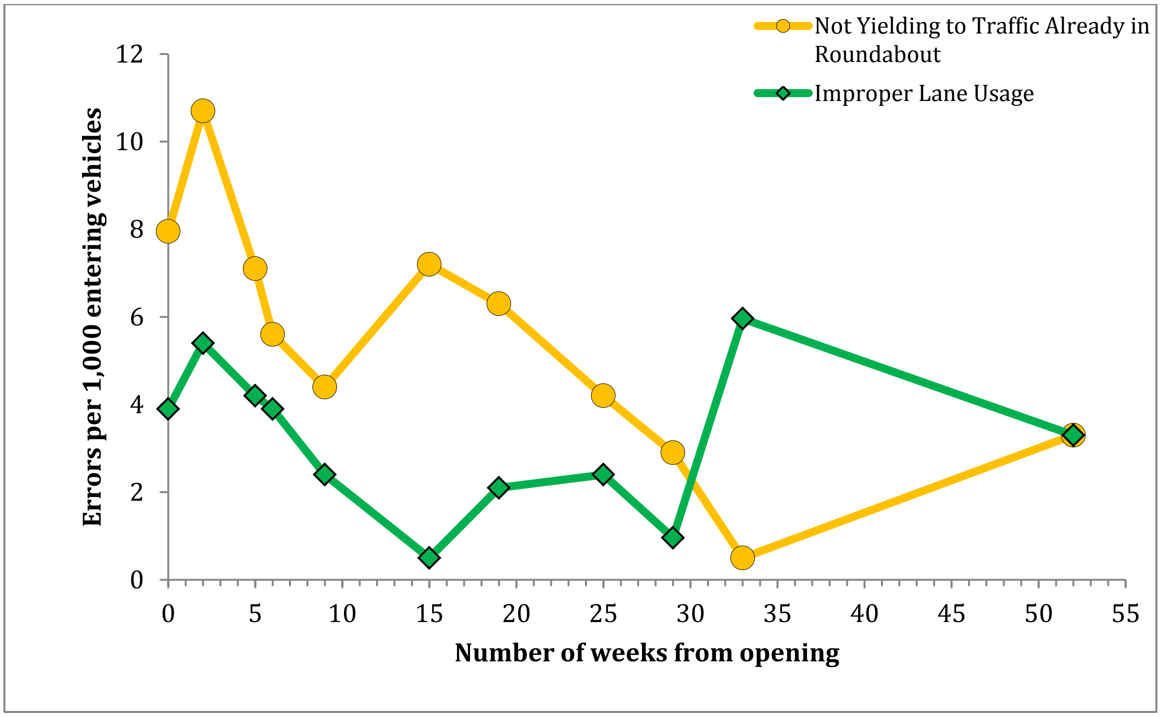


Figure 4.3: Driver errors: not yielding and improper lane usage

The errors which were expected to decline to the lowest rates included vehicles not giving ROW to trucks, left-turns (wrong-way), and stopping within the roundabout. With already very low error occurrences, they are not a significant safety concern. Stopping within the roundabout to allow approach vehicles to enter could perhaps have been attributed to the friendly nature of Fredericton drivers. Left-turns into the roundabout were expected to diminish after the initial confusion of unfamiliar drivers to the roundabout.

The roundabout was designed for transport trucks to require both lanes of the roundabout to pass through; therefore, transport trucks must receive right of way from passenger vehicles. Significant effort was put into making drivers aware that they must yield to transport trucks within the roundabout. Truck encroachment signs were placed on the roundabout approaches to indicate that drivers must yield to heavy vehicles. Passenger vehicles not giving ROW to trucks was largely uncommon (zero errors were observed in all months, bar September 2015 and January 2016 and September 2016 where this occurred 0.6, 0.5, and 0.6 times per 1,000 entering vehicles, respectively.). Educational campaigns undertaken by the City of Fredericton offered the recommendation to heavy vehicle operators to straddle both entry lanes to the roundabout. Truck operators straddling both entry lanes were observed at the roundabout during data collection. Straddling was shown to prevent vehicles from queuing beside a heavy vehicle, eliminating the possibility of an attempt of a passenger vehicle to enter the roundabout at the same times as the heavy vehicle. Low truck volumes were also a likely reason for the low number of ROW errors involving heavy vehicles.

4.2 Observed Collisions and PFI

The Region of Waterloo presents an empirical collision prediction model which uses the AADT for all movements to estimate the total daily conflicts (TDC) at each approach for roundabouts (Region of Waterloo 2014). These SPFs [Eq. 3.1 and Eq. 3.2] presented in section 3.1.2 were used to determine the potential for improvement of the Smythe Street roundabout.

A comparison between the expected collisions (based on the Waterloo (2014) safety performance function model) and observed collisions provided in Table 4.3.

Table 4.3: Potential for Improvement

	Expected Collisions (per 12 months)	**Observed Collisions** (per 12 months) September/15 – August/16	**PFI**
PDO	25.6	30	4.4
Injury	2.8	2	-0.8

ADT = 25, 200

Salem and Henderson (2015) presented an SPF which uses TDC, similar to Waterloo, which estimated 26.9 total collisions. A separate model presented by Salem and Henderson (2015) used circulating flow volume, which estimated 22.7 total collisions. The Synthesis of North American Roundabout Practice (TAC 2008) provides a safety performance function using only AADT, which estimated 5.6 and 0.38 PDO and injury collisions, respectively. The Region of Waterloo (2014) and Salem and Henderson (2015) both use models which take into account the turning movements within the roundabout, whereas, the TAC (2008) model does not. The turning movement of vehicles is a significant input for collision prediction (if all vehicles were right-turning zero collisions would occur). Due to the discrepancy between TAC and other models, as well as lack of movement consideration, the TAC model presented in The Synthesis of North American Roundabout Practise (2008) is not recommended when evaluating the safety performance of a roundabout.

Given the approximate ADT, the Smythe Street roundabout is expected to experience 25.6 PDO collisions per year in total (with 2.8 additional collisions resulting in injury) based on these SPFs. After a full year of observations (September 2015-August 2016), 32 collisions have occurred within the roundabout, 2 of which caused injury. While there is a PDO PFI of 4.4 collisions, it is important to note that 59% of the observed collisions occurred over a three month span during which the presence of a work zone downstream may have negatively impacted the observed collisions, shown in Figure 4.4 (construction months are denoted in red crosshatch). The roundabout was used as a detour during this construction which may have negatively impacted the observed collisions as well. It is possible that had the roundabout not been subjected to detoured traffic, that the PFI for PDO would be negative, indicating the roundabout would have been performing better than expected.

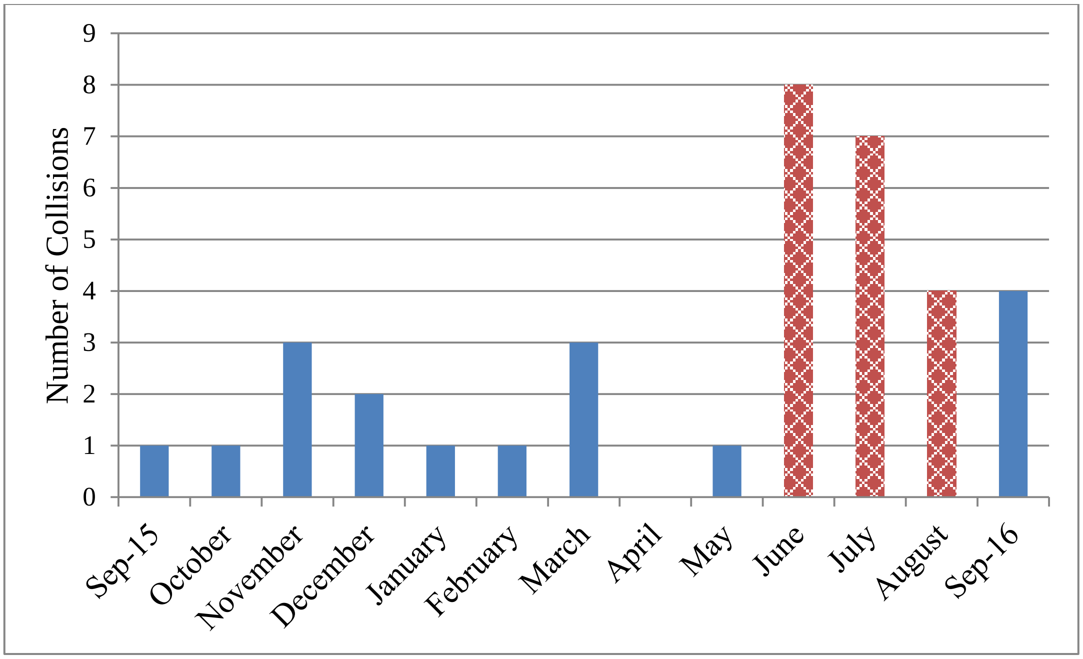


Figure 4.4: Observed collisions by month

Hourdos and Richfield (2014) categorized all relevant collisions from a Minnesota roundabout study into three categories: yield violations, turning violations, and lane change violations. The same categorization is appropriate for the collisions observed at the Smythe Street roundabout, with the addition of rear-end collisions. Hourdos and Richfield found that turning violations were responsible for the most severe crashes, the most common of which, making a left turn from the outer lane. A comparison of the collision causes from Hourdos and Richfield and this study are presented in Figure 4.5.

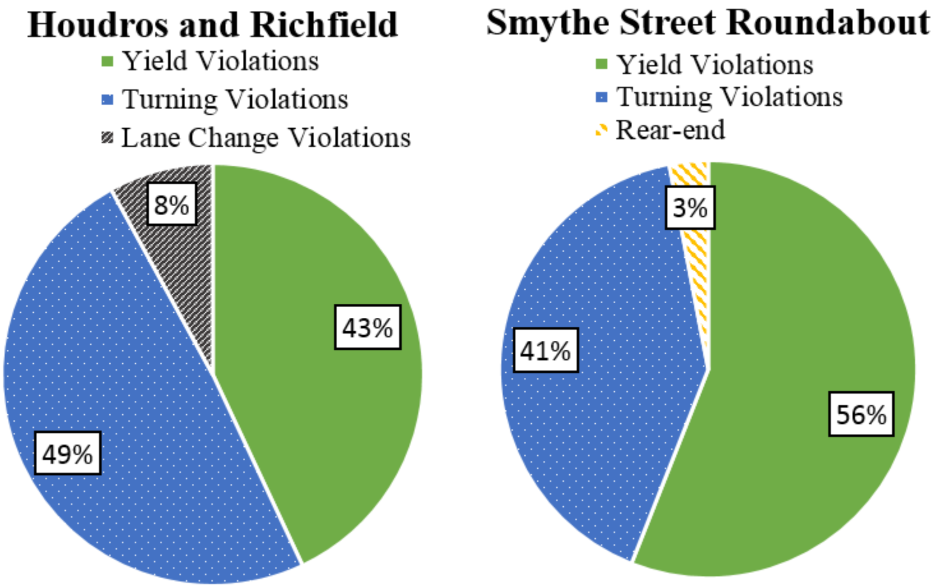


Figure 4.5: Hourdos & Richfield vs. Smythe St. roundabout collision configurations

Of the collisions observed at the Smythe Street roundabout, 41% resulted from an improper lane change (a turning violation), compared to 49% by Hourdos and Richfield. Yield violations were the most prominent collision type in this study, with the 56% of collisions resulting due to yield violations, compared to 43% found by Hourdos and Richfield study. Collisions resulting from an improper lane represented 8% of the total observed collisions from Hourdos and Richfield; however, zero collisions were observed to occur at the Smythe Street roundabout as a result of this error. Interestingly, it was the most commonly observed error, but the least likely to cause a collision. Rear-end collisions were not identified by Houdros and Richfield; however, 3% of the collisions observed at the Smythe Street roundabout were rear-end collisions. It is important to note that Hourdos and Richfield based their study on 89 relevant collisions, whereas, the Smythe Street roundabout results are based on only 32 relevant collisions.

Roundabouts in western France were studied and 202 total collisions involving personal injury were found to have occurred at 175 roundabouts, the majority (37%) of collisions were caused by “refusal of priority on entry” (i.e. yield violations) (Alphand, Noelle & Guichet, 1991). This agrees with Hourdos and Richfield’s finding of 43% and 56% found at the Smythe Street Roundabout; therefore, it can be deduced that the error causing the most concern for a two-lane roundabout involves drivers not yielding to traffic already present in the roundabout.

Towards the end of the research project the City of Fredericton decided to place an additional tab below the yield signs on each approach that reads “Yield to Both Lanes/Cedez Le Passage-Deux Voies” in both English and French, shown in Figure 4.6, despite The Waterloo Region having attempted the same countermeasure without success. It is unclear whether this has resulted in improved driver adherence as it was implemented during the final month of the research project.

Figure 4.6: Yield to both lanes signage

Four collision types accounted for 75% of the total collisions found in a Belgium study involving 399 collisions (Polders et *al.* 2010): rear-ends, collisions with central island, entering and circulating, and vulnerable road users. Entering/circulating (not yielding/improper lane chance) and rear-ends were also found to be a prominent collision type at the Smythe Street Roundabout. Collisions with the central island did not occur, which may be the result of a successful design. A raised central island lessens the likelihood of a collision with the central island as it prevents drivers from seeing the road alignment beyond the roundabout, which encourages drivers to decrease speeds. Entry path curvature also encourages drivers to decrease speed.

Driver type is important as one-third of collisions involved non-local drivers (shown in Figure 4.7), defined as those with a non-New Brunswick license. These drivers would not have likely been captured by the proactive educational program that was run by the City of Fredericton. Senior drivers were involved in one-third of the collisions; however, this is expected as approximately 31% of the driving population in Fredericton is 60 years of age or older (Statistics Canada 2012). Driver type is not inclusive, as a senior driver can also be a non-local driver; however, the driver type categories for these data did not overlap. Driver information could only be analyzed from collision reports from September 2015 to February 2016 (six months) as greater privacy measures were taken by the City of Fredericton Police Department from that point forward.

