2011

Capacity Estimation for Roundabouts with High Truck Volume Using Gap Acceptance Theory

Jason Dahl
University of Windsor

Capacity Estimation for Roundabouts with High Truck Volume Using Gap Acceptance Theory

By

Jason Dahl

A Thesis
Submitted to the Faculty of Graduate Studies
through the Department of Civil and Environmental Engineering
in Partial Fulfillment of the Requirements for the Degree of Master of Applied Science
at the University of Windsor

Windsor, Ontario, Canada

2011

Capacity Estimation for Roundabouts with High Truck Volume Using Gap Acceptance Theory

By

Jason Dahl

APPROVED BY:

Dr. H. Maoh, Department Reader
Department of Civil and Environmental Engineering

Dr. W. Anderson, Outside Program Reader
Department of Political Science

J. Tofflemire, Special Advisor
Department of Civil and Environmental Engineering

Dr. C. Lee, Advisor
Department of Civil and Environmental Engineering

Dr. B. Budkowska, Chair of Defense
Department of Civil and Environmental Engineering

September 12th, 2011

DECLARATION OF PREVIOUS PUBLICATION

This thesis includes material from two original papers that have been previously submitted for publication in a peer reviewed journal, as follows:

Dahl, J. and C. Lee (2011). *Empirical Estimation of Capacity for Roundabouts Using Adjusted Gap-Acceptance Parameters for Trucks*. Submitted for presentation at the 91st Transportation Research Board Annual meeting, and for publication in the Transportation Research Record. Washington, D.C., 20 pages.

I certify that I have obtained a written permission from the copyright owner(s) to include the above published material(s) in my thesis. I certify that the above material describes work completed during my registration as a graduate student at the University of Windsor.

I declare that, to the best of my knowledge, my thesis does not infringe upon anyone's copyright nor violate any proprietary rights and that any ideas, techniques, quotations, or any other material from the work of other people included in my thesis, published or otherwise, are fully acknowledged in accordance with the standard referencing practices. Furthermore, to the extent that I have included copyrighted material that surpasses the bounds of fair dealing within the meaning of the Canada Copyright Act, I certify that I have obtained written permission from the copyright owner(s) to include such material(s) in my thesis.

I declare that this is a true copy of my thesis, including any final revisions, as approved by my thesis committee and the Graduate Studies office, and that this thesis has not been submitted for a higher degree to any other University or Institution.

ABSTRACT

This study examines the effect of heavy vehicles (trucks) on entry capacity of roundabouts. The movements of vehicles were observed at 11 roundabouts in Vermont, Ontario and Wisconsin. Gap-acceptance parameters were estimated for cars and trucks separately; consistent with previous studies, it was found that critical headway and follow-up time were longer for trucks than cars. Follow-up times for truck-involved vehicle-following cases were found to be associated with central island diameter and entry angle. Gap-acceptance parameters for all entering vehicles were adjusted to a volume-weighted average of the gap-acceptance parameters for cars and trucks. Entry capacity was estimated using existing capacity models with the adjusted gap-acceptance parameters, and compared with the observed capacity at three roundabouts. The capacity models with adjusted gap-acceptance parameters estimated capacity more accurately than the models with unadjusted parameters. Microscopic traffic simulation model was also effective in representing truck characteristics and their impact on roundabout operation.

Keywords: Roundabout, Capacity, Truck, Heavy vehicle, Gap acceptance

ACKNOWLEDGEMENTS

I would personally like to thank my supervisor, Dr. Chris Lee, for his continued support, guidance, assistance, and overall persistence throughout the course of this project. His encouragement has allowed me to learn and accomplish much more than I had expected, travel to various parts of the continent, and recapture my excitement in this field of engineering. Thanks to my evaluation committee of Dr. Hanna Maoh, Dr. William P. Anderson, Mr. John D. Tofflemire, and Dr. Barabara Budkowska. Additional thanks to Dr. Sreekanta Das and Dr. Shaohong Cheng for guidance while considering grad school. Thanks to Ms. Adinda Van Espen for helping me collect some field data from video footage.

Thanks also goes to Ms. Andrea Bill at the University of Wisconsin-Madison, Mr. Patrick Fleming at Wisconsin Department of Transportation, Mr. Egerton Heath at Region of Waterloo and Mr. Lee A. Rodegerdts at Kittelson & Associates, Inc. for providing the video records and geometric drawings used in the study. I would also thank Dr. Ning Wu and Dr. Rod Troutbeck for providing the information on the critical headway. This research was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC).

I would like to thank all of my friends and colleagues at the University, specifically Corey and Kevin, for their support and kind words; it's good to not be suffering alone (just kidding). I'd also like to thank my friends outside of graduate school, for keeping me focused and positive. Thanks to Adam, Amy, Heather, Jeff, Jordan, Mark, and Sarah; and thanks to all of the roommates and band mates I've had the privilege to meet these last few years. Extra thanks to

Charles, Pawel and Sonia, for lending me their homes, couches and pantries while I attended conferences outside of Windsor during this time.

Finally, thanks to my family, for always encouraging me to continue my education. Special thanks to Aunt Jane and Uncle Dave, and to my grandparents Nick and Anna Bauer, for their boundless love, support and belief in me. Thanks for helping me become the person I am today.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

C_e	entry capacity (pcu/h)
e_{HV}	passenger car equivalent of a heavy vehicle (pcu/veh) (default is 2.0)
$F(t)$	cumulative probability that the headway is less than or equal to t
$F_a(t)$	cumulative probability distribution function of an accepted gap t
f_c	constant that depends on the geometry of the circle
f_{HV}	heavy vehicle factor
$F_{tc}(t)$	cumulative probability distribution function of the critical headway
$F_r(t)$	cumulative probability distribution function of a maximum rejected gap t
p_{truck}	percentage of trucks within the entry flow
q_c	circulating flow (pcu/h)
t_a	an accepted gap (sec)
t_c	critical headway (sec)
$t_{c,car}$	critical headway for cars (sec)
$t_{c,truck}$	critical headway for trucks (sec)
t'_c	critical headway adjusted for heavy vehicle effects in the entry flow (sec)
t_f	follow-up time (sec)
t'_f	follow-up time adjusted for heavy vehicle effects in the entry flow (sec)
$t_{f,cc}$	follow-up time of a car following a car (car/car)
$t_{f,ct}$	follow-up time of a truck following a car (car/truck)

$t_{f,tc}$	follow-up time of a car following a truck (truck/car)
$t_{f,tt}$	follow-up time of a truck following a truck (truck/truck)
t_r	maximum rejected gap (sec)
α	proportion of free vehicles
Δ	minimum headway between the circulating vehicles (sec)
Δ_e	equivalent travel time (sec)
$\Delta_{e,car}$	equivalent travel time for cars (sec)
$\Delta_{e,truck}$	equivalent travel time for trucks (sec)
λ	decay constant (sec^{-1})

1 INTRODUCTION

1.1 Overview

A roundabout is an unsignalized intersection with a circulating roadway and entry legs where entering vehicles must yield to the circulating vehicles. Currently, there are over 150 roundabouts in Canada (Rasheed, 2010) and over 1600 in the United States (Kittleson & Associates, 2011). Roundabouts have positive effects on traffic operation, safety, environment and society. Since vehicles are not required to completely stop when there is no conflict, traffic delay is reduced. Due to a shorter queue at the entry, the vehicle storage space of approach roadways can be reduced. The reduction in delay and frequency of stop-and-go movements results in the reduced fuel consumption, air pollution, and noise. Also, the landscaping of a roundabout could improve aesthetics and increase property value of the surrounding area. The following empirical studies reported that roundabouts have particularly safety benefits and operational efficiency.

For instance, total crashes were reduced by 35% and injury crashes were reduced by 76% for roundabouts compared to the other intersection types in the United States (Rodegerdts et al., 2010). Similar results have also been found in Australia, France, Germany, Netherlands and the United Kingdom - crash and injury reduction by 61% and 87%, respectively (Rodegerdts et al., 2010).

Crash reduction is mainly due to lower number of conflict points within the intersection. A conflict point is a point where paths of two vehicles diverge, merge or cross. For example, single-lane roundabouts reduce the number of conflict points from 32 to 8 as illustrated in Figure

1-1. Multi-lane roundabouts also reduce the total number of conflict points compared to the other multi-lane intersections.

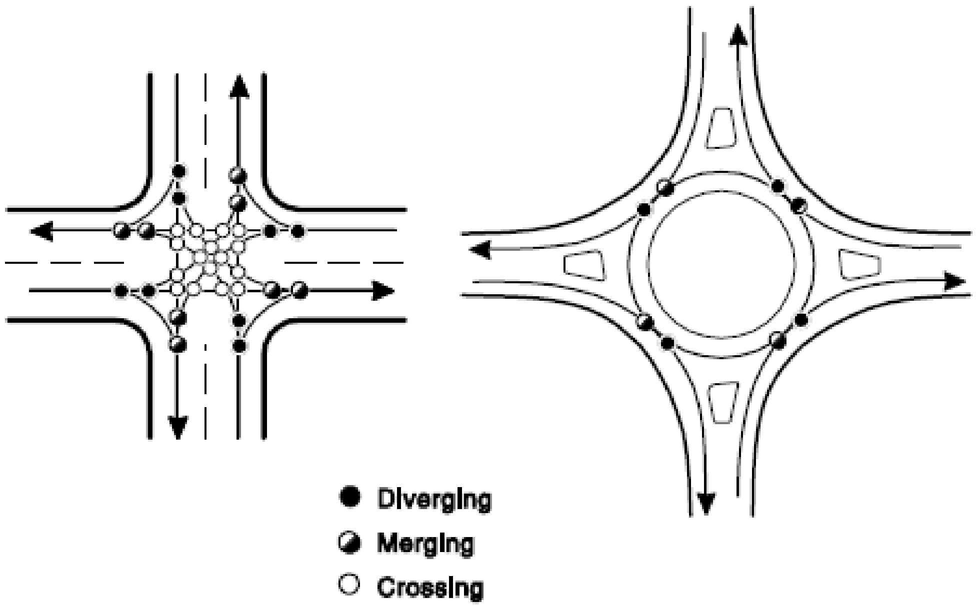


Figure 1-1. Comparison of Vehicle Conflict Points between Intersections and Single-lane Roundabouts
(Source: Rodegerdts et al., 2010)

In addition to safety benefits, roundabouts also operate with lower delays compared to the other intersections. In practice, operational efficiency of roundabouts is evaluated based on the *entry capacity*. The entry capacity is defined as the maximum number of vehicles that can enter the roundabout in unit time (the *entry flow*) at a given entry leg for a given flow in a circulatory roadway (the *circulating flow*). In general, as the circulating (or conflicting) flow increases, the capacity decreases due to less opportunity for entry. Delay is estimated based on the capacity and the demand entry flow.