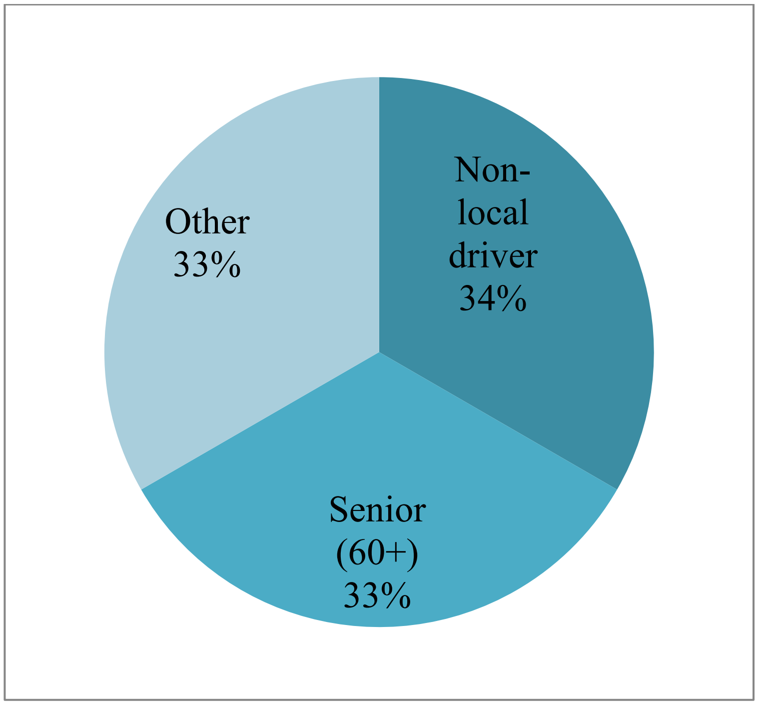


Figure 4.7: Collision driver type

4.3 Capacity Analysis

Estimates of approach volumes for each vehicular movement and pedestrians crossing were derived from 55 minutes of UAV video footage beginning at 4:40pm on a Tuesday during a detour that produced near saturated conditions at the Smythe Street roundabout. Volume counts were not completed in both the morning and evening peak periods, as suggested by Robinson and Rodegerdts (2010), as the afternoon was known to have a higher volume count than the morning, resulting in a greater likelihood of over-saturated conditions. The counts were then proportionally increased to represent a full 60 minute observation count. The volume counts for each turning movement are depicted in Figure 4.8.

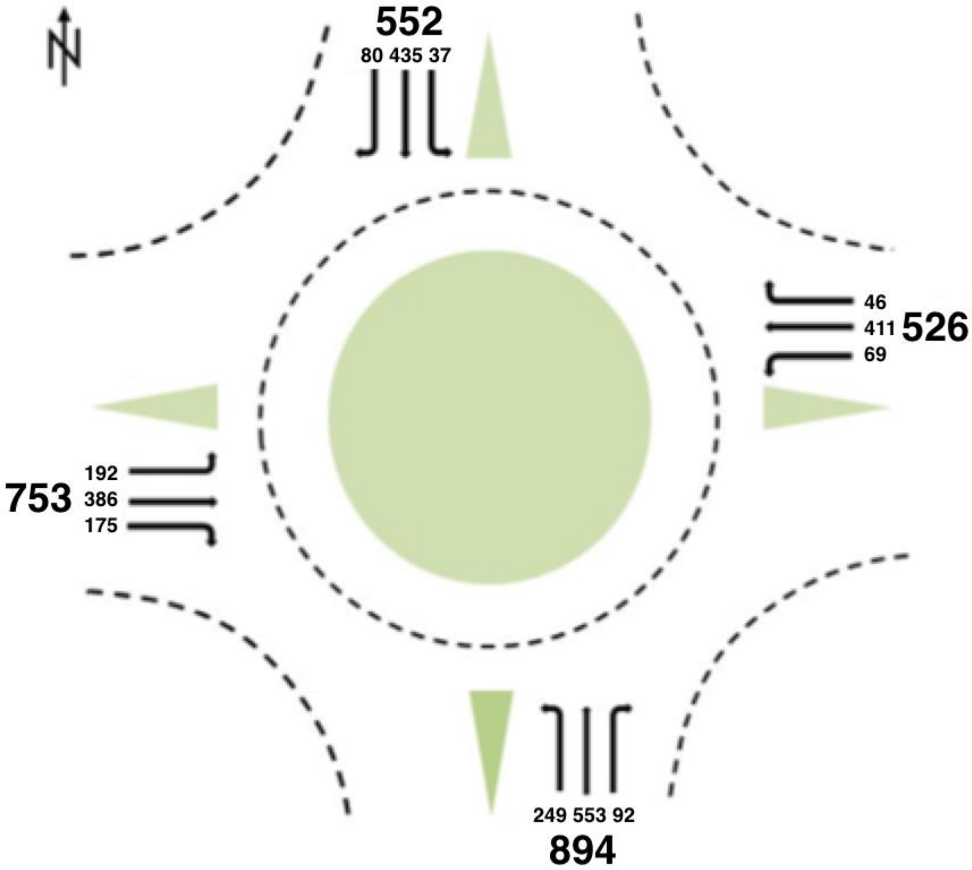


Figure 4.8: Roundabout turning movements during peak hour

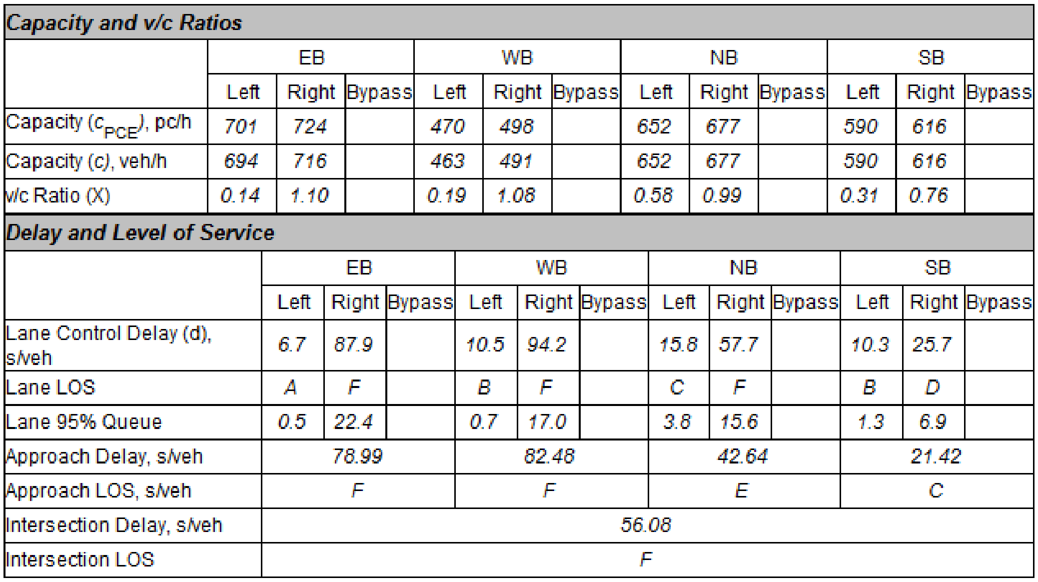
The percentage of heavy vehicles on the eastbound through approach and the westbound through approach were 2%, while all other approaches were 0%. The westbound approach is the only approach with a crosswalk, which saw five pedestrians over the hour. The majority of through-drivers preferred the right/through lane to the left/through lane as shown in Table 4.4.

Table 4.4: Through-drivers Lane Preference

	Left-lane (%)	Right-lane (%)
Northbound	28	72
Eastbound	14	86
Southbound	36	64
Westbound	11	89
HCS 2010 Default Values	47	53

For a left-through and through-right lane configuration, HCS 2010 assumes driver lane preferences as 47% in left lane and 53% in the right lane in the absence of field data. Caution is suggested when conditions are near capacity to use the default values. The assumed values provided by HCS 2010 are significantly different than what was observed in the field (where 72% or more of drivers preferred the right lane). It is notable that using the HCS 2010 default values to describe the Smythe Street roundabout provides a capacity analysis which is highly inaccurate.

The observed volumes were evaluated using HCS 2010 with the objective to determine if the software’s suggested LOS agreed with the observed LOS, indicating that the roundabout was not in an over-saturated condition. The data output from HCS 2010 is shown in Figure 4.9.



Capacity and v/c Ratios	EB			WB			NB			SB		
	Left	Right	Bypass	Left	Right	Bypass	Left	Right	Bypass	Left	Right	Bypass
Capacity (c_{PCE}), pc/h	701	724		470	498		652	677		590	616	
Capacity (*c*), veh/h	694	716		463	491		652	677		590	616	
v/c Ratio (X)	0.14	1.10		0.19	1.08		0.58	0.99		0.31	0.76	

Delay and Level of Service	EB			WB			NB			SB		
	Left	Right	Bypass	Left	Right	Bypass	Left	Right	Bypass	Left	Right	Bypass
Lane Control Delay (d), s/veh	6.7	87.9		10.5	94.2		15.8	57.7		10.3	25.7	
Lane LOS	A	F		B	F		C	F		B	D	
Lane 95% Queue	0.5	22.4		0.7	17.0		3.8	15.6		1.3	6.9	
Approach Delay, s/veh	78.99			82.48			42.64			21.42		
Approach LOS, s/veh	F			F			E			C		
Intersection Delay, s/veh	56.08											
Intersection LOS	F											

Figure 4.9: HCS 2010 output for Smythe Street Roundabout 2016

The volume-to-capacity (v/c) ratio for both the westbound right/through lane (1.08) and the eastbound right/through lane (1.10) exceed one, indicating that the software predicts that the demand exceeds the capacity. The right/through lane for the northbound approach (0.99) is very close to exceeding capacity. Given that these were observed volumes, all v/c ratios should be predicted to be less than 1.0. This is an indication that the software overestimates the length of critical and follow-up headways required by local drivers.

Robinson and Rodegerdts (2000) state that the acceptable degree of saturation for an entry lane should be less than 0.85, as any exceedence of this range will cause drivers to experience unacceptable delay. Three of four right-through lanes within the roundabout experience some degree of saturation (v/c ratio) greater than 0.85. Regardless of the control delay experienced, if the volume-to-capacity ratio exceeds one for a given lane, a LOS F is given to that lane (NCHRP 2007). The southbound approach was operating at a LOS C (a delay of 10-25 seconds) which indicates it is performing well. An overall LOS F was given to the roundabout, indicating an overall unacceptable delay.

The left/through lane on each approach was found to function well (at a LOS A, B or C), which was due to the low volume of vehicles travelling in the lane. Figure 4.9 indicates that the through movement on all approaches had the highest volumes, with the majority of drivers (64% or higher) preferring the right lane for a through movement. The data presented in Figure 4.9 indicate that the left/through lane on all four approaches were operating at above capacity (unlike the right/through lane), and therefore could handle more through drivers should they select the left lane. It is plausible that drivers give preference to the right lane for a through movement because they perceive the left lane as either a left turn only, or that they predict the left lane will have a greater delay for a through movement as commonly found at a signalized intersection.

Estimating the overall roundabout capacity requires all four approaches to be in a queued state simultaneously. Queuing on all four approaches was not observed during the period covered by the UAV video; however, the over-estimation of v/c ratios and delay by HCS 2010 is evidence that it is not calibrated properly to reflect local driver characteristics. The westbound approach delay estimated by HCS 2010 indicated that a 56 sec/veh delay was experienced; however, what was observed in the video footage was lower than this delay.

The original intention was to observe the Smythe Street roundabout in a fully-saturated condition to determine its operational capacity, given that capacity characteristics at two-lane roundabouts are rarely observed in Canada. Inputs are consequently based on observations made in regions that may not best represent the driver behavior found in Eastern Canada. Caution is recommended from HCM 2010 to acknowledge that calibration will be needed for the software to reflect local conditions (Lenters and Rudy 2010). The discrepancy between the HCS 2010 software output and what was actually observed at the Smythe Street Roundabout indicates that there is a need for proper calibration of accepted headways so that engineers can be confident in LOS analysis undertaken for two-lane roundabouts.

4.4 Critical and Follow-up Headway

The evening peak hour of video footage yielded 55 minutes where the north and southbound lanes were operating at capacity. From the video footage, 612 critical headway times and 460 follow-up times were observed for the right and left approach lanes. Results from Raff’s Method, Wu’s method, and a comparison of the results are presented in the following section.

4.4.1 Raff’s Method

The critical headways were sorted into rejected and accepted headways and then grouped in intervals of 0.3 seconds, shown in Table 4.3. The accepted and rejected probability for each range of headway was then determined based on the total number accepted and rejected headways, respectively. The intersection of the accumulative probability of acceptance and the accumulative probability of rejection is equal to the critical headway according to Raff’s method, shown in Figure 4.8. The intersection value taken from Figure 4.5 is equal to approximately 3.5 seconds; however, this correlates to a range of headway between 3.2-3.5 seconds as shown in Table 4.3. The resultant critical headway provided by Raff’s method is therefore an approximate value in the range between 3.2-3.5 seconds.

Table 4.5: Right Lane Headway Raff's Method

Range of Headway	Accepted No.	Rejected No.	Accepted Probability	Accumulative Prob. of Acceptance	Rejected Prob.	Accumulative Prob. of Rejection
0-1.1	0	23	0.000	0.000	0.104	1.000
1.1-1.4	1	18	0.011	0.011	0.081	0.896
1.4-1.7	0	21	0.000	0.011	0.095	0.815
1.7-2.0	1	34	0.011	0.022	0.153	0.721
2.0-2.3	3	33	0.034	0.056	0.149	0.568
2.3-2.6	2	21	0.022	0.079	0.095	0.419
2.6-2.9	4	14	0.045	0.124	0.063	0.324
2.9-3.2	5	17	0.056	0.180	0.077	0.261
3.2-3.5	6	15	0.067	0.247	0.068	0.185
3.5-3.8	8	7	0.090	0.337	0.032	0.117
3.8-4.1	12	8	0.135	0.472	0.036	0.086
4.1-4.4	10	1	0.112	0.584	0.005	0.050
4.4-4.7	8	2	0.090	0.674	0.009	0.045
4.7-5.0	7	3	0.079	0.753	0.014	0.036
5.0-5.3	8	1	0.090	0.843	0.005	0.023
5.3-5.6	2	0	0.12	0.76	0.00	0.00
5.6-5.9	0	0	0.00	0.76	0.00	0.00
5.9-6.2	0	0	0.00	0.76	0.00	0.00
6.2-6.5	0	0	0.00	0.76	0.00	0.00
6.5-6.8	2	0	0.12	0.88	0.00	0.00
6.8-7.1	0	0	0.00	0.88	0.00	0.00
7.1-7.4	0	0	0.00	0.88	0.00	0.00