Table 1-1. Comparison of Delay between Signalized Intersection in 1999 and Roundabout in 2000 at Intersection of US-5, I-91 and VT-9
(Source: Reddington, 2001)

Peak Hour	Signalized intersection (1999)		Roundabout (2000)		Change (sec)
	Delay (sec)	Vehicles/hour	Delay (sec)	Vehicles/hour	
AM	44	1216	12	1870	-33
PM	46	2764	26	2812	-20

Reddington (2001) observed that after a signalized intersection was changed to a roundabout in Brattleboro, Vermont, delay was greatly reduced as shown in Table 1-1. Similarly, an annual reduction in delay by 5,000-10,000 hours was observed at a roundabout in Maine (Garder, 1998). This is mainly because vehicles are not required to completely stop when there is no conflict, and a long queue at the intersection can be avoided. Due to this reduction in delay and frequency of stop-and-go movements, roundabouts can also reduce fuel consumption, air pollution, and noise.

As roundabouts have become more favourable, more roundabouts have been built on or near main highways with high truck volume. Statistics have shown that there are a large number of trucks and truck-involved crashes on Canadian roadways. In Canada, there are approximately 18.6 million registered vehicles and 295,000 of the vehicles are heavy trucks (Natural Resources Canada, 2007). However, trucks travel longer distance than light vehicles; 66,640km/veh/year compared to 16,300km/veh/year (Statistics Canada, 2003). In particular, there is a large number of trucks in Windsor. In 2003, 6.3 million passenger vehicles and 1.6 million trucks crossed the Windsor-Detroit international crossing (Baldwin, 2005). Mayhew et al. (2004) reported that trucks account for almost 5% of all motor vehicle injuries, and 20% of deaths in Canada and trucks have higher rates of fatal crashes per vehicle, and per unit distance.

However, if the proportion of trucks is higher, traffic operation of the roundabouts is more likely to be influenced by trucks. Trucks have slower acceleration, require wider turning radius, and have larger blind spots of vision than passenger cars. They also obstruct the view of the other circulating/entering vehicles. Slower acceleration of trucks requires larger gaps to enter roundabout and results in a longer queue of trucks at the yield line. Wider turning radius requires larger space for truck turning movement and trucks are more likely to obstruct the circulating vehicles in adjacent lanes at a multi-lane roundabout. Obstructed view consequently reduces the speeds of the circulating vehicles. Thus, it is important to consider these effects of truck turning movement of efficiency and safety of roundabouts. For this research, a truck is defined as an 18-wheeler.

To account for the effect of trucks on the capacity, the capacity has been adjusted based on truck's longer length and lower speed, and percentage of trucks. In conventional approach (TRB, 2000), the capacity is adjusted for trucks by converting the number of vehicles to passenger car units (pcu). Since trucks are weighted higher than passenger cars, it is expected that capacity decreases more rapidly as the number of trucks in the circulating flow increases.

However, this adjustment method does not capture the effect of trucks on driver's gap-acceptance behavior, which is essential to understand mechanism of roundabout operation affected by trucks (Troutbeck, 1993). Driver's gap acceptance behavior is likely to differ between cars and trucks due to slower truck entry and longer gaps required by trucks.

Current roundabout capacity estimation models were developed based on the gap-acceptance theory which describes the capacity in a function of the circulating flow, the critical headway and the follow-up time. The *critical headway* is defined as the minimum time gap between the circulating vehicles accepted by the entering vehicles. The *follow-up time* is defined as the time gap between two queued vehicles that enter the roundabout using the same gap between the circulating vehicles. However, most past studies only assume single values of the critical headway and the follow-up time for cars and trucks. Thus, there is a need to incorporate the difference of car and truck gap-acceptance behaviour into a roundabout capacity model.

1.2 Objectives of Thesis

The objectives of this research are 1) to identify the limitations of the existing roundabout capacity estimation methods with respect to truck traffic, 2) to develop a method to take into account the effect of trucks on capacity and, 3) to evaluate the accuracy of capacity estimation using the proposed method by comparing with the observed capacity.

1.3 Organization of Thesis

This thesis is organized into six chapters. Chapter 2 reviews the literature on the capacity estimation models for roundabouts, and the methods of considering trucks in the estimation of the capacity. Chapter 3 describes the procedures of considering the effects of trucks on the capacity used in this study. Chapter 4 describes the data and collection methods used in this study. Chapter 5 presents the results and analysis of this study. Chapter 6 includes the conclusions and recommends future research.

2 LITERATURE REVIEW

2.1 Gap Acceptance Capacity Models

Roundabout capacity has been estimated using various capacity models developed based on the gap acceptance theory. The gap acceptance method estimates the capacity based on the distribution of headways within the circulating flow, the critical-headway and the follow-up time.

2.1.1 Headway Distribution

The gap acceptance models assume that the headways (i.e. the time between consecutive vehicles passing the conflict point) of the circulating flow follows a certain distribution. Typically, the distribution follows an M1 (negative exponential), M2 (shifted negative exponential), or M3 (bunched exponential) (Cowan, 1997). The distributions are expressed as follows:

$$F(t) = 1 - e^{-\lambda t} \text{ for } t \geq 0 \qquad \text{(M1)} \qquad (2.1)$$

$$F(t) = 1 - e^{-\lambda (t - \Delta)} \text{ for } t \geq 0 \qquad \text{(M2)} \qquad (2.2)$$

$$F(t) = 1 - \alpha \cdot e^{-\lambda (t - \Delta)} \text{ for } t \geq 0 \qquad \text{(M3)} \qquad (2.3)$$

where $F(t)$ is the cumulative probability that the headway is less than or equal to t, Δ is the minimum headway between the circulating vehicles (sec), λ is the decay constant (sec^{-1}), and α is the proportion of free vehicles (i.e. vehicle manoeuvre is not affected by the lead vehicle). The decay constant λ is calculated using the following expression (Cowan, 1997):

$$\lambda = \frac{q_c \cdot \alpha}{1 - q_c \Delta} \qquad (2.4)$$

where q_c is the circulating flow (pcu/h). All distributions were developed based on the assumption that the arrival of vehicles follows a Poission distribution. The M1 distribution is the simplest form but does not assume a minimum headway. The M2 distribution is the M1 distribution with headways shifted by a minimum non-zero headway. The M3 distribution has additional assumption of “bunching” of vehicles within the circulating flow in congested conditions. Troutbeck (1994) suggested that the proportion of free (unbunched) vehicles at a roundabout is dependent on the circulating flow as follows:

$$\alpha = 0.75(1 - q_c) \tag{2.5}$$

Alternatively, Akçelik (2003) suggested that α can be estimated using the following equation:

$$\alpha = \max\left(\frac{(1 - q_c)}{1 - (1 - k_d)\Delta q_c}, 0.001\right) \tag{2.6}$$

where k_d is a constant (= 2.2 for roundabouts). Eq. 2.5 and 2.6 assume that the proportion of free vehicles decreases as the circulating flow increases due to shorter headways.

The M1 and M2 distributions are often favoured due to their simplicity, and in some cases the M3 distribution provides more realistic results (Akçelik & Chung, 2003). More complex but less widely used distributions also exist to define headway distribution (Sullivan & Troutbeck, 1994; Akçelik & Chung, 2003).

2.1.2 Capacity Models

The headway distribution functions can be used in conjunction with gap-acceptance parameters to derive the capacity estimation models. These models are macroscopic analytical models which express the capacity in an exponential function of the circulating flow. The exponential function is reasonable because the rate of reduction in capacity generally decreases as the circulating flow increases and capacity never reaches zero (Polus et al., 2003). For example, the capacity model adapted in the Highway Capacity Manual (HCM) 2000 (TRB, 2000) assumes that headways follow an M1 distribution (Eq. 2.1), and is described as follows:

$$C_e = \frac{3600 \cdot q_c \cdot e^{-q_c t_c}}{1 - e^{-q_c t_f}} \tag{2.7}$$

where C_e is the entry capacity (pcu/h), t_c is the critical headway (sec), and t_f is the follow-up time (sec). This capacity model was revised in the HCM 2010 (TRB, 2010) as follows:

$$C_e = \frac{3600}{t_f} e^{-\left(\frac{t_c - 0.5 t_f}{3600}\right) q_c} \tag{2.8}$$

The above capacity model is an exponential regression model developed based on a gap-acceptance theory (Akçelik, 2011). Unlike the HCM 2000, the critical headways were assumed to be different for different roundabout geometry. Geometry is classified in terms of the numbers of circulating lanes and entry lanes. In this model, shorter critical headways were used for a multi-lane roundabout (4.11 s for one lane entry; 4.11 s and 4.29 s for right and left entry lanes, respectively, in case of multi-lane entry) than a one-lane roundabout (5.19 s for all entry lanes). The follow-up time for all roundabout geometry is 3.19 s.

The capacity models were also derived using the M2 distribution (Eq. 2.2) and an M3 distribution (Eq. 2.3) as shown in Eq. 2.9 and 2.10, respectively (Tanner, 1967; Troutbeck, 1986):

$$C_e = \frac{3600 \cdot q_c \cdot (1 - \Delta \cdot q_c) \cdot e^{-q_c (t_c - \Delta)}}{1 - e^{-q_c t_f}} \text{ (Tanner, 1967)} \tag{2.9}$$

$$C_e = \frac{3600 \cdot q_c \cdot \alpha \cdot e^{-\lambda (t_c - \Delta)}}{1 - e^{-\lambda t_f}} \qquad \text{(Troutbeck, 1986)} \tag{2.10}$$

Troutbeck (1999) suggested that although the entering vehicles must yield to the circulating vehicles at roundabouts, they occasionally violate this priority rule and enter the roundabout with insufficient time gap. This results in delay in the circulating flow to accommodate the entering vehicles. This system is called a "limited priority system". Given that trucks require longer time gaps to enter and longer time gaps are less likely to occur in the circulating flow, it is expected that trucks are more likely to violate the priority rule. It was found that the limited priority merge can have significant effect on the entry capacity at two-lane roundabouts. The capacity is adjusted as follows (Troutbeck, 1999):

$$C_e = \frac{3600 \cdot q_c \cdot C \cdot \alpha \cdot e^{-\lambda (t_c - \Delta)}}{1 - e^{-\lambda t_f}} \tag{2.11}$$

where $C = \dfrac{e^{\lambda t_f} - 1}{e^{\lambda t_f} - e^{\lambda \beta} - \lambda \beta e^{-\lambda \beta}}$, $t_f \le t_c \le t_f + \Delta$

Tanyel et al. (2007) had tested the M1, M2 and M3 capacity models and found that the M3 model performed best for the six roundabouts in Turkey. However, it was found that the M1 model performed best for the roundabouts in the U.S. (TRB, 2000).

2.1.3 Critical Headway

Critical headways are estimated using the distributions of gap acceptance and rejection data. Three methods are commonly used for estimating the critical headway: 1) the graphical method, 2) the maximum likelihood method and 3) the probability equilibrium method (Wu, 2006). The graphical method determines the critical headway by using cumulative distributions of individual entry vehicles' accepted and rejected gaps. A gap is considered accepted if the driver of the entering vehicle perceives that the gap is sufficiently long enough for them to enter the roundabout (as indicated by the vehicle entry). Otherwise, the gap is rejected. The critical headway is then determined at the point of intersection between the two cumulative distribution curves of the accepted gaps and rejected gaps plotted on the same graph; an example based on empirical data is shown in Figure 2-1.