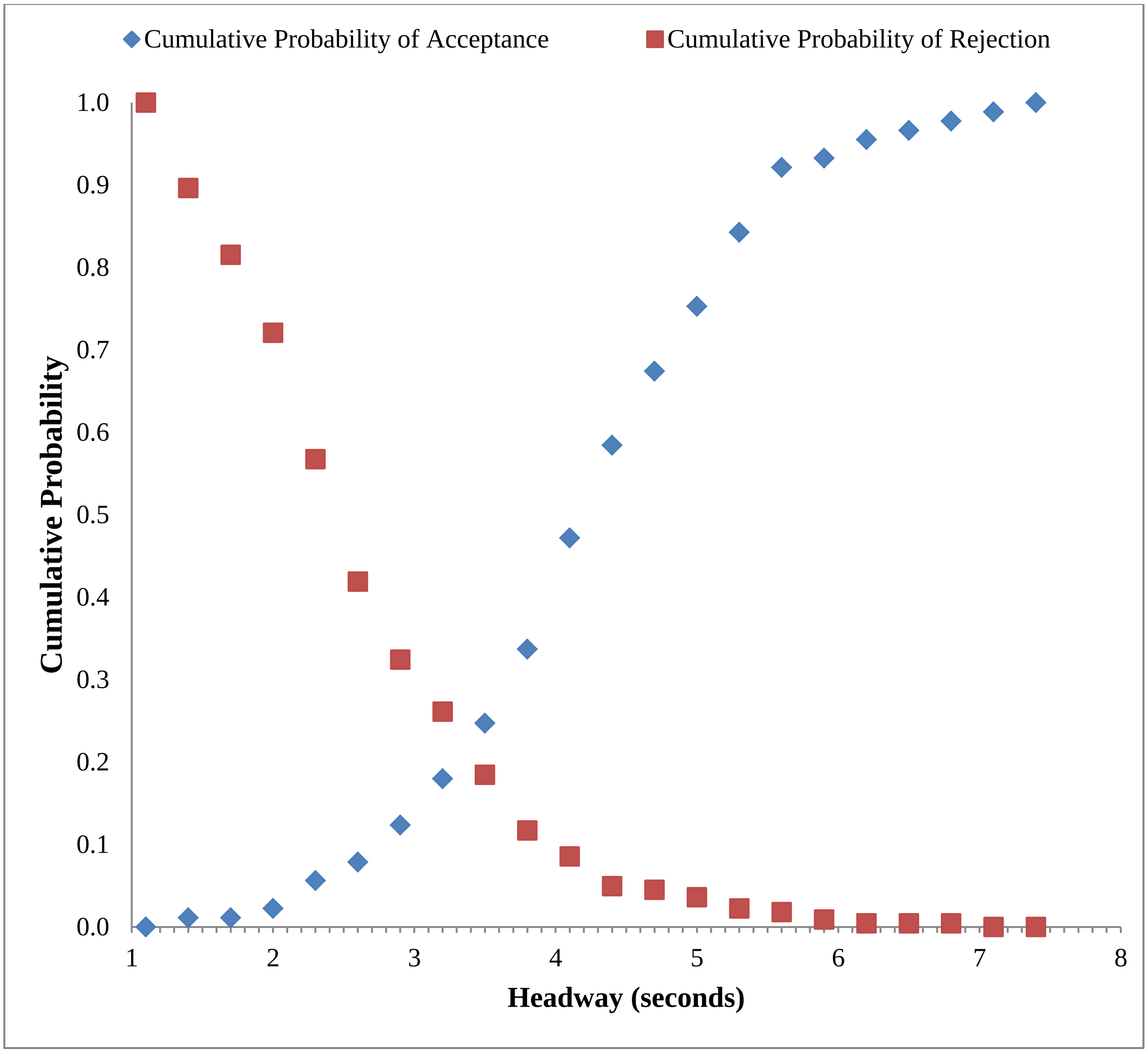


Figure 4.10: Right lane headway Raff's method

Similarly, the same procedure was undertaken for the left lane, shown in Table 4.6 and Figure 4.11. The intersection value taken from Figure 4.11 is equal to approximately 3.6 seconds; which correlates to a range of headway between 3.5-3.8 seconds as shown in Table 4.6.

Table 4.6: Left Lane Headway Raff's Method

Range of Headway	Accepted No.	Rejected No.	Accepted Probability	Accumulative Prob. of Acceptance	Rejected Prob.	Accumulative Prob. of Rejection
0-1.1	0	26	0.000	0.000	0.104	1.000
1.1-1.4	1	18	0.020	0.020	0.072	0.896
1.4-1.7	0	30	0.000	0.020	0.120	0.823
1.7-2.0	1	33	0.020	0.039	0.133	0.703
2.0-2.3	0	34	0.000	0.039	0.137	0.570
2.3-2.6	0	22	0.000	0.039	0.088	0.434
2.6-2.9	2	22	0.039	0.078	0.088	0.345
2.9-3.2	2	17	0.039	0.118	0.068	0.257
3.2-3.5	2	23	0.039	0.157	0.092	0.189
3.5-3.8	2	8	0.039	0.196	0.032	0.096
3.8-4.1	5	1	0.098	0.294	0.004	0.064
4.1-4.4	12	5	0.235	0.529	0.020	0.060
4.4-4.7	3	4	0.059	0.588	0.016	0.040
4.7-5.0	4	1	0.078	0.667	0.004	0.024
5.0-5.3	4	1	0.078	0.745	0.004	0.020
5.3-5.6	3	2	0.059	0.804	0.008	0.016
5.6-5.9	2	1	0.039	0.843	0.004	0.008
5.9-6.2	1	1	0.020	0.863	0.004	0.004
6.2-6.5	2	0	0.039	0.902	0.000	0.000
6.5-6.8	3	0	0.059	0.961	0.000	0.000
6.8-7.1	0	0	0.000	0.961	0.000	0.000
7.1-7.4	2	0	0.039	1.000	0.000	0.000

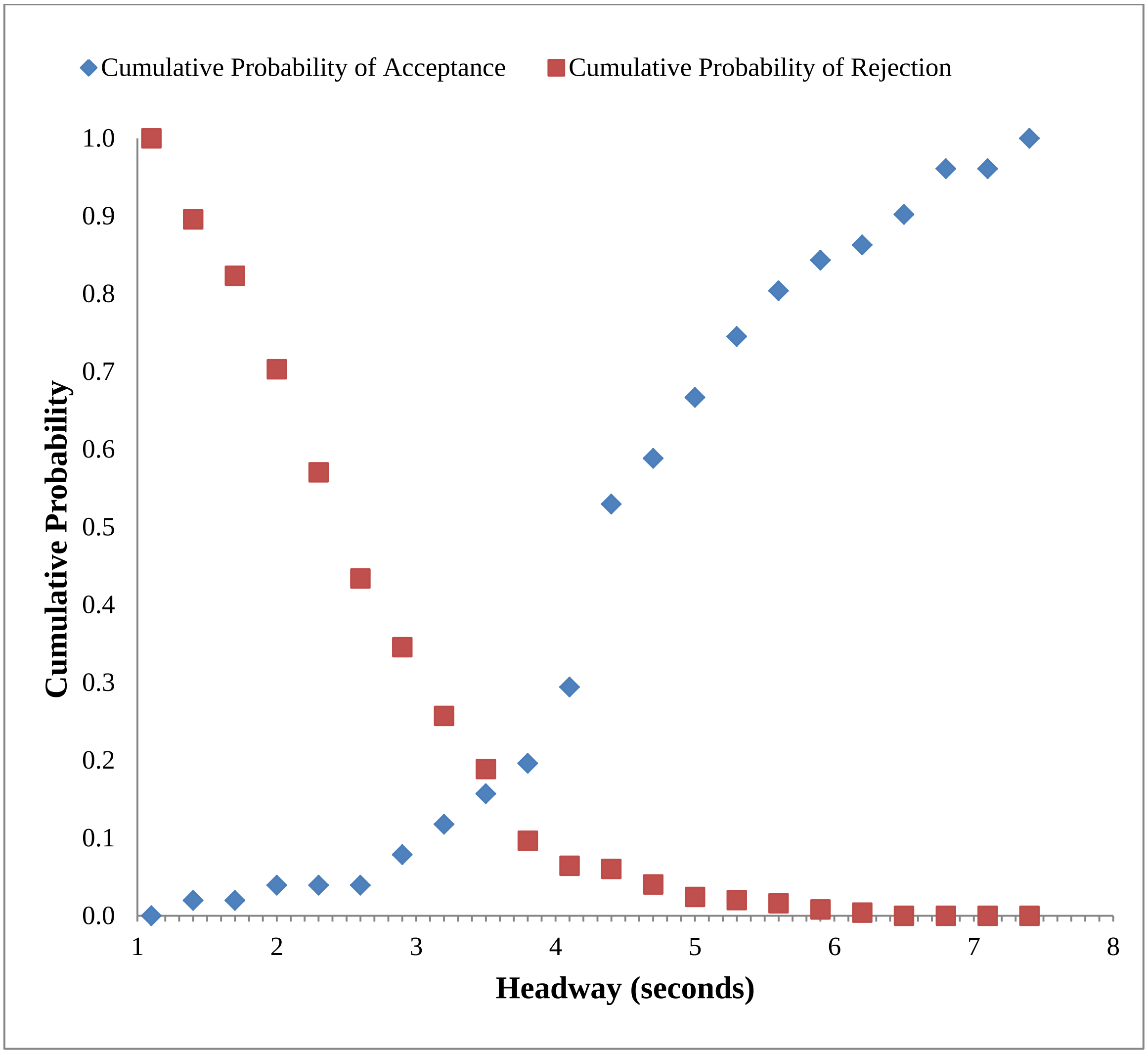


Figure 4.11: Left lane headway Raff's method

4.4.2 Wu's Method

The analysis using Wu's method is far more extensive than Raff's. An excerpt of the results from the Wu's analysis is presented in Table 4.7, with the full data set included in Table A.1 in Appendix A. Headways were sorted as accepted or rejected (A/R) to determine the PDF (probability density function) of both accepted, $F_a(t_j)$, and rejected headways $F_r(t_j)$ using Equation 3.8, shown in columns five and six of Table 4.7.The probability of the estimated critical gap, $F_{tc}(t_j)$ was determined using Equation 3.9, shown in column seven. The frequencies of the estimated critical gaps, p_{tc}, and the class mean, $t_{d,j}$,were determined using Equation 3.10 and 3.11, respectively. The mean value of the estimated critical gap, t_c, was determined as the sum of the frequency of the estimated critical gap multiplied by the class mean. Short hand for the equations described in Section 3.2.6 are listed in row two of Table 4.7 for clarity. The critical gap determined by Wu’s Method for the right lane was 3.21 seconds.

Table 4.7: Right Lane Headway Wu's Method

1	2	3	4	5	6	7	8	9	10
Headway (sec)	**A/R**	**No. R**	**No. A**	$\mathbf{F_r(t_j)}$	$\mathbf{F_a(t_j)}$	$\mathbf{F_{tc}(t_j)}$	$\mathbf{p_{tc}}$	$\mathbf{t_{d,j}}$	$\mathbf{t_c}$
t_j		n_r	n_a	n_r/n_{max}	n_a/n_{max}	$\frac{F_a(t_j)}{F_a(t_j) + (1- F_r(t_j))}$	$F_{tc}(t_j)-F_{tc}(t_{j-1})$	$(t_j + t_{j-1})/2$	$p_{tc}*t_{d,j}$
00:00.10	R	1	0	0.005	0.000	0.000	0.000	00:00.10	00:00.00
00:00.44	R	2	0	0.009	0.000	0.000	0.000	00:00.27	00:00.00
00:00.54	R	3	0	0.014	0.000	0.000	0.000	00:00.49	00:00.00
00:00.56	R	4	0	0.018	0.000	0.000	0.000	00:00.55	00:00.00
00:00.59	R	5	0	0.023	0.000	0.000	0.000	00:00.57	00:00.00
00:00.59	R	6	0	0.027	0.000	0.000	0.000	00:00.59	00:00.00
00:00.59	R	7	0	0.032	0.000	0.000	0.000	00:00.59	00:00.00
00:00.63	R	8	0	0.036	0.000	0.000	0.000	00:00.61	00:00.00

This process was repeated for the left lane headway, where the critical headway was determined to be 3.35 seconds, an excerpt of the data is shown below in Table 4.8, with the full data presented in Table A.2 in Appendix A.

Table 4.8: Left Lane Headway Wu's Method

1	2	3	4	5	6	7	8	9	10
Headway (sec)	**A/R**	**No. R**	**No. A**	**$F_r(t_j)$**	**$F_a(t_j)$**	**$F_{tc}(t_j)$**	**p_{tc}**	**$t_{d,j}$**	**t_c**
t_j		n_r	n_a	n_r/n_{max}	n_a/n_{max}	$\frac{F_a(t_j)}{F_a(t_j) + (1- F_r(t_j))}$	$F_{tc}(t_j)-F_{tc}(t_{j-1})$	$(t_j + t_{j-1})/2$	$p_{tc} * t_{d,j}$
00:00.18	R	1	0	0.004	0.000	0.000	0.000	00:00.18	00:00.00
00:00.31	R	2	0	0.008	0.000	0.000	0.000	00:00.24	00:00.00
00:00.51	R	3	0	0.012	0.000	0.000	0.000	00:00.41	00:00.00
00:00.53	R	4	0	0.016	0.000	0.000	0.000	00:00.52	00:00.00
00:00.54	R	5	0	0.020	0.000	0.000	0.000	00:00.53	00:00.00
00:00.62	R	6	0	0.024	0.000	0.000	0.000	00:00.58	00:00.00
00:00.62	R	7	0	0.028	0.000	0.000	0.000	00:00.62	00:00.00
00:00.66	R	8	0	0.032	0.000	0.000	0.000	00:00.64	00:00.00

4.4.3 Follow-up Headway

An average of the 460 observed follow-up headways was taken to represent the follow-up headway accepted by the majority of drivers. The follow-up headways ranged from 0.51 seconds to 7.10 seconds. The average follow-up headway value was 3.02 seconds.

4.4.4 Comparison of Raff, Wu, and HCS Values

A comparison of the critical and follow-up headway values determined by Raff and Wu's method to the default values given in HCS 2010 and HCM 6th Edition is presented in Table 4.9.

Table 4.9: Comparison of Raff, Wu, and HCS

Method	Follow-up Headway (sec)	Critical Headway (sec)		Intersection Delay (sec)	LOS
		Right	Left		
HCM 2010	4.29	4.11	4.29	56.08	F
Raff	3.02	3.20-3.50	3.50-3.80	27.11	C
Wu	3.02	3.21	3.35	21.44	C

The roundabout intersection delay using the default HCS 2010, which were the standard values accepted at the time of analysis, indicated a level of service F, while both Raff and Wu's method indicate a level of service C. The difference in indicating that a facility is failing (LOS F) versus at or near free flow (LOS C), is significant. The video footage during the peak hour appeared to be near free flow, which agrees with the LOS indicated by Wu's and Raff's method. Both Raff and Wu's method provide values which indicate that the default values currently used by HCS 2010 are not accurate for this jurisdiction. HCS 6th Edition published new critical and follow-up headway values after this analysis was completed. The critical headway for the right lane was increased from 4.11 seconds to 4.32 seconds and the left lane increased from 4.29 seconds to 4.65 seconds, which opposes the findings of Raff and Wu’s analysis. On the contrary, the follow-up headway was reduced from 4.29 seconds to 3.186 for both lanes, which supports the findings of Raff and Wu’s analysis.

The data presented by Giuffre *et al.* (2006) in Table 2.2 describes observed values in Canada for critical and follow-up headway. The minimum value listed in Table 2.2 has been taken to be conservative when comparing it to Wu’s method; however, the minimum critical headway of 3.5 seconds and follow-up headway of 4.6 seconds presented by Giuffre *et al.* (2006) is significantly higher than the values found with Wu. This suggests that even the most conservative critical and follow-up headway values currently used in capacity software are overestimated.

Raff’s method does lack a theoretical basis, but instead relies on its historical reputation of accuracy. Raff’s method provided a range of 0.3 seconds for both the right (3.2-3.5 seconds) and left (3.5-3.8 seconds) lane for the critical headway. The upper value for each lane was taken to be conservative (3.5 seconds for the right lane and 3.8 seconds for the left). The critical headways for each lane were then used to compute the intersection delay and resulting level of service. Raff’s method requires interpreting an intersection point to 1/10th of a second from a graph to determine the critical headway, which can be guesswork and is not ideal for determining a discrete value.