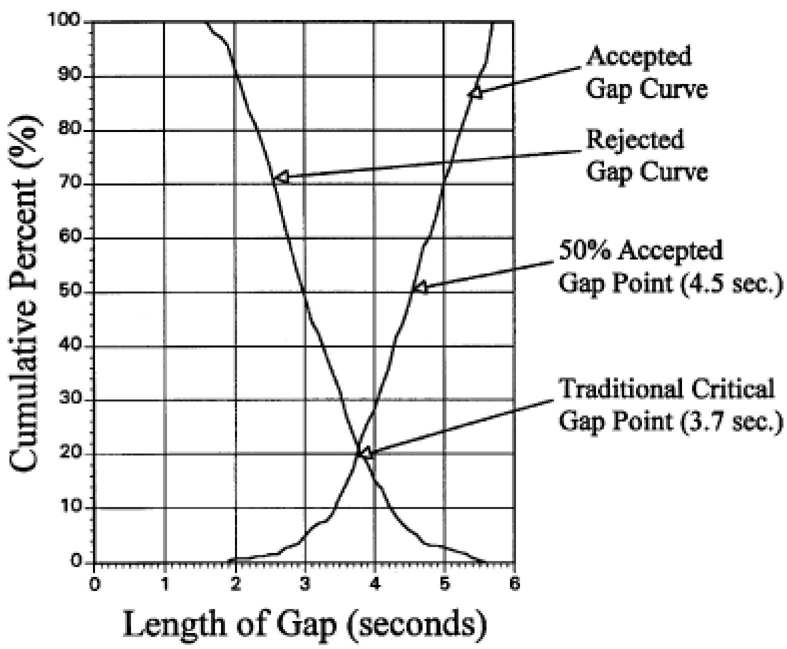


Figure 2-1. Determination of Critical Headway using Graphical Method.
(Source: Flannery and Datta, 1997)

The maximum likelihood method (Troutbeck, 1989), assumes that the probability distribution function (PDF) of the critical headway ($F_{tc}(t)$) follows a lognormal distribution. The parameters of this PDF are obtained by maximizing the following likelihood function:

$$L = \prod_{i=1}^{n} [F_a(t) - F_r(t)] \tag{2.12}$$

where $F_a(t)$ is the PDF of an accepted gap t and $F_r(t)$ is the PDF of a maximum rejected gap t_r However, this method only accounts for the maximum rejected gap, not all rejected gaps. Also, it requires iterative calculation to maximize the above likelihood function.

To overcome these limitations, the probability equilibrium method assumes that the probability distribution function (PDF) of the critical headway is described as follows (Wu, 2006):

$$F_{tc}(t) = \frac{F_a(t)}{F_a(t) + 1 - F_r(t)} \tag{2.13}$$

where $F_{tc}(t)$ is the PDF of the critical headway. If a time gap t is sorted in an ascending order, j = 1, 2, …, N, the critical headway is calculated using the following expression:

$$t_c = \sum_{j}^{N} [p_{tc}(t_j) \cdot (t_j + t_{j-1})/2] \tag{2.14}$$

where $p_{tc}(t_j)$ is the frequencies of the estimated critical headways between j and j-1. This method does not assume the distribution of gaps, and accounts for all relevant rejected gaps, not only the maximum rejected gaps unlike the maximum likelihood method.

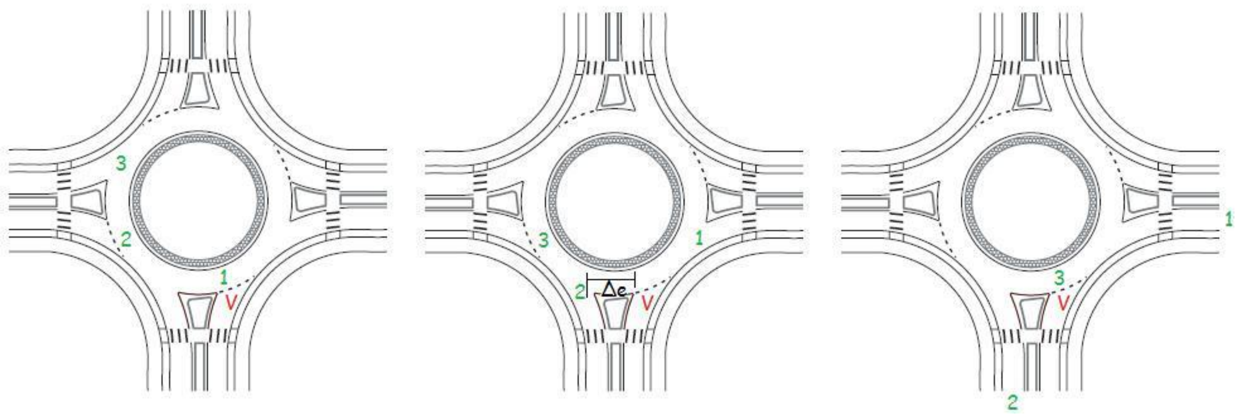
The critical headway is negatively correlated with higher circulating flow and higher speed of the circulating flow (Xu and Tian, 2008). Also, the critical headway is affected by the waiting time of entrance vehicles (Polus et al., 2003). As waiting time increases, drivers will become more aggressive and will accept shorter gaps. Consequently, this will reduce the critical headway. This could lead to forced entry manoeuvre, also known as *gap forcing*. When vehicles accept gaps which are shorter than the gap required to enter, the speed of the circulating flow will decrease (Polus and Shmueli, 1997).

2.1.4 Effects of Exiting Vehicles on Capacity

For the estimation of the critical gap, gaps are measured by taking the difference in times when two successive circulating vehicles arrive the conflict point with the entering vehicle. However, if the following circulating vehicle exits before the conflict point, the gap cannot be measured although the gap could have been perceived by the driver of the entering vehicle. Thus, there may be discrepancy between the measured gap and the perceived gap.

In this regard, Mereszczak et al. (2006) showed that the capacity at single-lane roundabouts was underestimated if the effect of exiting vehicles was not considered. Since an entering vehicle has no prior knowledge of the destinations of the circulating vehicle, the entering vehicle may yield to an exiting vehicle incorrectly assuming that they would have become in conflict. To capture the driver's perceived gap, the measured gap is adjusted using the "equivalent travel time" when the time gaps involve the exiting vehicles. The equivalent travel time is defined as the distance between the point of exit and the point of conflict, divided by the free-flow speed within the circulating roadway (Mereszczak et al., 2006).

To describe the method of considering the exiting vehicles, the following case is considered: Vehicle V is yielding to enter the roundabout, and Vehicles 1, 2 and 3 are the 1st, 2nd and 3rd vehicles, respectively, which travel along the circulatory roadway heading towards the leg where Vehicle V is yielding. Vehicles 1 and 3 cross the leg where Vehicle V is yielding, but Vehicle 2 exits. Vehicle 1 crosses in front of Vehicle V at t_1, Vehicle 2 exits at t_2, and Vehicle 3 crosses in front of Vehicle V at t_3. Figure 2-2 shows the sequential time instances of t_1, t_2 and t_3 from left to right:



Time instance t_1 Time instance t_2 Time instance t_3

Figure 2-2. Position of Circulating Vehicles at Various Time Instances.

When the exiting vehicles are not considered, the only time-gap in front of Vehicle V would be measured as t_3-t_1 since Vehicle 2 did not reach the point of conflict. When the exiting vehicles are considered, two gaps can be defined using the equivalent travel time (Δ_e) - the time it would have taken for Vehicle 2 to travel from the exiting leg to the point of conflict if it had not exit. Thus, the first gap is defined as $(t_2 - t_1) + \Delta_e$, and the second gap is defined as $t_3 - t_2$. Zheng et al. (2011) found that the critical headway and the follow-up time were reduced when the exiting vehicles were considered.

However, these studies assumed a single value of the equivalent travel time for all vehicle types. Since the term Δ_e is based on the free-flow speed of the circulating vehicles, it depends on whether the exiting vehicle is a car or a truck.

2.2 Empirical Capacity Models

Empirical capacity models are the models developed using the data collected from the existing roundabouts. These models do not require gap-acceptance behavior parameters. Instead, they directly describe the entry capacity as a function of the circulating flow. Some models include factors associated with the geometry of the roundabout.

Basic roundabout geometric features are shown in Figure 2-3. The main factors effecting capacity are the approach width, entry width and entry angle (Robinson et al., 2000). In general, wider entry width and approach width increase the entry capacity. The entry angle is related to the curvature of the approaching roadway, and a more direct path towards the circulating flow will increase the entry capacity. An inscribed circle diameter of 50m or less will have little effect on capacity (Robinson et al., 2000). Wider circulating road width will increase the capacity of the circulating flow.

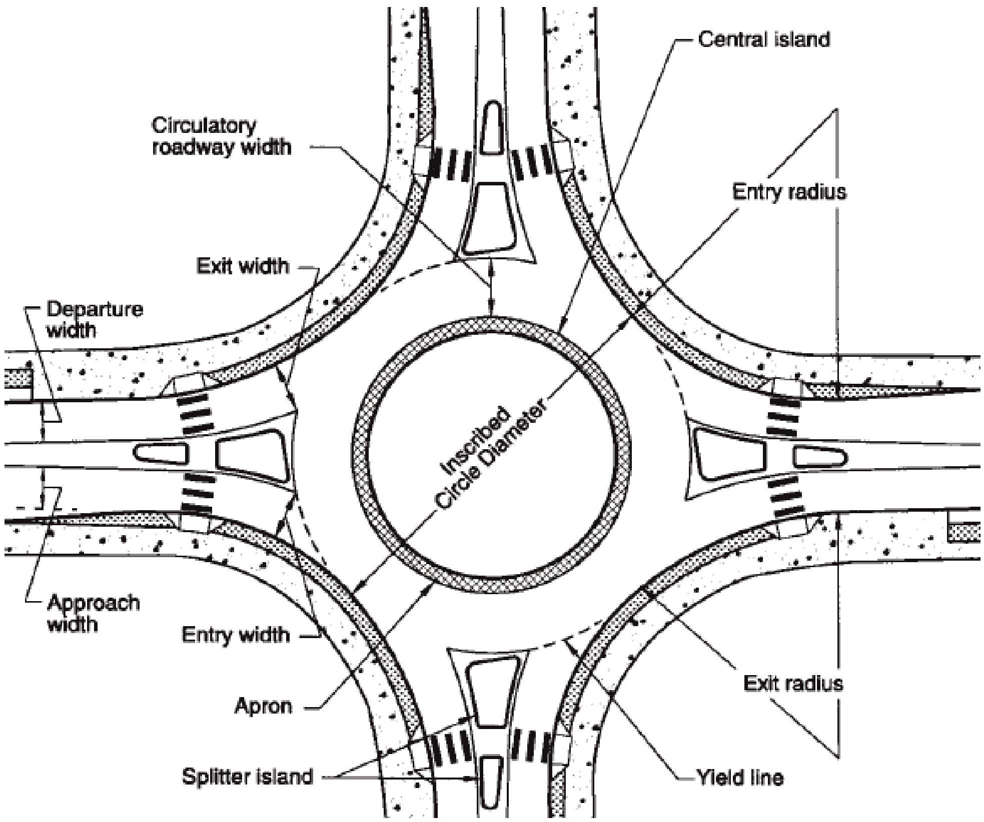


Figure 2-3. Basic Elements of Roundabout

(Source: Robinson et al., 2000)

For example, the empirical capacity model was developed in the U.K. (Kimber, 1980; Kimber, 1988) based on the data collected from 86 roundabouts. A linear relationship between the entry capacity and the circulating flow is described as follows:

$$C_e = F - f_c \cdot q_c \tag{2.15}$$

where F is a factor associated with the entry width, entry angle and width of the circulating flow, and f_c is a constant that depends on the geometry of the circle (in particular, inscribed circle diameter).