Wu’s method is based on the macroscopic probability equilibrium of the accepted and rejected gaps (Wu 2012). It provides an exact value for both the right and left critical headway with an associated variance. Raff’s method is typically characterized as underestimating the headway; however, Wu’s critical headway is in fact even less than Raff’s method. A comparison of the accumulative probability of acceptance (Fa) and rejection (Fr) produced by Raff’s and Wu’s methods for both the right and left lane are shown in Figures 4.12 and 4.13.

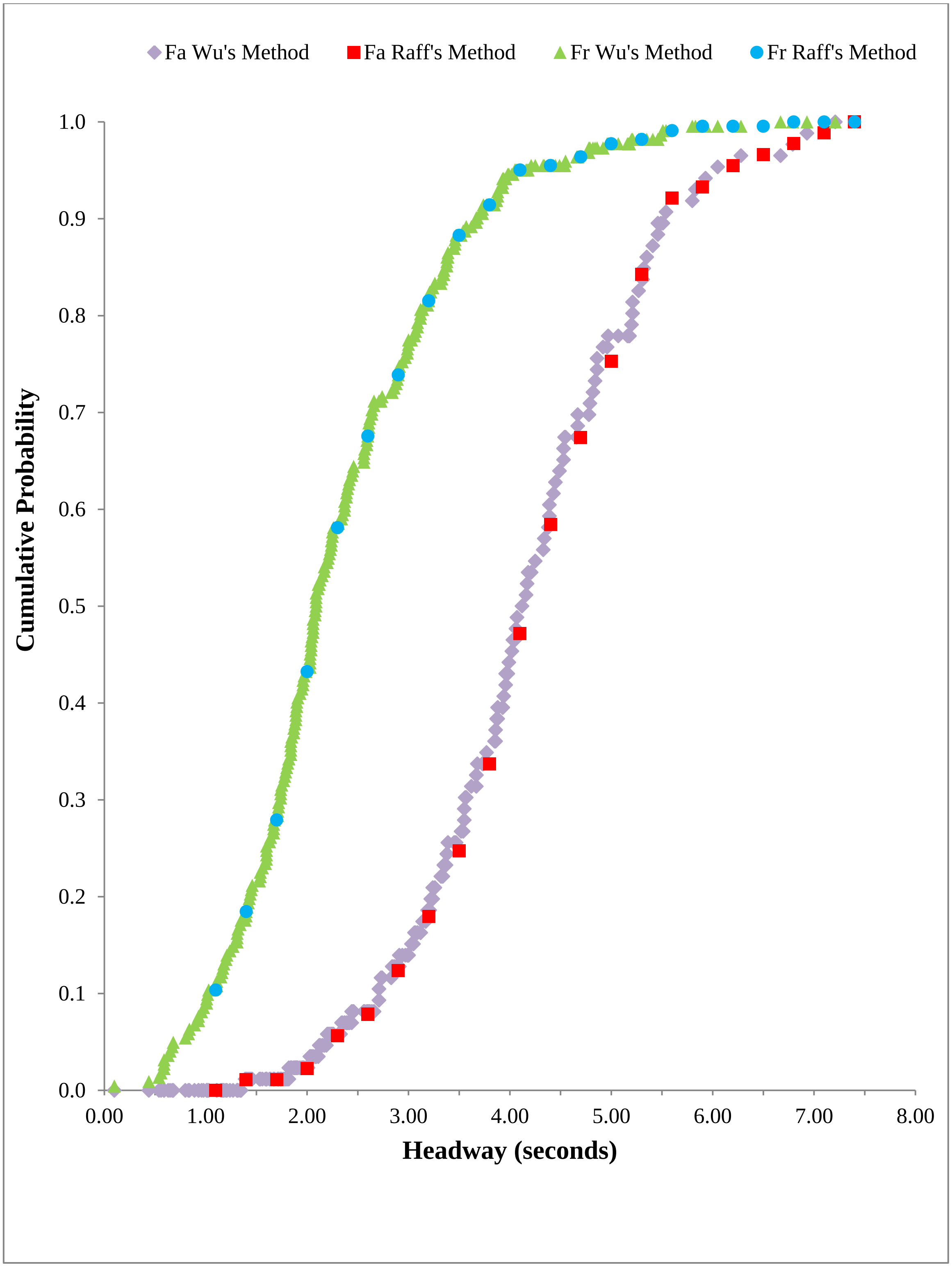


Figure 4.12: Right lane Wu and Raff comparison

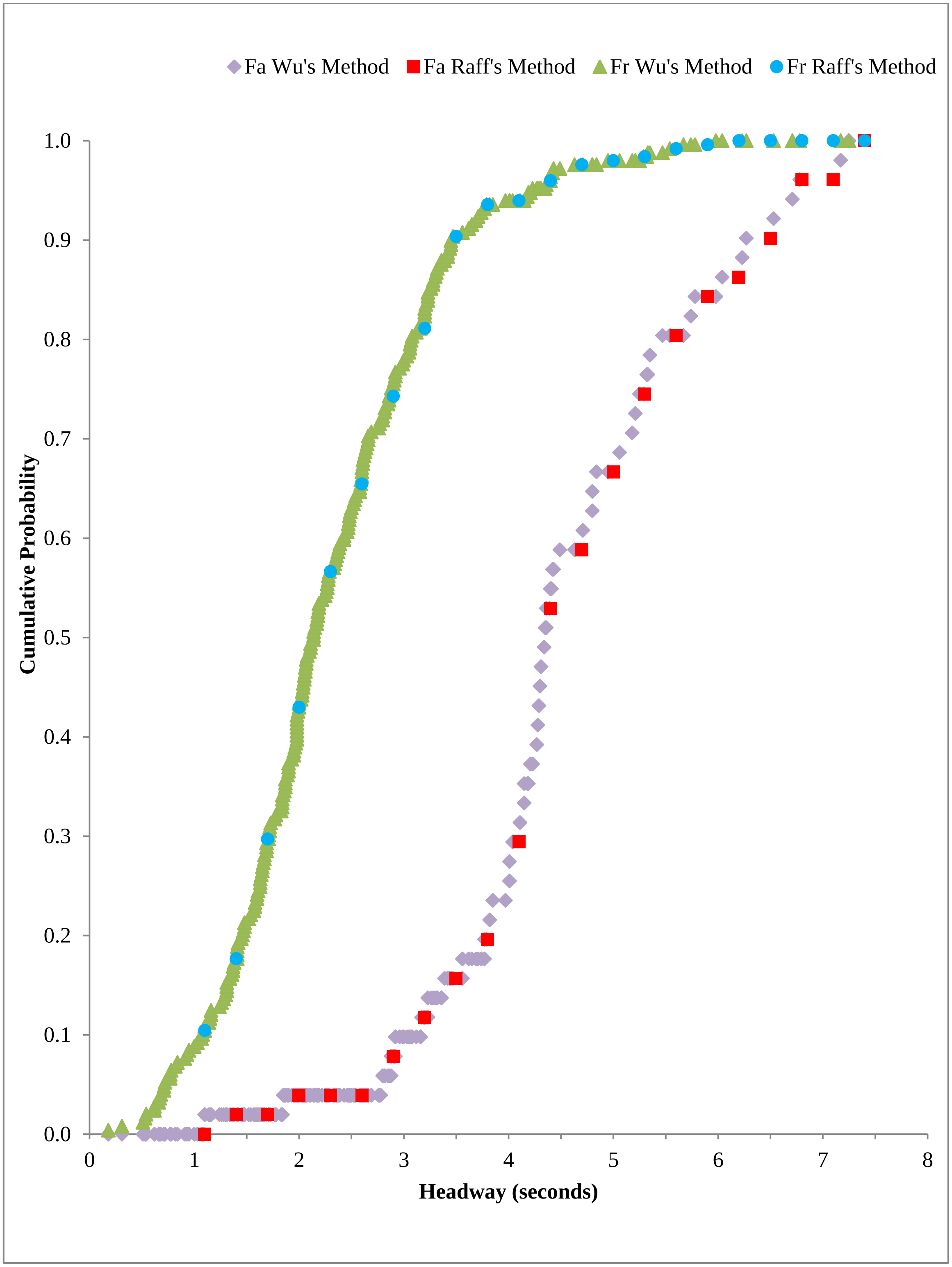


Figure 4.13: Left lane Wu and Raff comparison

The results produced by both methods are very similar. The right lane data set includes 90 accepted headway observations, while the left lane has only 51. The smoothness of the cumulative probability curve shown in Figure 4.12 compared to Figure 4.13 is likely due to the additional observations. While producing similar results, Wu’s method provides values which are of greater accuracy and precision than Raff’s method and should be taken as the true critical headway. Raff’s method is favoured based on its ease of use, but should be supplemented with a theoretically based method if possible to ensure precision.

Using the default values provided by HCS 2010 will result in an underestimate of a facility’s capacity for jurisdictions similar to Fredericton. HCM 2010 recommends that the default values used be calibrated to local conditions; however, collecting the amount of data required to accurately estimate critical and follow-up headways is likely not feasible for all jurisdictions.

5 CONCLUSIONS AND RECOMMENDATIONS

Fredericton's Smythe Street roundabout was the first two-lane facility developed in New Brunswick. Through this study it was observed over a year long period (September 2015-2016) to better understand driver performance and rate of adaptation to the facility. Research included observing and quantifying changes in driver error rates over time, analyzing reported motor vehicle collisions, and quantifying facility capacity during periods of over-saturated demand.

5.1 Conclusions

Driver errors were evaluated first to determine how they changed over time. The majority of observed errors began to level off at 15-20 weeks, which is consistent with findings from other jurisdictions (FHWA 2007). An observed reduction in total errors of 74% was found over a 12 month period. The most commonly observed error was drivers changing lanes within the roundabout; however, the error causing the most collisions was drivers not yielding to traffic already in the roundabout.

Driver errors were categorized into six types, all of which saw a reduction throughout the year: changing lanes within roundabout (81%), not yielding to traffic already in roundabout (59%), stopping within roundabout to allow approach vehicles to enter (39%), left-turn into roundabout (100%), passenger vehicles not giving right-of-way (ROW) to trucks (0%), and improper lane usage (15%). Truck ROW was observed so rarely that estimates in change could not be developed.

Collisions within the roundabout can be delineated into three categories: yield violations (56%), turning violations (41%), and rear-end (3%). After a full year of observations 32 collisions have occurred within the roundabout, 30 of which were property damage only. It is important to note that 59% of the collisions occurred over a three month span during which the presence of a work zone downstream likely had a significant impact on the observed frequency. A comparison between the expected collisions (based on the Region of Waterloo (2014) SPF model) and observed collisions provides a potential for improvement of 4.4 property damage only and -0.4 injury collisions per year. This means that the roundabout has performed slightly worse from a PDO standpoint, but better than expected from an injury perspective.

An original objective was to observe the roundabout during a period of over-saturated demand to quantify the facility's overall capacity. The roundabout was not observed in a completely over-saturated state as anticipated during a traffic re-route which occurred during the summer months due to construction. Instead, volume counts from the footage were evaluated through HCS 2010 software for predictions relative to LOS. The operational LOS provided by HCS 2010 was a LOS F, which was significantly worse than what was observed at the roundabout. Most importantly, v/c ratios were predicted for individual approaches that exceeded 1.0, indicating an overly conservative estimate of critical and follow-up headways. An analysis of critical and follow-up headway default values was then undertaken to determine if the HCS 2010 default values are accurate representations of what was observed. Two methods were used: Wu's method and Raff's method, both of which indicated the roundabout was actually operating at a

LOS C, which is consistent with what was observed in person. This confirmed that the HCS 2010 default values for critical and follow-up headways are underestimated and do not reflect local driver characteristics. More appropriate estimates for critical and follow-up headways were developed.

5.2 Recommendations

The following section summarizes recommendations for programs and future developments similar to the Smythe Street two-lane roundabout, the use of UAVs for traffic monitoring, and future research recommendations.

- Pavement marking guidelines for two-lane roundabouts should stipulate that circulating lane lines be solid rather than broken. The broken lines may be misinterpreted by drivers, leading them to believe they are permitted to change lanes within the roundabout. Drivers changing lanes were the cause of 41% of the observed collisions at the Smythe Street roundabout. Solid pavement marking guidelines may improve the safety of two-lane roundabouts, particularly for novice drivers who are not familiar with the proper usage of a two-lane roundabout. The use of solid lane lines would be consistent with current U.S. national standards (MUTCD 2009).
- Future public educational campaigns undertaken to familiarize local drivers with two-lane roundabouts should emphasize the importance of yielding to both lanes,

as 56% of the collisions which occurred at the roundabout resulted from a yield violation.

- Further monitoring is required to determine if the “Yield To Both Lanes” signage at all approaches reduces the number of drivers not yielding to vehicles inside the roundabout. The Waterloo Region did not have success implementing similar signage previously. Approximately 56% of all collisions observed resulted from a yield violation; therefore, mitigating this error would be a significant safety improvement.

- An analysis of critical and follow-up headway default values was undertaken to determine if the HCS 2010 default values are accurate representations of what was observed. Two methods were used: Wu’s method and Raff’s method, both of which indicated the default values for critical and follow-up headways are too conservative and do not reflect local driver characteristics. More appropriate estimates for critical and follow-up headways were developed and are recommended for capacity analysis in New Brunswick.

- Safety performance functions for multi-lane roundabouts should be used with caution as current published studies produce a wide range of values. Studies which are 5-10 years old have been shown to inaccurately predict the number of collisions occurring at a roundabout. Furthermore, safety performance functions which take into account total daily conflicts (i.e. individual lane volumes) were shown to be significantly more accurate. When possible, the most current safety performance function which requires total daily conflicts should be used.

- Design features (raised centre island, reverse curves, narrow shoulders, urban-style illumination, curbing) seem to have been successful given the lack of collisions associated with excessive approach speeds.