A capacity model was also developed in Switzerland using the data collected from seven roundabouts (Simon, 1991) as follows:

$$C_e = 1500 - 0.888 \cdot q_g \tag{2.16}$$

where q_g is a volume which depends on the circulating flow, the geometry of the circle and the geometry of the approaching legs.

In Germany, the relationship between the entry capacity and the circulating flow was described in an exponential function based on the data collected from 10 roundabouts (Stuwe, 1991).

$$C_e = Ae^{\left(\frac{-Bq_c}{10000}\right)} \tag{2.17}$$

where A and B are the parameters associated with geometric factors including the number of circulating lanes, and the number of entrance lanes. The model calibrated for single entry lane, single circulating lane roundabouts in the U.S. is as follows (NCHRP, 2007):

$$C_e = 1130 \cdot e^{(-0.0010 q_c)} \tag{2.18}$$

Figure 2-3 compares empirical capacity models among different countries.

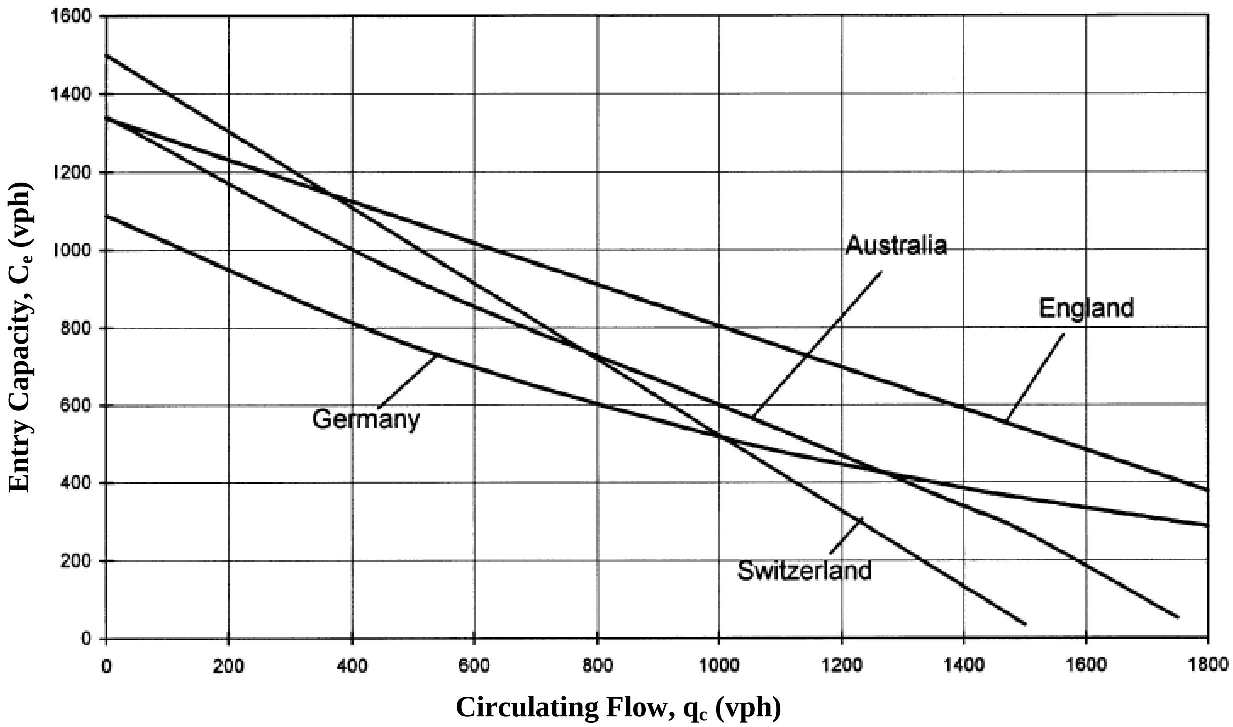


Figure 2-4. Comparison of Empirical Roundabout Capacity Models.
(Source: Polus and Shmueli, 1997)

However, since empirical models are calibrated for local traffic conditions, they cannot be generally applicable to the other areas. Thus, the gap acceptance model was preferred since it can better describe driver behaviour and more logically determine the capacity than the empirical models.

2.3 Microscopic Traffic Simulation Models

In addition to gap-acceptance and empirical models, roundabout capacity can also be estimated using microscopic traffic simulation models. One of the advantages with simulation models, as opposed to the macroscopic analytical models is that the capacity can be estimated for closely spaced roundabouts within road network (Qiu and Yin, 2011). In addition, the individual car and truck movements can be observed and how they come into conflict with other vehicles. The examples of microscopic traffic simulation models are VISSIM, PARAMICS and CORSIM. Of these, VISSIM (PTV AG, 2011) is the most commonly used for roundabout capacity analysis.

There are two ways to model yielding of the entering vehicles within VISSIM: priority rules (Isebrands et al., 2011) and conflict areas (Fellendorf and Vortisch, 2010). Priority rules can be used to define the critical headway for the yielding vehicles. The vehicles yield until an appropriately sized gap is available in the circulating flow and only enter the roundabout if the available gap is longer than the critical headway. These priority rules are set by users for each entry lane and circulating lane (Trueblood and Dale, 2003). Alternatively, conflict areas can be used to define the area where the circulating and entering vehicles are in conflict. Acceptable gaps are determined based on the entering vehicle's acceleration and the minimum headway between the entering vehicle and the circulating vehicles.

The simulation models need to be calibrated and validated to ensure that the simulation reflects actual traffic conditions (Isebrands et. al., 2011). Conflict areas are more advantageous than priority rules since they are less complex to reflect the difference in car and truck driving behaviour. Wei et al. (2011) observed that the simulation using conflict areas displayed more realistic driver behaviour than priority rules.

2.4 Effect of Trucks on Capacity

Some studies have considered the effects of trucks on roundabout capacity. The HCM 2000 (TRB, 2000) and HCM 2010 (TRB, 2010) methods convert the number of vehicles into passenger car unit (pcu) using the following heavy vehicle factor:

$$f_{HV} = \frac{1}{1+(e_{HV}-1)\,p_{HV}} \tag{2.19}$$

where e_{HV} is the passenger car equivalent of a heavy vehicle (pcu/veh) (default value is 2.0), and p_{HV} is the proportion of heavy vehicles in the traffic stream. The flow in veh/h is divided by f_{HV} to calculate the flow in pcu/h. Although this method is simple, there is a lack of consideration of difference in driver gap-acceptance behavior between cars and trucks.

In this regard, an Australian report (Troutbeck, 1993) suggested that the critical headway and the follow-up time are different for heavy vehicles and cars. It suggested that factors be included to take into account this difference as follows:

$$(t_c)_{HV} = f_{GA}(t_c)_C\,,\ (t_f)_{HV} = f_{GA}(t_f)_C \tag{2.20}$$

where $(t_c)_{HV}$ and $(t_c)_C$ are the critical headways for heavy vehicles and cars (sec), respectively, $(t_f)_{HV}$ and $(t_f)_C$ are the follow-up time for heavy vehicles and cars (sec), respectively, and f_{GA} is the gap-acceptance parameter factor. The factor f_{GA} is greater than or equal to 1 to reflect longer critical headway and follow-up time for heavy vehicles than cars. However, the study found that there was no need to adjust gap-acceptance parameters for heavy vehicle (i.e. f_{GA} = 1) based on the field data for one traffic circle. The study also suggested that the critical headway is longer when the driver enters in front of heavy vehicles than cars.

Zheng et al. (2011) empirically observed that the critical headway for trucks was longer than the critical headway for cars and motor cycles. Based on the data collected from one roundabout in Wisconsin, the critical headway for trucks and cars were 5.0 s and 4.1 s, respectively, in left lane and, they were 4.7 s and 3.3 s, respectively, in right lane.

Arçelik & Associates Pty Ltd (2011) suggested the adjustment of the critical headway and the follow-up time for entire entry flow using the heavy vehicle factor as follows:

$$t'_c = \frac{t_c}{f_{HV}}, \; t'_f = \frac{t_f}{f_{HV}} \tag{2.21}$$

where t'_c and t'_f are the critical headway and follow-up time adjusted for heavy vehicle effects in the entry flow. Similar to the method proposed by Troutbeck (1993), the critical headway and the follow-up time are equally adjusted by a single factor. Since the heavy vehicle factor decreases with higher truck percentage, Eq. 2.21 reflects that the critical headway and the follow-up time increase as truck percentage increase.

However, there is a need to investigate the validity of the same adjustment factor for both critical headway and follow-up time. Although some studies (e.g. Troutbeck, 1993) reported the effect of the gap-acceptance parameters adjusted for heavy vehicles on the reduced capacity, there have been a few empirical studies to investigate this effect using more extensive field data. Thus, further studies are needed to examine the effect of trucks on driver gap-acceptance behavior and incorporate such effect into the capacity estimation of roundabouts.

3 PROCEDURE

3.1 Capacity Model using Adjusted Gap-Acceptance Parameters

In order to reflect the effect of trucks on capacity, gap-acceptance parameters should be determined for cars and trucks separately. Then the representative gap-acceptance parameters for entire entry flow can be calculated as a volume-weighted average of the parameters for cars and trucks.

3.1.1 Adjusting Critical Headway

The critical headways of cars and trucks are weighed in proportion to the percentage of cars and trucks within the entry flow. If the entry flow consists of cars and trucks only, the critical headway is calculated as follows:

$$t'_c = t_{c,car} \cdot (1 - p_{truck}) + t_{c,truck} \cdot p_{truck} \tag{3.1}$$

where t'_c is the adjusted critical headway (sec), p_{truck} is the percentage of trucks within the entry flow, and $t_{c,car}$ and $t_{c,truck}$ are the critical headways for cars and trucks, respectively (sec). The term $(1 - p_{truck})$ represents the percentage of cars within the entry flow. As p_{truck} increases, t'_c is more influenced by $t_{c,truck}$, and thus is expected to increase since $t_{c,truck}$ is generally longer than $t_{c,car}$.

Additionally, it is expected that trucks and cars may travel the circulatory roadway at different speed, the effects of the exiting vehicles by vehicle type will be taken into account when calculating the critical headway as described in Section 2.1.4. More specifically, the minimum headway (Δ_e) will be separately estimated for the exiting cars and trucks - $\Delta_{e,car}$ and $\Delta_{e,truck}$, respectively.

3.1.2 Adjusting Follow-up Time

Similar to the critical headway, the follow-up times of cars and trucks are weighed in proportion to the percentage of cars and trucks within the entry flow. However, since cars and trucks have different operational characteristics (e.g. acceleration, headway), the follow-up time varies by the type of two entering vehicles in a queue - the lead vehicle, and the following vehicle which enters the circulatory roadway using the same gap as the lead vehicle. Assuming that there are only cars and trucks, four cases of vehicle-following conditions are defined as follows:

1) car followed by car (car/car)
2) car followed by truck (car/truck)
3) truck followed by car (truck/car), and
4) truck followed by truck (truck/truck)

Assuming that each vehicle type has equal chance of being the lead or following vehicle, the follow-up time can be calculated as follows:

$$t'_f = t_{f,cc} \cdot (1 - p_{truck})(1 - p_{truck}) + t_{f,ct} \cdot (1 - p_{truck}) \cdot p_{truck} + t_{f,tc} \cdot p_{truck} \cdot (1 - p_{truck}) + t_{f,tt} \cdot p_{truck} \cdot p_{truck}$$

This equation can be re-written as follows:

$$t'_f = t_{f,cc} \cdot (1 - p_{truck})^2 + (t_{f,ct} + t_{f,tc}) \cdot (1 - p_{truck}) \cdot p_{truck} + t_{f,tt} \cdot p_{truck}^2 \tag{3.2}$$

where t'_f is the adjusted follow-up time (sec), and $t_{f,cc}$, $t_{f,ct}$, $t_{f,tc}$, and $t_{f,tt}$ are follow-up times for a car following a car (car/car), a truck following a car (car/truck), a car following a truck (truck/car), and a truck following a truck (truck/truck), respectively (sec). The follow-up times for each vehicle-following case were weighted based on the probability of lead-vehicle and following-vehicle combination. As p_{truck} increases, weights of the follow-up times associated with trucks ($t_{f,ct}$, $t_{f,tc}$, and $t_{f,tt}$) increase. Since $t_{f,ct}$, $t_{f,tc}$, and $t_{f,tt}$ are generally longer than $t_{f,cc}$ due to truck's lower acceleration, t'_f is expected to increase as p_{truck} increases.

3.1.3 Adjusting Capacity

These adjusted gap-acceptance parameters (t'_c, t'_f) can then be used to estimate the capacity using the aforementioned macroscopic analytical capacity models by replacing the existing gap-acceptance parameters (t_c, t_f) (Eq. 2.7-2.10). Since these gap-acceptance parameters are sensitive to the percentage of trucks within the entry flow, the capacity will vary as the truck percentage changes.

3.2 Capacity Estimation using Computerized Models

In addition to the above analytical models, the roundabout capacity can also be estimated using two computerized models: SIDRA (Akçelik & Associates Pty Ltd., 2011) and VISSIM (PTV AG, 2011). These are commercial software that has been widely used for the roundabout traffic analysis. SIDRA is a macroscopic analytical model which imports demand entry flows, turning movements and geometry, and estimates the capacity and delay. The model was developed based on the gap acceptance theory. Headways were assumed to follow the M3 distribution. The model also considers the effects of geometry on the gap acceptance parameters and the capacity.

On the other hand, VISSIM is a microscopic simulation model which mimics individual vehicle movements considering various driving and vehicle performance conditions (such as vehicle speeds, acceleration/deceleration, lane change restrictions and right-of-way allocation). The model does not require the assumed distribution of headways unlike the macroscopic analytical model. The capacity estimated using SIDRA and VISSIM will be compared to the capacity estimated using the adjusted gap-acceptance parameters.

4 DATA

4.1 Studied Roundabouts

To observe car and truck movements at roundabouts, video footage for 11 roundabouts in Vermont, Ontario and Wisconsin was obtained. The locations and dates of video footage are shown in Table 4-1. Some roundabouts were chosen since truck volumes were high. Dimensions of road geometry for each roundabout were manually measured from the geometric drawings. Table 4-2 shows a summary of the measured geometric features.

TABLE 4-1. Location of Studied Roundabouts and Dates of Video Footage

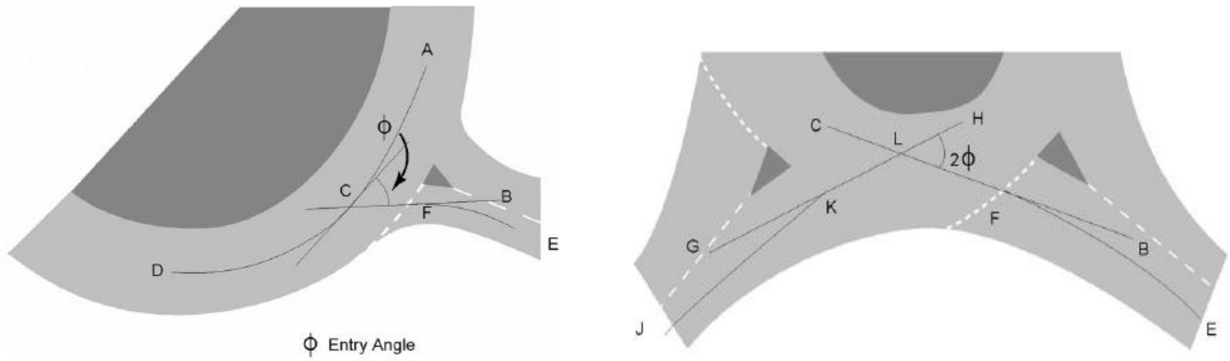
Roundabout	Intersecting roads	City, State or Province	Date of video footage	Time of Day
Brattleboro	Vermont Route 9 & US Route 5	Brattleboro, VT	Jul. 16th, 2003	Unknown
Waterloo	Arthur Street & Sawmill Road	Waterloo, ON	Jan. 13th, 2011	1:00PM – 3:00PM
32&57	STH 57 & STH 32 (Broadway Street)	De Pere, WI	May 19th, 2010	11:17 AM – 6:38 PM
78&92	78/92/8th Street & CTH ID	Madison, WI	Apr. 8th, 2010	12:22 PM – 6:22 PM
42&43	STH 42 & IH 43 Northbound off ramp (east)	Sheboygan, WI	Apr. 22nd, 2010	12:59 PM – 5:59 PM
Vanguard	STH 42 & Vanguard Avenue	Sheboygan, WI	Apr. 23rd, 2010	11:37 PM – 6:00 PM
Bennett	STH 18 & Bennett Road	Dodgeville, WI	Mar. 30th, 2010	1:00 PM – 6:00 PM
Moorland North	Moorland Road & IH 43 (north)	New Berlin, WI	May 5th, 2010	1:40 PM – 6:04 PM
Moorland South	Moorland Road & IH 43 (south)	New Berlin, WI	May 12th, 2010	11:45 PM – 5:59 PM
Thompson North	Thompson Dr & STH 30 Eastbound off-ramp	Madison, WI	Apr. 29th, 2010	1:06 PM – 2:15 PM
Thompson South	Thompson Dr & Commercial Avenue	Madison, WI	Apr. 13th, 2010	12:02 PM – 1:35 PM

Table 4-2. Geometric Factors of Roundabouts

Roundabout	No. of legs	inscribed circle diameter (m)	central island diameter (m)	truck apron (m)	entry width (m)	exit width (m)	circulatory roadway width (m)	splitter island width (m)	entry angle (deg)
Brattleboro	4	56.0	32.4	2.4	9.7	9.7	12.2	5.0	30.0
Waterloo	4	60.0	40.0	3.3	8.3	8.3	10.0	10.8	17.8
32&57	4	53.3	22.9	3.8	9.1	9.1	11.4	9.0	23.8
78&92	4	38.6	13.7	4.3	6.9	7.7	9.4	4.9	27.0
42&43	4[a]	47.6	22.9	3.8	8.4	8.4	9.9	8.4	27.5
Vanguard	4	61.0	25.9	4.6	7.6	9.1	9.1	12.4	20.6
Bennett	4	57.0	29.0	3.8	9.9	8.4	10.7	13.9	24.4
Moorland North	4[b]	50.0	31.2	1.9	6.7	6.7	7.2	10.3	27.5
Moorland South	4[c]	37.0	19.2	1.9	5.8	5.3	6.3	8.8	21.9
Thompson North	4	50.7	29.0	0.8	7.6	9.1	10.7	8.4	23.8
Thompson South	3[c]	42.0	22.9	0.8	7.6	9.1	9.1	6.9	25.0

[a] There is no exit at one leg and no entrance at another leg.
[b] There is no exit at one leg and no entrance at another leg. There are also multiple bypass lanes.
[c] There is no exit at one leg.

All the geometric features except entry angle could be measured by scaling distances from the drawing. Entry angle is the angle between the entering roadway and the circulating roadway. The method of measuring this angle depends on the spacing between the adjacent entry legs as shown in Figure 4-1. Figure 4-1 (a) shows that for a roundabout with larger spacing between legs, the entry angle is the angle between the line BC tangent to the entry path (EF) at the point of entry (F), and the line tangent to the circulating path (AD) at the point which BC intersects (C). Figure 4-1 (b) shows that for a roundabout with shorter spacing between legs, the entry angle is half of the angle between the line BC tangent to the entry path (EF) at the point of entry (F) and the line GH tangent to the exit path (JK) at the point of exit (K).



(a) Long spaced entry (b) Short spaced entry

Figure 4-1. Measurement of Entry Angle.
(Source: The Highways Agency, 2007)

Note: Since the figure is from a U.K. design guide, the direction of travel is clockwise and to the left.

Sample screenshots of video footage and geometric drawings of the Brattleboro, Waterloo and 32&57 roundabouts are shown in Figure 4-2. The geometric drawings and video footages for all roundabouts in larger scale are shown in Appendix A and Appendix B, respectively. In particular, the Brattleboro, Waterloo and 32&57 roundabouts are the busiest among the studied roundabouts due to high travel demand indicated by queued entering vehicles, with the observed truck percentage of 11%, 5% and 19% respectively. Thus the entry capacity can be observed from these roundabouts. Figure 4-3 shows the location of these roundabouts (marked in blue). These roundabouts are all located near major highways, where truck volumes are typically higher.