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Appendix A - Wu’s Method Critical Headway

Table A.6.1: Left Lane Critical Headway Wu's Method

Headways (sec)	**A/ R**	**No. R**	**No. A**	$F_r(t_j)$	$F_a(r)$	$F_{tc}(t_j)$	$F_{tc}(t_j)$- $F_{tc}(t_{j-1})$	$t_{d,j}$	t_c
00:00.18	r	1	0	0.004	0.000	0.000	0.000	00:00.18	00:00.00
00:00.31	r	2	0	0.008	0.000	0.000	0.000	00:00.24	00:00.00
00:00.51	r	3	0	0.012	0.000	0.000	0.000	00:00.41	00:00.00
00:00.53	r	4	0	0.016	0.000	0.000	0.000	00:00.52	00:00.00
00:01.00	r	5	0	0.020	0.000	0.000	0.000	00:00.76	00:00.00
00:00.62	r	6	0	0.024	0.000	0.000	0.000	00:00.81	00:00.00
00:00.62	r	7	0	0.028	0.000	0.000	0.000	00:00.62	00:00.00
00:00.66	r	8	0	0.032	0.000	0.000	0.000	00:00.64	00:00.00
00:00.67	r	9	0	0.036	0.000	0.000	0.000	00:00.67	00:00.00
00:00.68	r	10	0	0.040	0.000	0.000	0.000	00:00.68	00:00.00
00:00.71	r	11	0	0.044	0.000	0.000	0.000	00:00.70	00:00.00
00:00.71	r	12	0	0.048	0.000	0.000	0.000	00:00.71	00:00.00
00:00.72	r	13	0	0.052	0.000	0.000	0.000	00:00.71	00:00.00
00:00.77	r	14	0	0.056	0.000	0.000	0.000	00:00.74	00:00.00
00:00.77	r	15	0	0.060	0.000	0.000	0.000	00:00.77	00:00.00
00:00.78	r	16	0	0.064	0.000	0.000	0.000	00:00.78	00:00.00
00:00.82	r	17	0	0.068	0.000	0.000	0.000	00:00.80	00:00.00
00:00.84	r	18	0	0.072	0.000	0.000	0.000	00:00.83	00:00.00
00:00.91	r	19	0	0.076	0.000	0.000	0.000	00:00.87	00:00.00
00:00.93	r	20	0	0.080	0.000	0.000	0.000	00:00.92	00:00.00
00:00.95	r	21	0	0.084	0.000	0.000	0.000	00:00.94	00:00.00
00:01.00	r	22	0	0.088	0.000	0.000	0.000	00:00.97	00:00.00
00:01.03	r	23	0	0.092	0.000	0.000	0.000	00:01.02	00:00.00
00:01.07	r	24	0	0.096	0.000	0.000	0.000	00:01.05	00:00.00
00:01.08	r	25	0	0.100	0.000	0.000	0.000	00:01.07	00:00.00
00:01.09	r	26	0	0.104	0.000	0.000	0.000	00:01.08	00:00.00
00:01.10	a	26	1	0.104	0.020	0.021	0.021	00:01.09	00:00.02
00:01.10	r	27	1	0.108	0.020	0.022	0.000	00:01.10	00:00.00
00:01.14	r	28	1	0.112	0.020	0.022	0.000	00:01.12	00:00.00
00:01.15	r	29	1	0.116	0.020	0.022	0.000	00:01.15	00:00.00
00:01.16	r	30	1	0.120	0.020	0.022	0.000	00:01.16	00:00.00
00:01.16	r	31	1	0.124	0.020	0.022	0.000	00:01.16	00:00.00
00:01.24	r	32	1	0.129	0.020	0.022	0.000	00:01.20	00:00.00
00:01.26	r	33	1	0.133	0.020	0.022	0.000	00:01.25	00:00.00
00:01.28	r	34	1	0.137	0.020	0.022	0.000	00:01.27	00:00.00

00:01.30	r	35	1	0.141	0.020	0.022	0.000	00:01.29	00:00.00
00:01.31	r	36	1	0.145	0.020	0.022	0.000	00:01.31	00:00.00
00:01.31	r	37	1	0.149	0.020	0.023	0.000	00:01.31	00:00.00
00:01.31	r	38	1	0.153	0.020	0.023	0.000	00:01.31	00:00.00
00:01.34	r	39	1	0.157	0.020	0.023	0.000	00:01.33	00:00.00
00:01.36	r	40	1	0.161	0.020	0.023	0.000	00:01.35	00:00.00
00:01.37	r	41	1	0.165	0.020	0.023	0.000	00:01.36	00:00.00
00:01.37	r	42	1	0.169	0.020	0.023	0.000	00:01.37	00:00.00
00:01.38	r	43	1	0.173	0.020	0.023	0.000	00:01.38	00:00.00
00:01.41	r	44	1	0.177	0.020	0.023	0.000	00:01.40	00:00.00
00:01.41	r	45	1	0.181	0.020	0.023	0.000	00:01.41	00:00.00
00:01.41	r	46	1	0.185	0.020	0.023	0.000	00:01.41	00:00.00
00:01.41	r	47	1	0.189	0.020	0.024	0.000	00:01.41	00:00.00
00:01.42	r	48	1	0.193	0.020	0.024	0.000	00:01.42	00:00.00
00:01.45	r	49	1	0.197	0.020	0.024	0.000	00:01.44	00:00.00
00:01.46	r	50	1	0.201	0.020	0.024	0.000	00:01.46	00:00.00
00:01.47	r	51	1	0.205	0.020	0.024	0.000	00:01.47	00:00.00
00:01.48	r	52	1	0.209	0.020	0.024	0.000	00:01.48	00:00.00
00:01.48	r	53	1	0.213	0.020	0.024	0.000	00:01.48	00:00.00
00:01.52	r	54	1	0.217	0.020	0.024	0.000	00:01.50	00:00.00
00:01.54	r	55	1	0.221	0.020	0.025	0.000	00:01.53	00:00.00
00:01.57	r	56	1	0.225	0.020	0.025	0.000	00:01.56	00:00.00
00:01.58	r	57	1	0.229	0.020	0.025	0.000	00:01.57	00:00.00
00:01.58	r	58	1	0.233	0.020	0.025	0.000	00:01.58	00:00.00
00:01.60	r	59	1	0.237	0.020	0.025	0.000	00:01.59	00:00.00
00:01.60	r	60	1	0.241	0.020	0.025	0.000	00:01.60	00:00.00
00:01.61	r	61	1	0.245	0.020	0.025	0.000	00:01.61	00:00.00
00:01.63	r	62	1	0.249	0.020	0.025	0.000	00:01.62	00:00.00
00:01.63	r	63	1	0.253	0.020	0.026	0.000	00:01.63	00:00.00
00:01.63	r	64	1	0.257	0.020	0.026	0.000	00:01.63	00:00.00
00:01.64	r	65	1	0.261	0.020	0.026	0.000	00:01.63	00:00.00
00:01.65	r	66	1	0.265	0.020	0.026	0.000	00:01.64	00:00.00
00:01.65	r	67	1	0.269	0.020	0.026	0.000	00:01.65	00:00.00
00:01.66	r	68	1	0.273	0.020	0.026	0.000	00:01.66	00:00.00
00:01.67	r	69	1	0.277	0.020	0.026	0.000	00:01.67	00:00.00
00:01.67	r	70	1	0.281	0.020	0.027	0.000	00:01.67	00:00.00
00:01.69	r	71	1	0.285	0.020	0.027	0.000	00:01.68	00:00.00
00:01.69	r	72	1	0.289	0.020	0.027	0.000	00:01.69	00:00.00
00:01.69	r	73	1	0.293	0.020	0.027	0.000	00:01.69	00:00.00
00:01.71	r	74	1	0.297	0.020	0.027	0.000	00:01.70	00:00.00
00:01.71	r	75	1	0.301	0.020	0.027	0.000	00:01.71	00:00.00

00:01.72	r	76	1	0.305	0.020	0.027	0.000	00:01.72	00:00.00
00:01.72	r	77	1	0.309	0.020	0.028	0.000	00:01.72	00:00.00
00:01.73	r	78	1	0.313	0.020	0.028	0.000	00:01.73	00:00.00
00:01.77	r	79	1	0.317	0.020	0.028	0.000	00:01.75	00:00.00
00:01.78	r	80	1	0.321	0.020	0.028	0.000	00:01.78	00:00.00
00:01.83	r	81	1	0.325	0.020	0.028	0.000	00:01.81	00:00.00
00:01.84	r	82	1	0.329	0.020	0.028	0.000	00:01.83	00:00.00
00:01.84	r	83	1	0.333	0.020	0.029	0.000	00:01.84	00:00.00
00:01.84	r	84	1	0.337	0.020	0.029	0.000	00:01.84	00:00.00
00:01.84	r	85	1	0.341	0.020	0.029	0.000	00:01.84	00:00.00
00:01.85	a	85	2	0.341	0.039	0.056	0.027	00:01.85	00:00.05
00:01.86	r	86	2	0.345	0.039	0.057	0.000	00:01.86	00:00.00
00:01.87	r	87	2	0.349	0.039	0.057	0.000	00:01.87	00:00.00
00:01.87	r	88	2	0.353	0.039	0.057	0.000	00:01.87	00:00.00
00:01.87	r	89	2	0.357	0.039	0.058	0.000	00:01.87	00:00.00
00:01.89	r	90	2	0.361	0.039	0.058	0.000	00:01.88	00:00.00
00:01.90	r	91	2	0.365	0.039	0.058	0.000	00:01.90	00:00.00
00:01.90	r	92	2	0.369	0.039	0.059	0.000	00:01.90	00:00.00
00:01.90	r	93	2	0.373	0.039	0.059	0.000	00:01.90	00:00.00
00:01.93	r	94	2	0.378	0.039	0.059	0.000	00:01.92	00:00.00
00:01.95	r	95	2	0.382	0.039	0.060	0.000	00:01.94	00:00.00
00:01.95	r	96	2	0.386	0.039	0.060	0.000	00:01.95	00:00.00
00:01.96	r	97	2	0.390	0.039	0.060	0.000	00:01.96	00:00.00
00:01.97	r	98	2	0.394	0.039	0.061	0.000	00:01.96	00:00.00
00:01.98	r	99	2	0.398	0.039	0.061	0.000	00:01.97	00:00.00
00:01.98	r	100	2	0.402	0.039	0.062	0.000	00:01.98	00:00.00
00:01.98	r	101	2	0.406	0.039	0.062	0.000	00:01.98	00:00.00
00:01.98	r	102	2	0.410	0.039	0.062	0.000	00:01.98	00:00.00
00:01.98	r	103	2	0.414	0.039	0.063	0.000	00:01.98	00:00.00
00:01.98	r	104	2	0.418	0.039	0.063	0.000	00:01.98	00:00.00
00:01.98	r	105	2	0.422	0.039	0.064	0.000	00:01.98	00:00.00
00:01.99	r	106	2	0.426	0.039	0.064	0.000	00:01.99	00:00.00
00:02.00	r	107	2	0.430	0.039	0.064	0.000	00:01.99	00:00.00
00:02.00	r	108	2	0.434	0.039	0.065	0.000	00:02.00	00:00.00
00:02.02	r	109	2	0.438	0.039	0.065	0.000	00:02.01	00:00.00
00:02.03	r	110	2	0.442	0.039	0.066	0.000	00:02.03	00:00.00
00:02.03	r	111	2	0.446	0.039	0.066	0.000	00:02.03	00:00.00
00:02.04	r	112	2	0.450	0.039	0.067	0.000	00:02.03	00:00.00
00:02.04	r	113	2	0.454	0.039	0.067	0.000	00:02.04	00:00.00
00:02.05	r	114	2	0.458	0.039	0.067	0.000	00:02.04	00:00.00
00:02.05	r	115	2	0.462	0.039	0.068	0.000	00:02.05	00:00.00

00:02.06	r	116	2	0.466	0.039	0.068	0.000	00:02.06	00:00.00
00:02.06	r	117	2	0.470	0.039	0.069	0.000	00:02.06	00:00.00
00:02.07	r	118	2	0.474	0.039	0.069	0.000	00:02.07	00:00.00
00:02.07	r	119	2	0.478	0.039	0.070	0.000	00:02.07	00:00.00
00:02.08	r	120	2	0.482	0.039	0.070	0.001	00:02.08	00:00.00
00:02.10	r	121	2	0.486	0.039	0.071	0.001	00:02.09	00:00.00
00:02.11	r	122	2	0.490	0.039	0.071	0.001	00:02.11	00:00.00
00:02.11	r	123	2	0.494	0.039	0.072	0.001	00:02.11	00:00.00
00:02.14	r	124	2	0.498	0.039	0.072	0.001	00:02.12	00:00.00
00:02.14	r	125	2	0.502	0.039	0.073	0.001	00:02.14	00:00.00
00:02.14	r	126	2	0.506	0.039	0.074	0.001	00:02.14	00:00.00
00:02.15	r	127	2	0.510	0.039	0.074	0.001	00:02.15	00:00.00
00:02.17	r	128	2	0.514	0.039	0.075	0.001	00:02.16	00:00.00
00:02.17	r	129	2	0.518	0.039	0.075	0.001	00:02.17	00:00.00
00:02.18	r	130	2	0.522	0.039	0.076	0.001	00:02.17	00:00.00
00:02.18	r	131	2	0.526	0.039	0.076	0.001	00:02.18	00:00.00
00:02.19	r	132	2	0.530	0.039	0.077	0.001	00:02.19	00:00.00
00:02.19	r	133	2	0.534	0.039	0.078	0.001	00:02.19	00:00.00
00:02.22	r	134	2	0.538	0.039	0.078	0.001	00:02.21	00:00.00
00:02.25	r	135	2	0.542	0.039	0.079	0.001	00:02.24	00:00.00
00:02.26	r	136	2	0.546	0.039	0.080	0.001	00:02.25	00:00.00
00:02.27	r	137	2	0.550	0.039	0.080	0.001	00:02.27	00:00.00
00:02.27	r	138	2	0.554	0.039	0.081	0.001	00:02.27	00:00.00
00:02.28	r	139	2	0.558	0.039	0.082	0.001	00:02.27	00:00.00
00:02.28	r	140	2	0.562	0.039	0.082	0.001	00:02.28	00:00.00
00:02.29	r	141	2	0.566	0.039	0.083	0.001	00:02.28	00:00.00
00:02.33	r	142	2	0.570	0.039	0.084	0.001	00:02.31	00:00.00
00:02.34	r	143	2	0.574	0.039	0.084	0.001	00:02.34	00:00.00
00:02.35	r	144	2	0.578	0.039	0.085	0.001	00:02.35	00:00.00
00:02.36	r	145	2	0.582	0.039	0.086	0.001	00:02.35	00:00.00
00:02.37	r	146	2	0.586	0.039	0.087	0.001	00:02.36	00:00.00
00:02.38	r	147	2	0.590	0.039	0.087	0.001	00:02.37	00:00.00
00:02.39	r	148	2	0.594	0.039	0.088	0.001	00:02.38	00:00.00
00:02.43	r	149	2	0.598	0.039	0.089	0.001	00:02.41	00:00.00
00:02.43	r	150	2	0.602	0.039	0.090	0.001	00:02.43	00:00.00
00:02.46	r	151	2	0.606	0.039	0.091	0.001	00:02.45	00:00.00
00:02.47	r	152	2	0.610	0.039	0.091	0.001	00:02.47	00:00.00
00:02.47	r	153	2	0.614	0.039	0.092	0.001	00:02.47	00:00.00
00:02.48	r	154	2	0.618	0.039	0.093	0.001	00:02.48	00:00.00
00:02.48	r	155	2	0.622	0.039	0.094	0.001	00:02.48	00:00.00
00:02.49	r	156	2	0.627	0.039	0.095	0.001	00:02.48	00:00.00