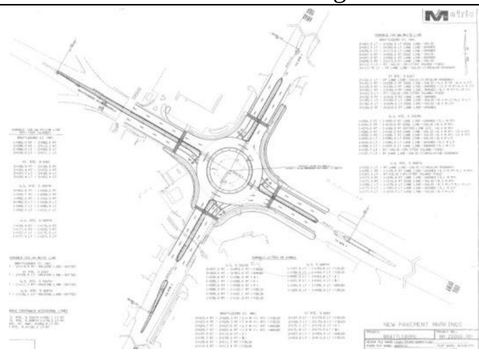
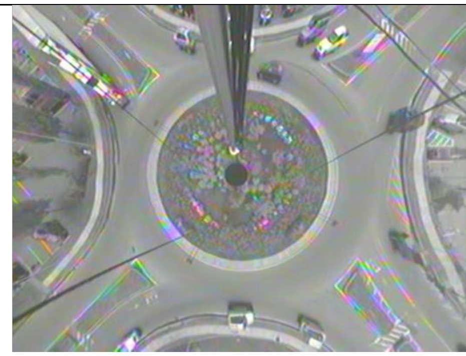
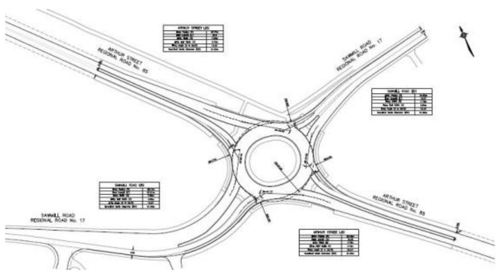
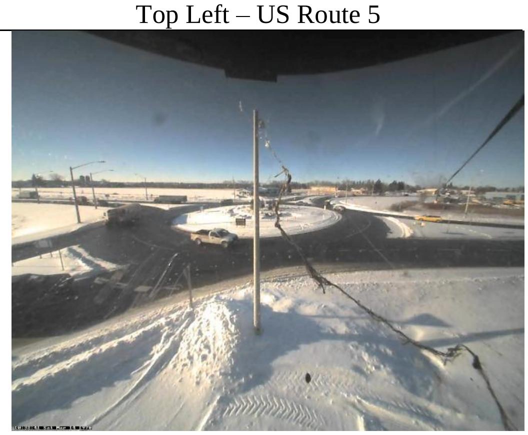
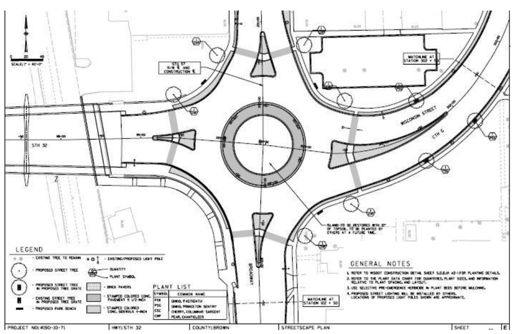
Roundabout	Geometric drawing	Video screenshot
Brattleboro See notes below images for road names	 Top Left – Brattleboro State Highway (to I-91) Bottom Left – US Route 5 Bottom Right – Vermont Route 9 Top Right – US Route 5	 Bottom Left – Brattleboro State Highway Bottom Right – US Route 5 Top Right – Vermont Route 9 Top Left – US Route 5
Waterloo	 Top Left & Bottom Right – Arthur Street Bottom Left & Top Right – Sawmill Road	 Top Left & Bottom Right – Arthur Street Bottom Left & Top Right – Sawmill Road
32&57	 Top – Broadway/State Highway 57 Left – State Highway 32 Bottom – Broadway Avenue Right – Wisconsin Street	 Top Right – Broadway/State Highway 57 Top Left – State Highway 32 Bottom Left – Broadway Avenue Bottom Right – Wisconsin Street

Figure 4-2. Geometric Drawings and Screenshots of Video Footage for the Brattleboro, Waterloo and 32&57 Roundabouts.

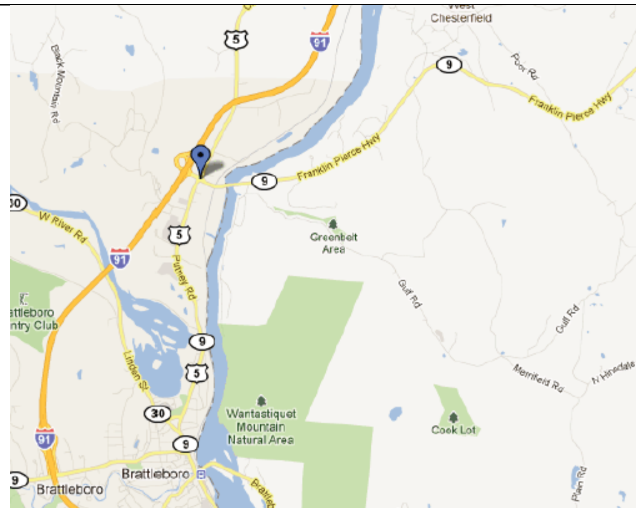
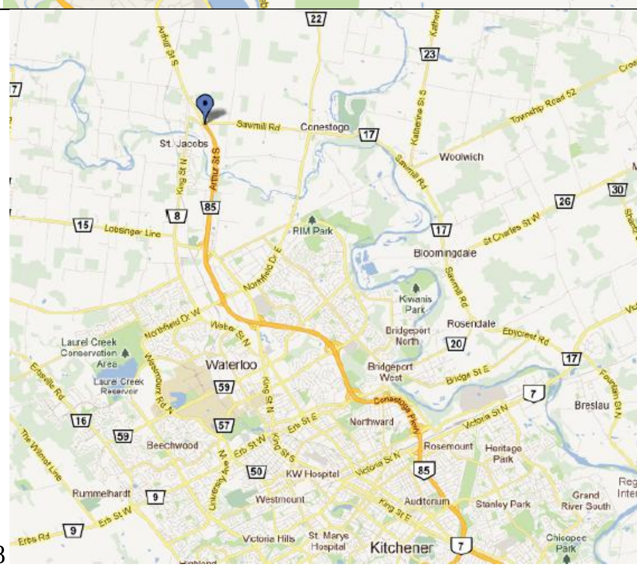
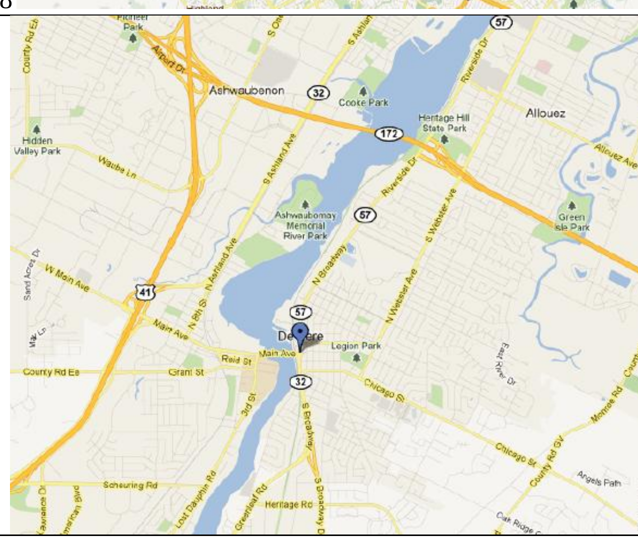
Roundabout	Roundabout Location
Brattleboro Intersection of US Route 5 and VT Route 9. Interstate highway 91 to the West of roundabout. The city of Brattleboro to the south. The city of Keene to the east.	
Waterloo Intersection of Arthur (17) and Sawmill (85). To the south, Highway 85 turns into Conestoga Parkway which feeds into the Region of Waterloo and the City of Kitchener. Further south east, Highway 85 turns into Highway 7 and Highway 8 which leads to Highway 401.	 8
32&57 Intersection of Highway 57 (Broadway) and 32 (Wisconsin/Main). Located in a downtown core between highway 172 and US Route 41. Highway 57 and 32 both head north past Highway 172, and into the city of Green Bay.	

Figure 4-3. Locations of the Brattleboro, Waterloo and 32&57 Roundabouts.
(Source: Google Map, 2011)

All of the roundabouts have full two circulatory lanes or partially one circulatory lane except for the Brattleboro and Thompson South roundabouts which have one circulatory lane only. Although the width of the circulatory lane at the Brattleboro and Thompson South roundabouts is wide enough for two lanes, there are no lane markings.

4.2 Data Collection

Gap acceptance/rejection, follow-up time and free-flow speed were collected from the video for the eleven roundabouts. Any unusual driver behaviour such as gap-forcing behavior, violation of the right-of-way, and unnecessarily tentative drivers was noted. All the data were collected manually, and they were kept for cars and trucks separately.

A total of 2,790 gap acceptance/rejection data points, 275 follow-up time data points, and 482 free-flow speed data points were recorded over 70 hours from video footage. Combined with the other data points collected for different analysis, 11,720 data points were collected over 200 hours from video footage.

4.2.1 Gap Acceptance/Rejection Data

Gap data includes the time of entry, time gap (sec), vehicle type (car or truck), and gap condition (accepted or rejected) at all entry legs which were visible from the video. Gaps were measured by taking the difference in times when two consecutive circulating vehicles passed the point of conflict for a given entry leg. A sample sheet of the gap acceptance/rejection data collection is shown in Table 4-3, and a complete sample for the 32&57 roundabout is shown in Appendix C.

Table 4-3. Sample Data Sheet for Gap Acceptance/Rejection

Time	Entry leg	Gap length (sec)		Rejected/ Accepted	Obstruction of circulating flow	Additional notes
	0-TR 1-TL 2-BL 3-BR	Car	Truck	0-reject 1-accept	0-no 1-yes	Queue/Flow/Driver Characteristics
0m19s	0	3.5		0	0	
	0	3		0	0	
	0	4.2		0	0	
	0	2.5		0	0	
	0	8		1	1	
	0	8		1	1	multiple cars entering; both lanes
0m38s	0		2.5	0	0	
	0		4.8	0	0	
	0		6.5	1	1	circulating flow slowed down for truck
0m50s	0	4.7		0	0	entering truck on TL ramp also backed up circulating flow
	0	9.5		1	0	

A total of 35 hours of video footage was viewed and 2,790 gap data points were collected from the eleven roundabouts. Approximately 5-10% of the gap data were influenced by the exiting vehicles. A minimum value of all of the time-gap data for each roundabout was taken as the minimum headway.

The headways of the circulating flow were also collected in each lane of the circulatory roadway. These data were collected concurrently with the gap acceptance/rejection data because those gaps constitute the headway distribution of the circulating flow. In case of two-lane roundabouts, the distributions of headways in both lanes are assumed to be the same and the sum of flows in two lanes was used as one circulating flow (Akçelik et al., 2003; Troutbeck et al., 1999).

4.2.2 Follow-up Time Data

The follow-up time data include the time of entry, follow-up times (sec), and the types of lead and following vehicles (car/car, car/truck, truck/car or truck/truck). Follow-up times were measured by taking the difference in times when two consecutive queued entering vehicles passed the entry point using the same gap between circulating vehicles for a given entry leg. If there are multiple entry lanes, follow-up times were measured in the lane(s) where the entering vehicles have conflict with the circulating vehicles. A sample sheet of the data collection is shown in Table 4-4.

Table 4-4 Sample Follow-up Time Information Collection Spreadsheet

Time	Follow-up Time (sec)			
	Car/Car	Car/Truck	Truck/Car	Truck/Truck
4m50s			5.4	
14m23s	2.3			
16m4s				9.5
17m56s			5.7	
19m35s	2.3			

The size of sample follow-up times was insufficient for the Thompson North and Thompson South roundabouts due to a lack of queued vehicles at the entry legs. A total of 23 hours of video footage was viewed and 275 follow-up time data points were collected from 9 roundabouts.

4.2.3 Free-flow Speed Data

Free-flow speeds for all major movements of cars and trucks within a circulatory roadway were also collected. Distances of the movement paths were measured using the geometric drawings, and free-flow travel times to traverse these paths were recorded by timing free-flow vehicles in the video; a vehicle was considered to be free-flowing when it could enter the roundabout without having to yield or slow down at entry. Free-flow speed was calculated as the distance of the path divided by the free-flow travel time. Free-flow speeds of cars and trucks were used to evaluate whether trucks generally obstructed the circulating flow due to their lower speed. Free-flow speeds were also used to consider the effect of the exiting vehicles on gaps, as described in Sections 2.1.4 and 3.1.