00:02.50	r	157	2	0.631	0.039	0.096	0.001	00:02.49	00:00.00
00:02.52	r	158	2	0.635	0.039	0.097	0.001	00:02.51	00:00.00
00:02.53	r	159	2	0.639	0.039	0.098	0.001	00:02.53	00:00.00
00:02.54	r	160	2	0.643	0.039	0.099	0.001	00:02.54	00:00.00
00:02.58	r	161	2	0.647	0.039	0.100	0.001	00:02.56	00:00.00
00:02.58	r	162	2	0.651	0.039	0.101	0.001	00:02.58	00:00.00
00:02.59	r	163	2	0.655	0.039	0.102	0.001	00:02.58	00:00.00
00:02.59	r	164	2	0.659	0.039	0.103	0.001	00:02.59	00:00.00
00:02.60	r	165	2	0.663	0.039	0.104	0.001	00:02.60	00:00.00
00:02.60	r	166	2	0.667	0.039	0.105	0.001	00:02.60	00:00.00
00:02.60	r	167	2	0.671	0.039	0.106	0.001	00:02.60	00:00.00
00:02.61	r	168	2	0.675	0.039	0.108	0.001	00:02.60	00:00.00
00:02.61	r	169	2	0.679	0.039	0.109	0.001	00:02.61	00:00.00
00:02.62	r	170	2	0.683	0.039	0.110	0.001	00:02.61	00:00.00
00:02.63	r	171	2	0.687	0.039	0.111	0.001	00:02.62	00:00.00
00:02.64	r	172	2	0.691	0.039	0.113	0.001	00:02.63	00:00.00
00:02.65	r	173	2	0.695	0.039	0.114	0.001	00:02.65	00:00.00
00:02.66	r	174	2	0.699	0.039	0.115	0.001	00:02.66	00:00.00
00:02.66	r	175	2	0.703	0.039	0.117	0.001	00:02.66	00:00.00
00:02.69	r	176	2	0.707	0.039	0.118	0.001	00:02.68	00:00.00
00:02.76	r	177	2	0.711	0.039	0.119	0.001	00:02.73	00:00.00
00:02.77	r	178	2	0.715	0.039	0.121	0.001	00:02.77	00:00.00
00:02.78	r	179	2	0.719	0.039	0.122	0.002	00:02.78	00:00.00
00:02.80	a	179	3	0.719	0.059	0.173	0.051	00:02.79	00:00.14
00:02.80	r	180	3	0.723	0.059	0.175	0.002	00:02.80	00:00.01
00:02.82	r	181	3	0.727	0.059	0.177	0.002	00:02.81	00:00.01
00:02.82	r	182	3	0.731	0.059	0.179	0.002	00:02.82	00:00.01
00:02.85	r	183	3	0.735	0.059	0.182	0.002	00:02.84	00:00.01
00:02.86	r	184	3	0.739	0.059	0.184	0.002	00:02.86	00:00.01
00:02.86	r	185	3	0.743	0.059	0.186	0.002	00:02.86	00:00.01
00:02.88	r	186	3	0.747	0.059	0.189	0.002	00:02.87	00:00.01
00:02.88	a	186	4	0.747	0.078	0.237	0.048	00:02.88	00:00.14
00:02.88	r	187	4	0.751	0.078	0.240	0.003	00:02.88	00:00.01
00:02.90	r	188	4	0.755	0.078	0.243	0.003	00:02.89	00:00.01
00:02.91	r	189	4	0.759	0.078	0.246	0.003	00:02.90	00:00.01
00:02.92	r	190	4	0.763	0.078	0.249	0.003	00:02.91	00:00.01
00:02.92	a	190	5	0.763	0.098	0.293	0.044	00:02.92	00:00.13
00:02.92	r	191	5	0.767	0.098	0.296	0.004	00:02.92	00:00.01
00:02.96	r	192	5	0.771	0.098	0.300	0.004	00:02.94	00:00.01
00:02.99	r	193	5	0.775	0.098	0.304	0.004	00:02.98	00:00.01
00:03.00	r	194	5	0.779	0.098	0.307	0.004	00:03.00	00:00.01

00:03.03	r	195	5	0.783	0.098	0.311	0.004	00:03.01	00:00.01
00:03.05	r	196	5	0.787	0.098	0.315	0.004	00:03.04	00:00.01
00:03.06	r	197	5	0.791	0.098	0.319	0.004	00:03.05	00:00.01
00:03.06	r	198	5	0.795	0.098	0.324	0.004	00:03.06	00:00.01
00:03.07	r	199	5	0.799	0.098	0.328	0.004	00:03.07	00:00.01
00:03.08	r	200	5	0.803	0.098	0.333	0.004	00:03.07	00:00.01
00:03.12	r	201	5	0.807	0.098	0.337	0.005	00:03.10	00:00.01
00:03.16	r	202	5	0.811	0.098	0.342	0.005	00:03.14	00:00.01
00:03.16	r	203	5	0.815	0.098	0.347	0.005	00:03.16	00:00.02
00:03.17	a	203	6	0.815	0.118	0.389	0.042	00:03.17	00:00.13
00:03.19	r	204	6	0.819	0.118	0.394	0.005	00:03.18	00:00.02
00:03.20	r	205	6	0.823	0.118	0.400	0.005	00:03.19	00:00.02
00:03.20	r	206	6	0.827	0.118	0.405	0.006	00:03.20	00:00.02
00:03.20	r	207	6	0.831	0.118	0.411	0.006	00:03.20	00:00.02
00:03.21	r	208	6	0.835	0.118	0.417	0.006	00:03.21	00:00.02
00:03.23	r	209	6	0.839	0.118	0.423	0.006	00:03.22	00:00.02
00:03.23	a	209	7	0.839	0.137	0.461	0.038	00:03.23	00:00.12
00:03.23	r	210	7	0.843	0.137	0.467	0.006	00:03.23	00:00.02
00:03.23	r	211	7	0.847	0.137	0.474	0.006	00:03.23	00:00.02
00:03.26	r	212	7	0.851	0.137	0.480	0.007	00:03.25	00:00.02
00:03.28	r	213	7	0.855	0.137	0.487	0.007	00:03.27	00:00.02
00:03.28	r	214	7	0.859	0.137	0.494	0.007	00:03.28	00:00.02
00:03.30	r	215	7	0.863	0.137	0.501	0.007	00:03.29	00:00.02
00:03.31	r	216	7	0.867	0.137	0.509	0.007	00:03.31	00:00.02
00:03.32	r	217	7	0.871	0.137	0.516	0.008	00:03.31	00:00.03
00:03.36	r	218	7	0.876	0.137	0.524	0.008	00:03.34	00:00.03
00:03.36	r	219	7	0.880	0.137	0.533	0.008	00:03.36	00:00.03
00:03.39	a	219	8	0.880	0.157	0.566	0.033	00:03.38	00:00.11
00:03.42	r	220	8	0.884	0.157	0.574	0.008	00:03.40	00:00.03
00:03.42	r	221	8	0.888	0.157	0.582	0.009	00:03.42	00:00.03
00:03.44	r	222	8	0.892	0.157	0.591	0.009	00:03.43	00:00.03
00:03.45	r	223	8	0.896	0.157	0.600	0.009	00:03.45	00:00.03
00:03.45	r	224	8	0.900	0.157	0.610	0.009	00:03.45	00:00.03
00:03.47	r	225	8	0.904	0.157	0.619	0.010	00:03.46	00:00.03
00:03.56	r	226	8	0.908	0.157	0.629	0.010	00:03.51	00:00.04
00:03.56	a	226	9	0.908	0.176	0.656	0.027	00:03.56	00:00.10
00:03.62	r	227	9	0.912	0.176	0.666	0.010	00:03.59	00:00.04
00:03.65	r	228	9	0.916	0.176	0.677	0.010	00:03.64	00:00.04
00:03.69	r	229	9	0.920	0.176	0.687	0.011	00:03.67	00:00.04
00:03.71	r	230	9	0.924	0.176	0.698	0.011	00:03.70	00:00.04
00:03.74	r	231	9	0.928	0.176	0.709	0.011	00:03.73	00:00.04

00:03.77	r	232	9	0.932	0.176	0.721	0.012	00:03.76	00:00.04
00:03.77	a	232	10	0.932	0.196	0.742	0.021	00:03.77	00:00.08
00:03.79	r	233	10	0.936	0.196	0.753	0.011	00:03.78	00:00.04
00:03.82	a	233	11	0.936	0.216	0.770	0.017	00:03.80	00:00.07
00:03.85	a	233	12	0.936	0.235	0.785	0.015	00:03.84	00:00.06
00:03.97	r	234	12	0.940	0.235	0.796	0.011	00:03.91	00:00.04
00:04.01	a	234	13	0.940	0.255	0.809	0.013	00:03.99	00:00.05
00:04.01	a	234	14	0.940	0.275	0.820	0.011	00:04.01	00:00.04
00:04.04	a	234	15	0.940	0.294	0.830	0.010	00:04.02	00:00.04
00:04.11	a	234	16	0.940	0.314	0.839	0.009	00:04.07	00:00.04
00:04.15	a	234	17	0.940	0.333	0.847	0.008	00:04.13	00:00.03
00:04.15	a	234	18	0.940	0.353	0.854	0.007	00:04.15	00:00.03
00:04.18	r	235	18	0.944	0.353	0.863	0.008	00:04.17	00:00.03
00:04.19	r	236	18	0.948	0.353	0.871	0.009	00:04.18	00:00.04
00:04.21	a	236	19	0.948	0.373	0.877	0.006	00:04.20	00:00.02
00:04.23	r	237	19	0.952	0.373	0.885	0.008	00:04.22	00:00.04
00:04.27	a	237	20	0.952	0.392	0.891	0.005	00:04.25	00:00.02
00:04.28	a	237	21	0.952	0.412	0.895	0.005	00:04.28	00:00.02
00:04.29	a	237	22	0.952	0.431	0.900	0.004	00:04.29	00:00.02
00:04.30	a	237	23	0.952	0.451	0.903	0.004	00:04.29	00:00.02
00:04.31	a	237	24	0.952	0.471	0.907	0.004	00:04.31	00:00.02
00:04.34	a	237	25	0.952	0.490	0.910	0.003	00:04.32	00:00.01
00:04.35	a	237	26	0.952	0.510	0.914	0.003	00:04.34	00:00.01
00:04.36	r	238	26	0.956	0.510	0.920	0.007	00:04.36	00:00.03
00:04.36	a	238	27	0.956	0.529	0.923	0.003	00:04.36	00:00.01
00:04.39	r	239	27	0.960	0.529	0.929	0.007	00:04.38	00:00.03
00:04.40	a	239	28	0.960	0.549	0.932	0.002	00:04.40	00:00.01
00:04.40	r	240	28	0.964	0.549	0.938	0.006	00:04.40	00:00.03
00:04.41	r	241	28	0.968	0.549	0.945	0.006	00:04.40	00:00.03
00:04.42	a	241	29	0.968	0.569	0.947	0.002	00:04.41	00:00.01
00:04.43	r	242	29	0.972	0.569	0.953	0.006	00:04.42	00:00.03
00:04.49	a	242	30	0.972	0.588	0.954	0.001	00:04.46	00:00.01
00:04.63	r	243	30	0.976	0.588	0.961	0.006	00:04.56	00:00.03
00:04.71	a	243	31	0.976	0.608	0.962	0.001	00:04.67	00:00.01
00:04.80	a	243	32	0.976	0.627	0.963	0.001	00:04.76	00:00.01
00:04.80	a	243	33	0.976	0.647	0.964	0.001	00:04.80	00:00.01
00:04.84	a	243	34	0.976	0.667	0.965	0.001	00:04.82	00:00.00
00:04.95	r	244	34	0.980	0.667	0.971	0.006	00:04.90	00:00.03
00:05.06	a	244	35	0.980	0.686	0.972	0.001	00:05.01	00:00.00
00:05.18	a	244	36	0.980	0.706	0.972	0.001	00:05.12	00:00.00
00:05.21	a	244	37	0.980	0.725	0.973	0.001	00:05.20	00:00.00

00:05.25	a	244	38	0.980	0.745	0.974	0.001	00:05.23	00:00.00
00:05.29	r	245	38	0.984	0.745	0.979	0.005	00:05.27	00:00.03
00:05.32	a	245	39	0.984	0.765	0.979	0.001	00:05.31	00:00.00
00:05.33	r	246	39	0.988	0.765	0.984	0.005	00:05.33	00:00.03
00:05.35	a	246	40	0.988	0.784	0.985	0.000	00:05.34	00:00.00
00:05.47	a	246	41	0.988	0.804	0.985	0.000	00:05.41	00:00.00
00:05.54	r	247	41	0.992	0.804	0.990	0.005	00:05.51	00:00.03
00:05.67	r	248	41	0.996	0.804	0.995	0.005	00:05.60	00:00.03
00:05.74	a	248	42	0.996	0.824	0.995	0.000	00:05.70	00:00.00
00:05.78	a	248	43	0.996	0.843	0.995	0.000	00:05.76	00:00.00
00:05.98	r	249	43	1.000	0.843	1.000	0.005	00:05.88	00:00.03
00:06.04	a	249	44	1.000	0.863	1.000	0.000	00:06.01	00:00.00
00:06.23	a	249	45	1.000	0.882	1.000	0.000	00:06.14	00:00.00
00:06.27	a	249	46	1.000	0.902	1.000	0.000	00:06.25	00:00.00
00:06.53	a	249	47	1.000	0.922	1.000	0.000	00:06.40	00:00.00
00:06.71	a	249	48	1.000	0.941	1.000	0.000	00:06.62	00:00.00
00:06.78	a	249	49	1.000	0.961	1.000	0.000	00:06.74	00:00.00
00:07.17	a	249	50	1.000	0.980	1.000	0.000	00:06.98	00:00.00
00:07.25	a	249	51	1.000	1.000	1.000	0.000	00:07.21	00:00.00
								Sum	**00:03.35**

Table A.6.2: Right Lane Critical Headway Wu's Method

Headway (sec)	**A/R**	**No. R**	**No. A**	**$F_r(t_j)$**	**$F_a(r)$**	**$F_{tc}(t_j)$**	**p_{tc}**	**$t_{d,j}$**	**t_c**
00:00.10	r	1	0	0.005	0.000	0.000	0.000	00:00.10	00:00.00
00:00.44	r	2	0	0.009	0.000	0.000	0.000	00:00.27	00:00.00
00:00.54	r	3	0	0.014	0.000	0.000	0.000	00:00.49	00:00.00
00:00.56	r	4	0	0.018	0.000	0.000	0.000	00:00.55	00:00.00
00:00.59	r	5	0	0.023	0.000	0.000	0.000	00:00.57	00:00.00
00:00.59	r	6	0	0.027	0.000	0.000	0.000	00:00.59	00:00.00
00:00.59	r	7	0	0.032	0.000	0.000	0.000	00:00.59	00:00.00
00:00.63	r	8	0	0.036	0.000	0.000	0.000	00:00.61	00:00.00
00:00.65	r	9	0	0.041	0.000	0.000	0.000	00:00.64	00:00.00
00:00.67	r	10	0	0.045	0.000	0.000	0.000	00:00.66	00:00.00
00:00.68	r	11	0	0.050	0.000	0.000	0.000	00:00.67	00:00.00
00:00.80	r	12	0	0.054	0.000	0.000	0.000	00:00.74	00:00.00
00:00.83	r	13	0	0.059	0.000	0.000	0.000	00:00.82	00:00.00
00:00.84	r	14	0	0.063	0.000	0.000	0.000	00:00.83	00:00.00
00:00.89	r	15	0	0.068	0.000	0.000	0.000	00:00.86	00:00.00
00:00.93	r	16	0	0.072	0.000	0.000	0.000	00:00.91	00:00.00

00:00.93	r	17	0	0.077	0.000	0.000	0.000	00:00.93	00:00.00
00:00.96	r	18	0	0.081	0.000	0.000	0.000	00:00.95	00:00.00
00:00.98	r	19	0	0.086	0.000	0.000	0.000	00:00.97	00:00.00
00:01.01	r	20	0	0.090	0.000	0.000	0.000	00:00.99	00:00.00
00:01.01	r	21	0	0.095	0.000	0.000	0.000	00:01.01	00:00.00
00:01.02	r	22	0	0.099	0.000	0.000	0.000	00:01.02	00:00.00
00:01.03	r	23	0	0.104	0.000	0.000	0.000	00:01.03	00:00.00
00:01.11	r	24	0	0.108	0.000	0.000	0.000	00:01.07	00:00.00
00:01.11	r	25	0	0.113	0.000	0.000	0.000	00:01.11	00:00.00
00:01.15	r	26	0	0.117	0.000	0.000	0.000	00:01.13	00:00.00
00:01.16	r	27	0	0.122	0.000	0.000	0.000	00:01.15	00:00.00
00:01.17	r	28	0	0.126	0.000	0.000	0.000	00:01.17	00:00.00
00:01.18	r	29	0	0.131	0.000	0.000	0.000	00:01.18	00:00.00
00:01.20	r	30	0	0.135	0.000	0.000	0.000	00:01.19	00:00.00
00:01.21	r	31	0	0.140	0.000	0.000	0.000	00:01.21	00:00.00
00:01.24	r	32	0	0.144	0.000	0.000	0.000	00:01.23	00:00.00
00:01.27	r	33	0	0.149	0.000	0.000	0.000	00:01.26	00:00.00
00:01.31	r	34	0	0.153	0.000	0.000	0.000	00:01.29	00:00.00
00:01.31	r	35	0	0.158	0.000	0.000	0.000	00:01.31	00:00.00
00:01.31	r	36	0	0.162	0.000	0.000	0.000	00:01.31	00:00.00
00:01.32	r	37	0	0.167	0.000	0.000	0.000	00:01.32	00:00.00
00:01.34	r	38	0	0.171	0.000	0.000	0.000	00:01.33	00:00.00
00:01.35	r	39	0	0.176	0.000	0.000	0.000	00:01.35	00:00.00
00:01.39	a	39	1	0.176	0.012	0.014	0.014	00:01.37	00:00.02
00:01.40	r	40	1	0.180	0.012	0.014	0.000	00:01.39	00:00.00
00:01.40	r	41	1	0.185	0.012	0.014	0.000	00:01.40	00:00.00
00:01.41	r	42	1	0.189	0.012	0.014	0.000	00:01.41	00:00.00
00:01.42	r	43	1	0.194	0.012	0.014	0.000	00:01.42	00:00.00
00:01.43	r	44	1	0.198	0.012	0.014	0.000	00:01.43	00:00.00
00:01.44	r	45	1	0.203	0.012	0.014	0.000	00:01.43	00:00.00
00:01.45	r	46	1	0.207	0.012	0.014	0.000	00:01.45	00:00.00
00:01.46	r	47	1	0.212	0.012	0.015	0.000	00:01.46	00:00.00
00:01.53	r	48	1	0.216	0.012	0.015	0.000	00:01.49	00:00.00
00:01.54	r	49	1	0.221	0.012	0.015	0.000	00:01.53	00:00.00
00:01.54	r	50	1	0.225	0.012	0.015	0.000	00:01.54	00:00.00
00:01.56	r	51	1	0.230	0.012	0.015	0.000	00:01.55	00:00.00
00:01.59	r	52	1	0.234	0.012	0.015	0.000	00:01.57	00:00.00
00:01.60	r	53	1	0.239	0.012	0.015	0.000	00:01.59	00:00.00
00:01.60	r	54	1	0.243	0.012	0.015	0.000	00:01.60	00:00.00
00:01.60	r	55	1	0.248	0.012	0.015	0.000	00:01.60	00:00.00
00:01.60	r	56	1	0.252	0.012	0.015	0.000	00:01.60	00:00.00

00:01.63	r	57	1	0.257	0.012	0.015	0.000	00:01.62	00:00.00
00:01.64	r	58	1	0.261	0.012	0.015	0.000	00:01.64	00:00.00
00:01.67	r	59	1	0.266	0.012	0.016	0.000	00:01.65	00:00.00
00:01.67	r	60	1	0.270	0.012	0.016	0.000	00:01.67	00:00.00
00:01.67	r	61	1	0.275	0.012	0.016	0.000	00:01.67	00:00.00
00:01.68	r	62	1	0.279	0.012	0.016	0.000	00:01.68	00:00.00
00:01.71	r	63	1	0.284	0.012	0.016	0.000	00:01.69	00:00.00
00:01.71	r	64	1	0.288	0.012	0.016	0.000	00:01.71	00:00.00
00:01.72	r	65	1	0.293	0.012	0.016	0.000	00:01.72	00:00.00
00:01.72	r	66	1	0.297	0.012	0.016	0.000	00:01.72	00:00.00
00:01.74	r	67	1	0.302	0.012	0.016	0.000	00:01.73	00:00.00
00:01.74	r	68	1	0.306	0.012	0.016	0.000	00:01.74	00:00.00
00:01.74	r	69	1	0.311	0.012	0.017	0.000	00:01.74	00:00.00
00:01.75	r	70	1	0.315	0.012	0.017	0.000	00:01.75	00:00.00
00:01.77	r	71	1	0.320	0.012	0.017	0.000	00:01.76	00:00.00
00:01.78	r	72	1	0.324	0.012	0.017	0.000	00:01.78	00:00.00
00:01.79	r	73	1	0.329	0.012	0.017	0.000	00:01.79	00:00.00
00:01.80	r	74	1	0.333	0.012	0.017	0.000	00:01.79	00:00.00
00:01.81	r	75	1	0.338	0.012	0.017	0.000	00:01.80	00:00.00
00:01.82	r	76	1	0.342	0.012	0.017	0.000	00:01.81	00:00.00
00:01.82	a	76	2	0.342	0.023	0.034	0.017	00:01.82	00:00.03
00:01.84	r	77	2	0.347	0.023	0.034	0.000	00:01.83	00:00.00
00:01.84	r	78	2	0.351	0.023	0.035	0.000	00:01.84	00:00.00
00:01.84	r	79	2	0.356	0.023	0.035	0.000	00:01.84	00:00.00
00:01.84	r	80	2	0.360	0.023	0.035	0.000	00:01.84	00:00.00
00:01.85	r	81	2	0.365	0.023	0.035	0.000	00:01.84	00:00.00
00:01.87	r	82	2	0.369	0.023	0.036	0.000	00:01.86	00:00.00
00:01.87	r	83	2	0.374	0.023	0.036	0.000	00:01.87	00:00.00
00:01.88	r	84	2	0.378	0.023	0.036	0.000	00:01.88	00:00.00
00:01.89	r	85	2	0.383	0.023	0.036	0.000	00:01.88	00:00.00
00:01.89	r	86	2	0.387	0.023	0.037	0.000	00:01.89	00:00.00
00:01.89	r	87	2	0.392	0.023	0.037	0.000	00:01.89	00:00.00
00:01.90	r	88	2	0.396	0.023	0.037	0.000	00:01.89	00:00.00
00:01.90	r	89	2	0.401	0.023	0.037	0.000	00:01.90	00:00.00
00:01.91	r	90	2	0.405	0.023	0.038	0.000	00:01.91	00:00.00
00:01.93	r	91	2	0.410	0.023	0.038	0.000	00:01.92	00:00.00
00:01.95	r	92	2	0.414	0.023	0.038	0.000	00:01.94	00:00.00
00:01.96	r	93	2	0.419	0.023	0.038	0.000	00:01.96	00:00.00
00:01.96	r	94	2	0.423	0.023	0.039	0.000	00:01.96	00:00.00
00:01.97	r	95	2	0.428	0.023	0.039	0.000	00:01.97	00:00.00
00:01.99	r	96	2	0.432	0.023	0.039	0.000	00:01.98	00:00.00

00:02.01	r	97	2	0.437	0.023	0.040	0.000	00:02.00	00:00.00
00:02.03	a	97	3	0.437	0.035	0.058	0.019	00:02.02	00:00.04
00:02.03	r	98	3	0.441	0.035	0.059	0.000	00:02.03	00:00.00
00:02.03	r	99	3	0.446	0.035	0.059	0.000	00:02.03	00:00.00
00:02.03	r	100	3	0.450	0.035	0.060	0.000	00:02.03	00:00.00
00:02.04	r	101	3	0.455	0.035	0.060	0.000	00:02.03	00:00.00
00:02.04	r	102	3	0.459	0.035	0.061	0.000	00:02.04	00:00.00
00:02.04	r	103	3	0.464	0.035	0.061	0.000	00:02.04	00:00.00
00:02.05	r	104	3	0.468	0.035	0.062	0.000	00:02.04	00:00.00
00:02.06	r	105	3	0.473	0.035	0.062	0.000	00:02.05	00:00.00
00:02.06	r	106	3	0.477	0.035	0.063	0.001	00:02.06	00:00.00
00:02.06	r	107	3	0.482	0.035	0.063	0.001	00:02.06	00:00.00
00:02.06	r	108	3	0.486	0.035	0.064	0.001	00:02.06	00:00.00
00:02.08	r	109	3	0.491	0.035	0.064	0.001	00:02.07	00:00.00
00:02.08	r	110	3	0.495	0.035	0.065	0.001	00:02.08	00:00.00
00:02.09	r	111	3	0.500	0.035	0.065	0.001	00:02.09	00:00.00
00:02.09	r	112	3	0.505	0.035	0.066	0.001	00:02.09	00:00.00
00:02.09	r	113	3	0.509	0.035	0.066	0.001	00:02.09	00:00.00
00:02.09	r	114	3	0.514	0.035	0.067	0.001	00:02.09	00:00.00
00:02.11	r	115	3	0.518	0.035	0.067	0.001	00:02.10	00:00.00
00:02.11	r	116	3	0.523	0.035	0.068	0.001	00:02.11	00:00.00
00:02.12	a	116	4	0.523	0.047	0.089	0.021	00:02.11	00:00.04
00:02.13	r	117	4	0.527	0.047	0.090	0.001	00:02.12	00:00.00
00:02.15	r	118	4	0.532	0.047	0.090	0.001	00:02.14	00:00.00
00:02.17	r	119	4	0.536	0.047	0.091	0.001	00:02.16	00:00.00
00:02.17	r	120	4	0.541	0.047	0.092	0.001	00:02.17	00:00.00
00:02.19	r	121	4	0.545	0.047	0.093	0.001	00:02.18	00:00.00
00:02.20	a	121	5	0.545	0.058	0.113	0.021	00:02.20	00:00.05
00:02.21	r	122	5	0.550	0.058	0.114	0.001	00:02.20	00:00.00
00:02.22	r	123	5	0.554	0.058	0.115	0.001	00:02.22	00:00.00
00:02.23	r	124	5	0.559	0.058	0.116	0.001	00:02.23	00:00.00
00:02.24	r	125	5	0.563	0.058	0.117	0.001	00:02.24	00:00.00
00:02.24	r	126	5	0.568	0.058	0.119	0.001	00:02.24	00:00.00
00:02.25	r	127	5	0.572	0.058	0.120	0.001	00:02.24	00:00.00
00:02.25	r	128	5	0.577	0.058	0.121	0.001	00:02.25	00:00.00
00:02.26	r	129	5	0.581	0.058	0.122	0.001	00:02.25	00:00.00
00:02.31	r	130	5	0.586	0.058	0.123	0.001	00:02.28	00:00.00
00:02.33	r	131	5	0.590	0.058	0.124	0.001	00:02.32	00:00.00
00:02.34	a	131	6	0.590	0.070	0.145	0.021	00:02.33	00:00.05
00:02.35	r	132	6	0.595	0.070	0.147	0.001	00:02.34	00:00.00
00:02.37	r	133	6	0.599	0.070	0.148	0.001	00:02.36	00:00.00

00:02.37	r	134	6	0.604	0.070	0.150	0.001	00:02.37	00:00.00
00:02.37	r	135	6	0.608	0.070	0.151	0.001	00:02.37	00:00.00
00:02.39	r	136	6	0.613	0.070	0.153	0.001	00:02.38	00:00.00
00:02.39	r	137	6	0.617	0.070	0.154	0.002	00:02.39	00:00.00
00:02.40	r	138	6	0.622	0.070	0.156	0.002	00:02.39	00:00.00
00:02.41	r	139	6	0.626	0.070	0.157	0.002	00:02.40	00:00.00
00:02.42	r	140	6	0.631	0.070	0.159	0.002	00:02.41	00:00.00
00:02.44	r	141	6	0.635	0.070	0.161	0.002	00:02.43	00:00.00
00:02.44	a	141	7	0.635	0.081	0.182	0.022	00:02.44	00:00.05
00:02.45	r	142	7	0.640	0.081	0.184	0.002	00:02.45	00:00.00
00:02.46	r	143	7	0.644	0.081	0.186	0.002	00:02.46	00:00.00
00:02.56	r	144	7	0.649	0.081	0.188	0.002	00:02.51	00:00.00
00:02.56	r	145	7	0.653	0.081	0.190	0.002	00:02.56	00:00.01
00:02.56	r	146	7	0.658	0.081	0.192	0.002	00:02.56	00:00.01
00:02.57	r	147	7	0.662	0.081	0.194	0.002	00:02.57	00:00.01
00:02.59	r	148	7	0.667	0.081	0.196	0.002	00:02.58	00:00.01
00:02.59	r	149	7	0.671	0.081	0.198	0.002	00:02.59	00:00.01
00:02.60	r	150	7	0.676	0.081	0.201	0.002	00:02.60	00:00.01
00:02.60	r	151	7	0.680	0.081	0.203	0.002	00:02.60	00:00.01
00:02.61	r	152	7	0.685	0.081	0.205	0.002	00:02.61	00:00.01
00:02.61	r	153	7	0.689	0.081	0.208	0.002	00:02.61	00:00.01
00:02.62	r	154	7	0.694	0.081	0.210	0.002	00:02.62	00:00.01
00:02.64	r	155	7	0.698	0.081	0.212	0.002	00:02.63	00:00.01
00:02.64	r	156	7	0.703	0.081	0.215	0.003	00:02.64	00:00.01
00:02.66	r	157	7	0.707	0.081	0.218	0.003	00:02.65	00:00.01
00:02.66	r	158	7	0.712	0.081	0.220	0.003	00:02.66	00:00.01
00:02.71	a	158	8	0.712	0.093	0.244	0.024	00:02.68	00:00.06
00:02.71	a	158	9	0.712	0.105	0.266	0.022	00:02.71	00:00.06
00:02.73	a	158	10	0.712	0.116	0.287	0.021	00:02.72	00:00.06
00:02.74	r	159	10	0.716	0.116	0.291	0.003	00:02.74	00:00.01
00:02.83	r	160	10	0.721	0.116	0.294	0.003	00:02.78	00:00.01
00:02.84	a	160	11	0.721	0.128	0.314	0.020	00:02.83	00:00.06
00:02.86	r	161	11	0.725	0.128	0.318	0.004	00:02.85	00:00.01
00:02.88	r	162	11	0.730	0.128	0.321	0.004	00:02.87	00:00.01
00:02.89	r	163	11	0.734	0.128	0.325	0.004	00:02.88	00:00.01
00:02.90	r	164	11	0.739	0.128	0.329	0.004	00:02.89	00:00.01
00:02.90	r	165	11	0.743	0.128	0.333	0.004	00:02.90	00:00.01
00:02.91	r	166	11	0.748	0.128	0.336	0.004	00:02.91	00:00.01
00:02.91	a	166	12	0.748	0.140	0.356	0.020	00:02.91	00:00.06
00:02.94	r	167	12	0.752	0.140	0.360	0.004	00:02.93	00:00.01
00:02.97	r	168	12	0.757	0.140	0.365	0.004	00:02.96	00:00.01