A sample sheet of the data collection is shown in Table 4-5. The two example paths are shown on a video screenshot in Figure 4-4. Eight hours of video footage was viewed and 482 data points were collected for free-flow speed from the 11 roundabouts.

Table 4-5. Sample Data Sheet for Free-flow Speed

Time	**Travel Time (s)**				**Speed (km/hr)**			
	Path1 W to S		Path2 S to N		Length of path1 = **27.4 m**		Length of path2 = **45.7 m**	
	Cars	Trucks	Cars	Trucks	Cars	Trucks	Cars	Trucks
0m20s	2.7				36.5			
0m30s	2.8				35.2			
1m25s			5.8				28.4	
1m50s			6.4				25.7	
3m55s		3.6				27.4		
4m15s		3.4				29.0		
5m00s				8				20.6

Figure 4-4. Example of Path for Estimation of Free-flow Speed.

4.2.4 Entry Capacity and Turning Movement Data

Finally, the entry capacity was observed at the Brattleboro, Waterloo and 32&57 roundabouts because regularly queued entering vehicles and saturated entry flows only occurred at these sites. The number of the entering vehicles at a given entry leg was recorded from the time when the first vehicle in a queue entered the roundabout to the time when the queue was cleared. The data were collected in one-minute intervals. During the same time period, the number of circulating vehicles that had conflicts with the entering vehicles from the given leg was also recorded. A sample sheet of the data collection is shown in Table 4-6. Seventy eight pairs of entering and circulating flows were taken. Total number of cars and trucks in each one minute interval was converted to total pcu. The passenger car equivalent (pce) for trucks was assumed to be 2.0, which is the commonly used value for trucks in roundabouts (Robinson at al., 2000). Although different pce values can also be assumed, this will only alter the total volume of vehicles, but not the gap-acceptance parameters. The one-minute entering and circulating flows were converted to hourly flows.

Table 4-6. Sample Data Sheet for Entry Capacity

Time interval	Entry leg	Entering vehicle	Circulating vehicle
	0-TR 1-TL 2-BL 3-BR	1-car 2-truck 3-other	
0:00-1:00	1	2	
			1
			1
			1
			1
			1
			1
			1
			1
			1
			1
			2
		1	
			1
			1
		1	
		1	
		1	
		1	
Total number of vehicles		6	13
Total pcu		7	14
Total flow (pcu/h)		420	840

The two computerized models (SIDRA and VISSIM) require the demand entry flow data in each approach (turning movement) rather than the data in each lane. To use these models, the turning movements for all vehicles were also collected from each leg in 5 minute intervals. Since it took a significant amount of time for tracing each individual vehicle’s turning movement, the data were only collected from the Brattleboro Roundabout for demonstration purpose. The data include the vehicle type, entry leg, and turning movement. A sample sheet of the data collection for 1 minute at one entry leg is shown in Table 4-7, and a summary of the demand flow for each approach is shown in Table 4-8. A total of 606 data points were collected.

Table 4-7. Sample Data Sheet for Turning Movements

Time	Entry leg	Vehicle Type	Turning movement
	0-TR 1-TL 2-BL 3-BR	1-car 2-truck	1 - Right turn 2 - Straight 3 - Left turn
2m3s	1	1	2
	1	1	2
	1	1	1
	1	1	3
2m13s	1	1	3
2m18s	1	1	2
	1	1	2
	1	1	2
	1	1	2
2m40s	1	1	1
2m50s	1	2	1
	1	1	2
2m58s	1	2	1

Table 4-8. Fifteen Minute Demand Entry Flow for Brattleboro Roundabout

Entry leg	Number of Cars				Number of Trucks			
	Right Turn	Through	Left Turn	U-Turn	Right Turn	Through	Left Turn	U-Turn
US Route 5 (North)	24	81	21	0	7	1	1	0
Vermont Route 9	27	45	39	0	0	4	1	0
US Route 5 (South)	50	66	56	6	1	0	0	0
Brattleboro State Highway	72	52	23	3	1	3	1	0

4.2.5 Calibration of Computerized Models

To collect the capacity and circulating flow data from SIDRA and VISSIM, the model parameters were selected such that the results reflect the actual geometry, traffic condition and driver behaviour at the Brattleboro roundabout. For SIDRA, the geometry of the roundabout was coded as shown in Figure 4-5 based on the values found in Table 4-2. The default value of the heavy vehicle factor (= 2.0) was used to consider the effect of trucks, and the default for including the effect of trucks only if truck volume percentage is over 5% was changed so that the effect of trucks can be considered for all percentages of trucks. Approach and exit speeds were assumed to be 60 km/hr which is the speed limit of the approach roadways, and no pedestrian traffic was assumed to reflect the actual conditions.

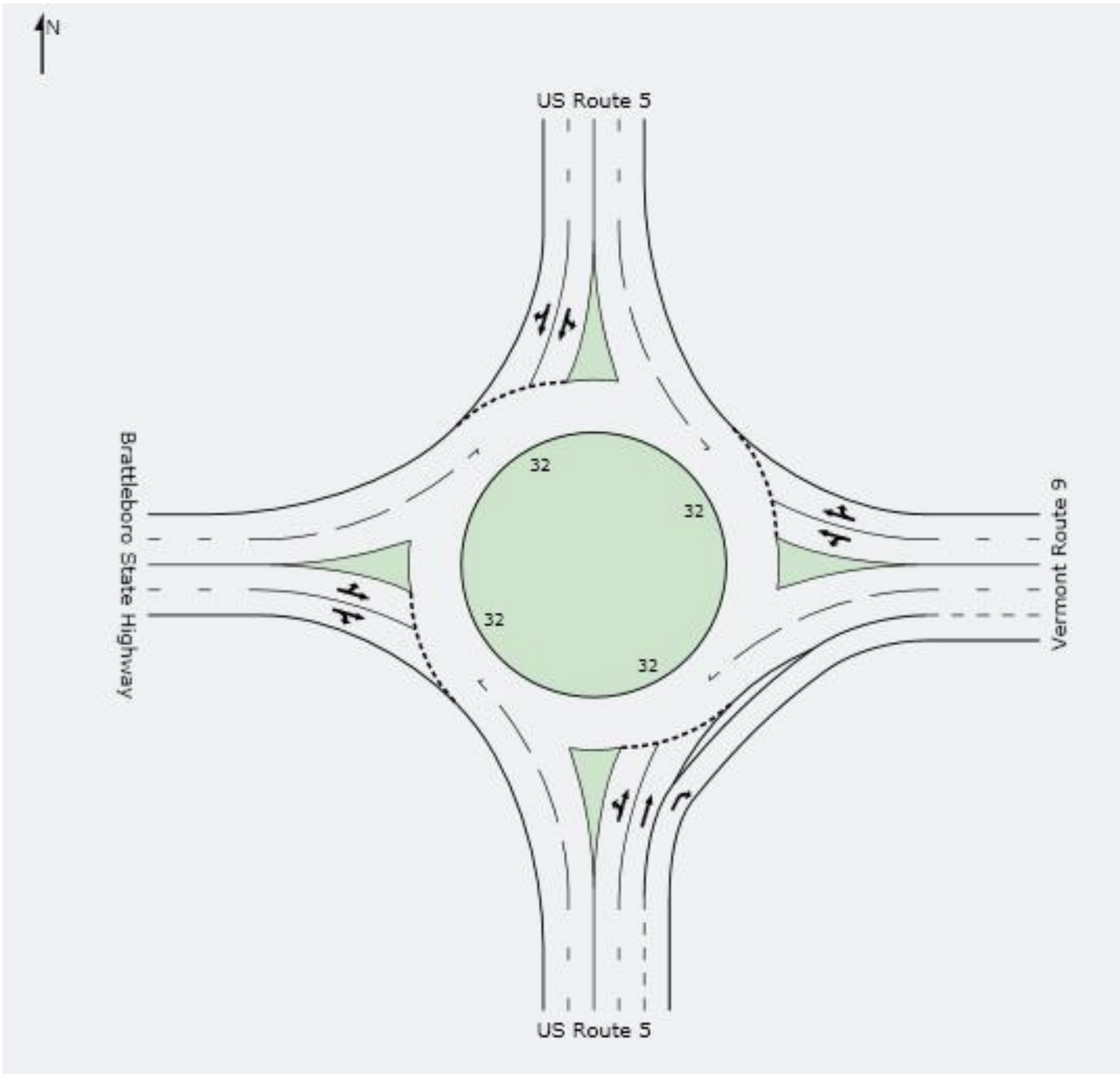


Figure 4-5. Geometric layout of Brattleboro Roundabout in SIDRA.

The Brattleboro roundabout was also coded in VISSIM using conflict areas. The right of way was designated as shown in Figure 4-6. In the figure, green links denote the path of the vehicles with right-of-way and red links denote the path of yielding vehicles. The default values of three conflict area parameters - front gap, rear gap and safety distance factor - were used (0.5 s, 0.5 s and 1.5, respectively). Front gap is the minimum time headway between the rear end of the circulating vehicle and the front end of the entering vehicle. Rear gap is the minimum time headway between the rear end of the entering vehicle (after it entered) and the front end of the following circulating vehicle. Safety distance factor defines the minimum distance headway between the circulating vehicle and the point of merge for the entering vehicles (PTV AG, 2011). Conflict areas will allow any vehicle within the conflict area to recognize any potential obstructions and adjust their speeds accordingly, even if they have priority on the circulatory roadway. This can reflect the obstruction of the circulating flow caused by the entering trucks within the roundabout.

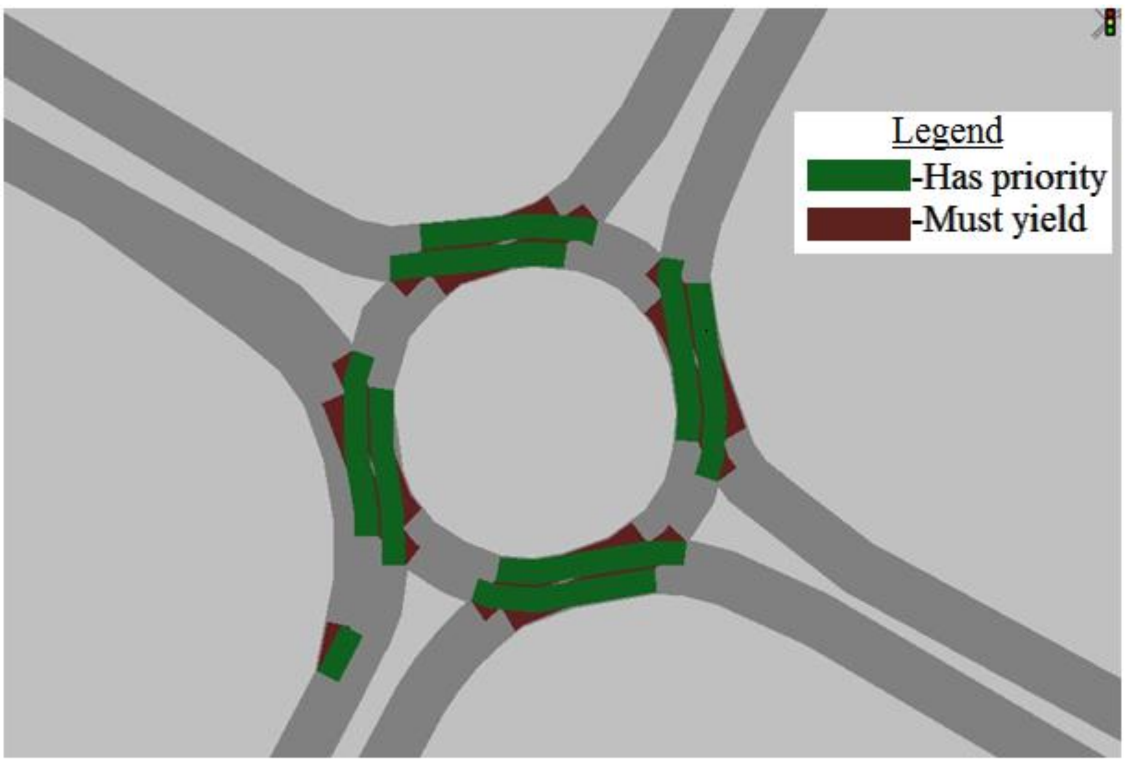


Figure 4-6. Designation of Right-of-way at Conflict Area in VISSIM.