00:02.99	r	169	12	0.761	0.140	0.369	0.004	00:02.98	00:00.01
00:02.99	r	170	12	0.766	0.140	0.373	0.004	00:02.99	00:00.01
00:03.00	r	171	12	0.770	0.140	0.378	0.005	00:02.99	00:00.01
00:03.00	r	172	12	0.775	0.140	0.383	0.005	00:03.00	00:00.01
00:03.03	a	172	13	0.775	0.151	0.402	0.019	00:03.02	00:00.06
00:03.05	r	173	13	0.779	0.151	0.406	0.005	00:03.04	00:00.01
00:03.06	a	173	14	0.779	0.163	0.424	0.018	00:03.05	00:00.05
00:03.07	r	174	14	0.784	0.163	0.430	0.005	00:03.06	00:00.02
00:03.09	r	175	14	0.788	0.163	0.435	0.005	00:03.08	00:00.02
00:03.09	r	176	14	0.793	0.163	0.440	0.005	00:03.09	00:00.02
00:03.12	r	177	14	0.797	0.163	0.445	0.005	00:03.11	00:00.02
00:03.12	r	178	14	0.802	0.163	0.451	0.006	00:03.12	00:00.02
00:03.12	r	179	14	0.806	0.163	0.457	0.006	00:03.12	00:00.02
00:03.14	a	179	15	0.806	0.174	0.474	0.017	00:03.13	00:00.05
00:03.17	r	180	15	0.811	0.174	0.480	0.006	00:03.16	00:00.02
00:03.19	a	180	16	0.811	0.186	0.496	0.016	00:03.18	00:00.05
00:03.20	r	181	16	0.815	0.186	0.502	0.006	00:03.20	00:00.02
00:03.20	r	182	16	0.820	0.186	0.508	0.006	00:03.20	00:00.02
00:03.21	r	183	16	0.824	0.186	0.514	0.006	00:03.20	00:00.02
00:03.22	a	183	17	0.824	0.198	0.529	0.015	00:03.21	00:00.05
00:03.24	r	184	17	0.829	0.198	0.536	0.006	00:03.23	00:00.02
00:03.24	a	184	18	0.829	0.209	0.550	0.014	00:03.24	00:00.05
00:03.26	r	185	18	0.833	0.209	0.557	0.007	00:03.25	00:00.02
00:03.32	a	185	19	0.833	0.221	0.570	0.013	00:03.29	00:00.04
00:03.33	r	186	19	0.838	0.221	0.577	0.007	00:03.33	00:00.02
00:03.34	r	187	19	0.842	0.221	0.584	0.007	00:03.34	00:00.02
00:03.35	a	187	20	0.842	0.233	0.596	0.012	00:03.34	00:00.04
00:03.35	r	188	20	0.847	0.233	0.603	0.007	00:03.35	00:00.02
00:03.37	r	189	20	0.851	0.233	0.610	0.007	00:03.36	00:00.02
00:03.38	a	189	21	0.851	0.244	0.622	0.012	00:03.38	00:00.04
00:03.38	r	190	21	0.856	0.244	0.629	0.007	00:03.38	00:00.02
00:03.38	r	191	21	0.860	0.244	0.636	0.007	00:03.38	00:00.02
00:03.39	a	191	22	0.860	0.256	0.647	0.011	00:03.39	00:00.04
00:03.39	r	192	22	0.865	0.256	0.654	0.007	00:03.39	00:00.03
00:03.45	r	193	22	0.869	0.256	0.662	0.008	00:03.42	00:00.03
00:03.46	r	194	22	0.874	0.256	0.670	0.008	00:03.46	00:00.03
00:03.46	r	195	22	0.878	0.256	0.678	0.008	00:03.46	00:00.03
00:03.47	r	196	22	0.883	0.256	0.686	0.008	00:03.47	00:00.03
00:03.52	a	196	23	0.883	0.267	0.695	0.009	00:03.50	00:00.03
00:03.54	r	197	23	0.887	0.267	0.704	0.008	00:03.53	00:00.03
00:03.55	a	197	24	0.887	0.279	0.712	0.009	00:03.54	00:00.03

00:03.55	a	197	25	0.887	0.291	0.721	0.008	00:03.55	00:00.03
00:03.56	a	197	26	0.887	0.302	0.729	0.008	00:03.56	00:00.03
00:03.57	r	198	26	0.892	0.302	0.737	0.008	00:03.57	00:00.03
00:03.62	a	198	27	0.892	0.314	0.744	0.007	00:03.60	00:00.03
00:03.67	r	199	27	0.896	0.314	0.752	0.008	00:03.64	00:00.03
00:03.67	a	199	28	0.896	0.326	0.759	0.007	00:03.67	00:00.02
00:03.67	r	200	28	0.901	0.326	0.767	0.008	00:03.67	00:00.03
00:03.68	a	200	29	0.901	0.337	0.773	0.006	00:03.68	00:00.02
00:03.73	r	201	29	0.905	0.337	0.781	0.008	00:03.71	00:00.03
00:03.73	r	202	29	0.910	0.337	0.789	0.008	00:03.73	00:00.03
00:03.74	r	203	29	0.914	0.337	0.798	0.008	00:03.74	00:00.03
00:03.77	a	203	30	0.914	0.349	0.803	0.005	00:03.76	00:00.02
00:03.85	a	203	31	0.914	0.360	0.808	0.005	00:03.81	00:00.02
00:03.86	r	204	31	0.919	0.360	0.816	0.008	00:03.86	00:00.03
00:03.86	a	204	32	0.919	0.372	0.821	0.005	00:03.86	00:00.02
00:03.87	a	204	33	0.919	0.384	0.826	0.004	00:03.86	00:00.02
00:03.88	r	205	33	0.923	0.384	0.834	0.008	00:03.87	00:00.03
00:03.88	a	205	34	0.923	0.395	0.838	0.004	00:03.88	00:00.02
00:03.88	r	206	34	0.928	0.395	0.846	0.008	00:03.88	00:00.03
00:03.93	r	207	34	0.932	0.395	0.854	0.008	00:03.90	00:00.03
00:03.93	r	208	34	0.937	0.395	0.862	0.008	00:03.93	00:00.03
00:03.93	r	209	34	0.941	0.395	0.871	0.009	00:03.93	00:00.03
00:03.94	a	209	35	0.941	0.407	0.874	0.003	00:03.94	00:00.01
00:03.96	a	209	36	0.941	0.419	0.877	0.003	00:03.95	00:00.01
00:03.96	a	209	37	0.941	0.430	0.880	0.003	00:03.96	00:00.01
00:03.98	r	210	37	0.946	0.430	0.888	0.008	00:03.97	00:00.03
00:03.99	a	210	38	0.946	0.442	0.891	0.003	00:03.99	00:00.01
00:04.02	a	210	39	0.946	0.453	0.893	0.002	00:04.00	00:00.01
00:04.03	a	210	40	0.946	0.465	0.896	0.002	00:04.03	00:00.01
00:04.05	r	211	40	0.950	0.465	0.904	0.008	00:04.04	00:00.03
00:04.06	a	211	41	0.950	0.477	0.906	0.002	00:04.05	00:00.01
00:04.07	a	211	42	0.950	0.488	0.908	0.002	00:04.07	00:00.01
00:04.12	a	211	43	0.950	0.500	0.910	0.002	00:04.10	00:00.01
00:04.16	a	211	44	0.950	0.512	0.912	0.002	00:04.14	00:00.01
00:04.17	a	211	45	0.950	0.523	0.913	0.002	00:04.17	00:00.01
00:04.18	a	211	46	0.950	0.535	0.915	0.002	00:04.18	00:00.01
00:04.21	r	212	46	0.955	0.535	0.922	0.007	00:04.20	00:00.03
00:04.25	a	212	47	0.955	0.547	0.924	0.002	00:04.23	00:00.01
00:04.33	a	212	48	0.955	0.558	0.925	0.001	00:04.29	00:00.01
00:04.34	a	212	49	0.955	0.570	0.927	0.001	00:04.34	00:00.01
00:04.38	a	212	50	0.955	0.581	0.928	0.001	00:04.36	00:00.01

00:04.39	a	212	51	0.955	0.593	0.929	0.001	00:04.39	00:00.01
00:04.39	a	212	52	0.955	0.605	0.931	0.001	00:04.39	00:00.01
00:04.43	a	212	53	0.955	0.616	0.932	0.001	00:04.41	00:00.01
00:04.45	a	212	54	0.955	0.628	0.933	0.001	00:04.44	00:00.01
00:04.49	a	212	55	0.955	0.640	0.934	0.001	00:04.47	00:00.01
00:04.53	a	212	56	0.955	0.651	0.935	0.001	00:04.51	00:00.00
00:04.53	a	212	57	0.955	0.663	0.936	0.001	00:04.53	00:00.00
00:04.54	a	212	58	0.955	0.674	0.937	0.001	00:04.54	00:00.00
00:04.55	r	213	58	0.959	0.674	0.943	0.006	00:04.55	00:00.03
00:04.66	r	214	58	0.964	0.674	0.949	0.006	00:04.61	00:00.03
00:04.67	a	214	59	0.964	0.686	0.950	0.001	00:04.67	00:00.00
00:04.67	a	214	60	0.964	0.698	0.951	0.001	00:04.67	00:00.00
00:04.78	r	215	60	0.968	0.698	0.957	0.006	00:04.73	00:00.03
00:04.78	r	216	60	0.973	0.698	0.963	0.006	00:04.78	00:00.03
00:04.79	a	216	61	0.973	0.709	0.963	0.001	00:04.78	00:00.00
00:04.82	a	216	62	0.973	0.721	0.964	0.001	00:04.80	00:00.00
00:04.84	a	216	63	0.973	0.733	0.964	0.001	00:04.83	00:00.00
00:04.86	a	216	64	0.973	0.744	0.965	0.001	00:04.85	00:00.00
00:04.86	a	216	65	0.973	0.756	0.965	0.001	00:04.86	00:00.00
00:04.92	a	216	66	0.973	0.767	0.966	0.001	00:04.89	00:00.00
00:04.96	r	217	66	0.977	0.767	0.971	0.006	00:04.94	00:00.03
00:04.97	a	217	67	0.977	0.779	0.972	0.000	00:04.96	00:00.00
00:05.07	a	217	67	0.977	0.779	0.972	0.000	00:05.02	00:00.00
00:05.16	a	217	67	0.977	0.779	0.972	0.000	00:05.11	00:00.00
00:05.17	a	217	67	0.977	0.779	0.972	0.000	00:05.16	00:00.00
00:05.18	a	217	67	0.977	0.779	0.972	0.000	00:05.17	00:00.00
00:05.18	a	217	67	0.977	0.779	0.972	0.000	00:05.18	00:00.00
00:05.20	r	218	68	0.982	0.791	0.978	0.006	00:05.19	00:00.03
00:05.21	a	218	69	0.982	0.802	0.978	0.000	00:05.20	00:00.00
00:05.21	a	218	70	0.982	0.814	0.978	0.000	00:05.21	00:00.00
00:05.27	a	218	71	0.982	0.826	0.979	0.000	00:05.24	00:00.00
00:05.31	a	218	72	0.982	0.837	0.979	0.000	00:05.29	00:00.00
00:05.32	a	218	73	0.982	0.849	0.979	0.000	00:05.31	00:00.00
00:05.35	a	218	74	0.982	0.860	0.979	0.000	00:05.33	00:00.00
00:05.41	a	218	75	0.982	0.872	0.980	0.000	00:05.38	00:00.00
00:05.46	a	218	76	0.982	0.884	0.980	0.000	00:05.43	00:00.00
00:05.46	a	218	77	0.982	0.895	0.980	0.000	00:05.46	00:00.00
00:05.49	r	219	77	0.986	0.895	0.985	0.005	00:05.48	00:00.03
00:05.51	r	220	77	0.991	0.895	0.990	0.005	00:05.50	00:00.03
00:05.54	a	220	78	0.991	0.907	0.990	0.000	00:05.53	00:00.00
00:05.80	r	221	79	0.995	0.919	0.995	0.005	00:05.67	00:00.03

00:05.83	a	221	80	0.995	0.930	0.995	0.000	00:05.81	00:00.00
00:05.93	a	221	81	0.995	0.942	0.995	0.000	00:05.88	00:00.00
00:06.05	a	221	82	0.995	0.953	0.995	0.000	00:05.99	00:00.00
00:06.28	a	221	83	0.995	0.965	0.995	0.000	00:06.17	00:00.00
00:06.67	r	222	83	1.000	0.965	1.000	0.005	00:06.48	00:00.03
00:06.79	a	222	84	1.000	0.977	1.000	0.000	00:06.73	00:00.00
00:06.93	a	222	85	1.000	0.988	1.000	0.000	00:06.86	00:00.00
00:07.21	a	222	86	1.000	1.000	1.000	0.000	00:07.07	00:00.00
								Sum	**00:03.21**

CURRICULUM VITAE

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Universities attended: University of New Brunswick, Bachelor of Science in Civil Engineering (2011-2015)

Publications:

Hildebrand, E.D. and C.J. Sowers, Monitoring Driver Adaptation to a Two-Lane Roundabout With Drones: A Case Study, accepted for publication at the 5th International Roundabout Conference, Transportation Research Board, Wisconsin, May 8-10, 2017.

Sowers C.J. and E.D. Hildebrand, Driver Adaptation to a New Multi-lane Roundabout: A New Perspective Using Drones. Canadian Institute of Transportation Engineers Conference, Kelowna, B.C., June 5-8, 2016.

Conference Presentations:

"Driver Adaptation to a New Multi-lane Roundabout: A New Perspective Using Drones", ITE Atlantic Chapter Annual Meeting, November 2016.