Vehicles were classified into two vehicle types: cars and trucks. Large heavy duty trucks (AASHTO WB67, length of 22.42 m) were used rather than the default single unit trucks because they have a long pivoting trailer. This reflects that trucks require wider turns than cars. Figure 4-7 shows that a circulating truck occupies more space than cars as it negotiates the curve. In the figure, the shorter lines indicate passenger cars whereas the longer lines with deflection indicate trucks. Different colours represent the types of vehicles classified by their routes. The desired speeds for cars and trucks were set to the observed free-flow speeds, which will be discussed in Section 5.2.

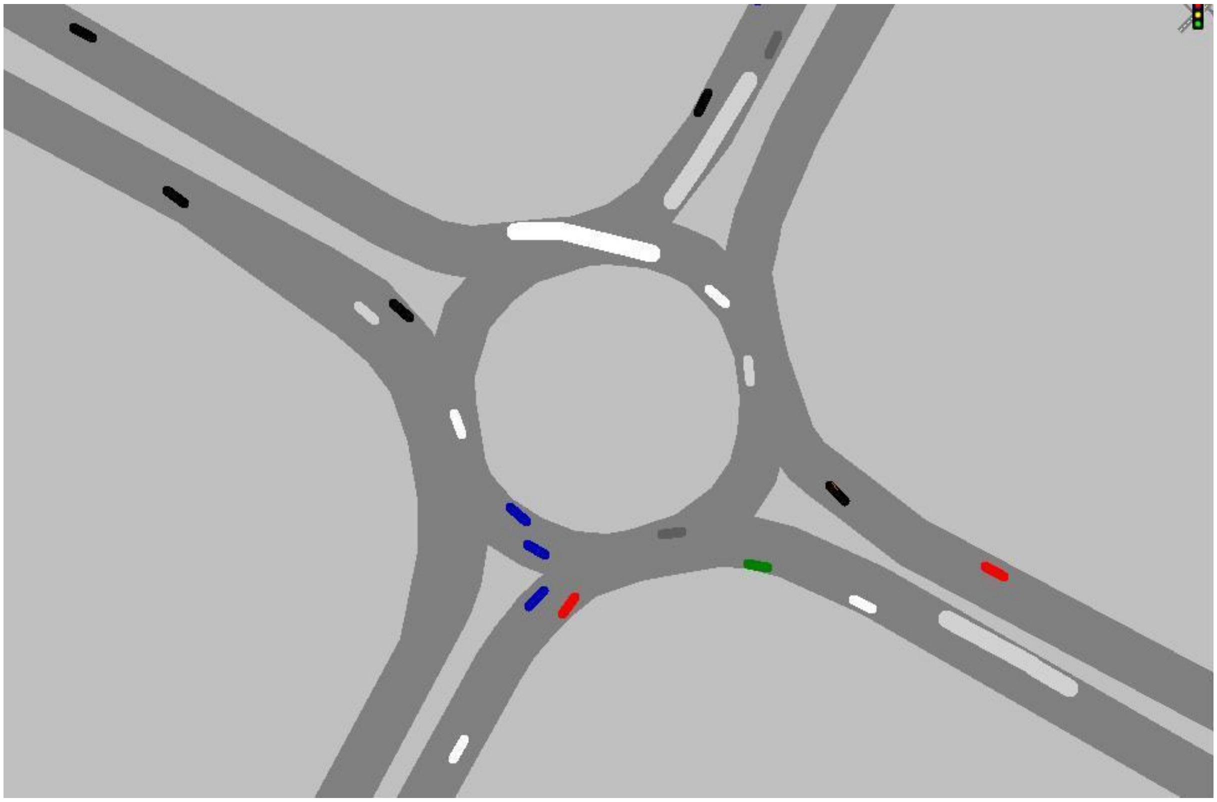


Figure 4-7. Simulation Screenshot of Brattleboro Roundabout in VISSIM.

Actual driving characteristics show that the circulating vehicles usually occupied one wide lane and did not travel in parallel with the other vehicles, particularly trucks. However, since connecting a two-lane entry leg to a single-lane circulatory roadway in VISSIM creates errors and merging problems, the circulatory roadway was assumed to be two lanes. Instead, minimum lateral distance to the vehicles on adjacent lanes was adjusted such that vehicles do not follow too close or travel in parallel with other vehicles on adjacent lanes. As the minimum lateral distance increases, vehicles are more likely to maintain longer distance with the vehicles on adjacent lanes. After the distance was adjusted to 15 m, the simulated circulating flow became similar to the observed circulating flow.

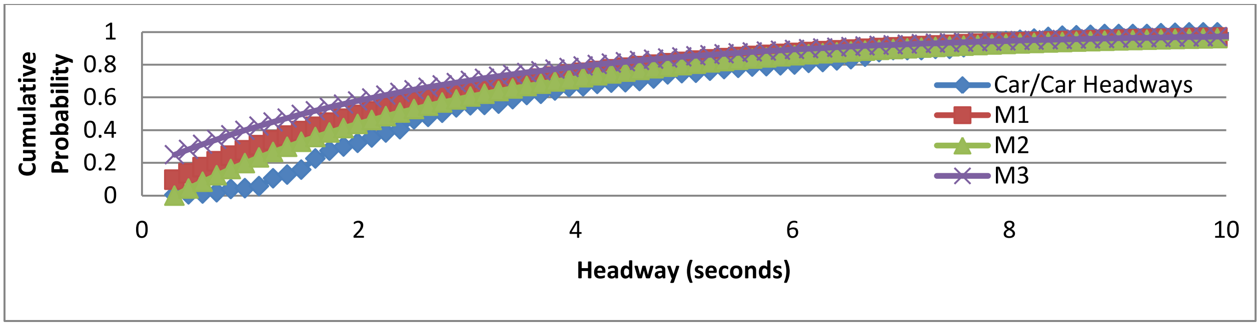
Due to the restricted lane changes within the roundabout, the length of approaching roadways and the default value for lane change movements were both increased to 600 m and 800 m, respectively. This provided sufficient time for cars and trucks to choose the proper lane for their turning movements before entering the roundabout.

5 RESULTS AND DISCUSSION

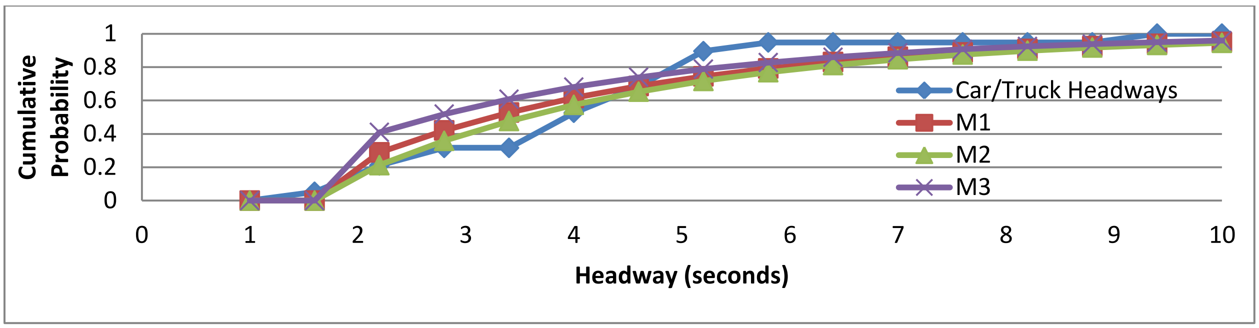
5.1 Headway Distribution

Headway data for the Brattleboro roundabout were collected for 15 minutes at all entry legs, and separated into the four vehicle-following cases, as was described for the follow-up time in Section 3.1.2. It was assumed that the circulating traffic flow was a single flow, as described in Section 4.2.1. The cumulative probability of headways was then plotted and compared with the M1, M2 and M3 distributions. The purpose of comparison was to determine whether the headway distributions for different vehicle-following cases are similar or not. The headway distributions for the cases of a) car/car, b) car/truck, c) truck/car and d) combined (all data points) were plotted in Figure 5-1. There was an insufficient amount of data points for the truck/truck case. The minimum headway (Δ) was assumed to be 0.3 s since this was the minimum headway observed from the video. The proportion of free vehicles (α) was assumed to be 0.75; and λ was calculated by using Equation 2.4, with q_c assumed to be equal to 1440 pcu/hr.

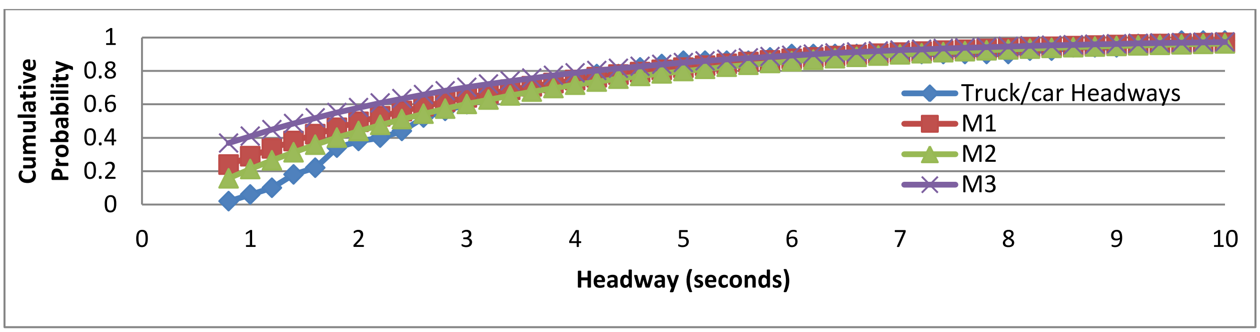
In general, all the headway distributions followed a similar trend. It should be noted that there was a higher proportion of longer headway (4-6 sec) for the car/truck case than the other cases. This suggests that trucks generally follow cars with longer time headway on the circulatory roadway due to their lower speed. On the other hand, the distribution for the car/car case (Figure 5-1 (a)) was very similar to the distribution for the combined case (Figure 5-1 (d)). This is likely due to the fact that a majority (86%) of the observed headways was for the car/car case (417 points compared to 17 for car/truck and 50 for truck/car).



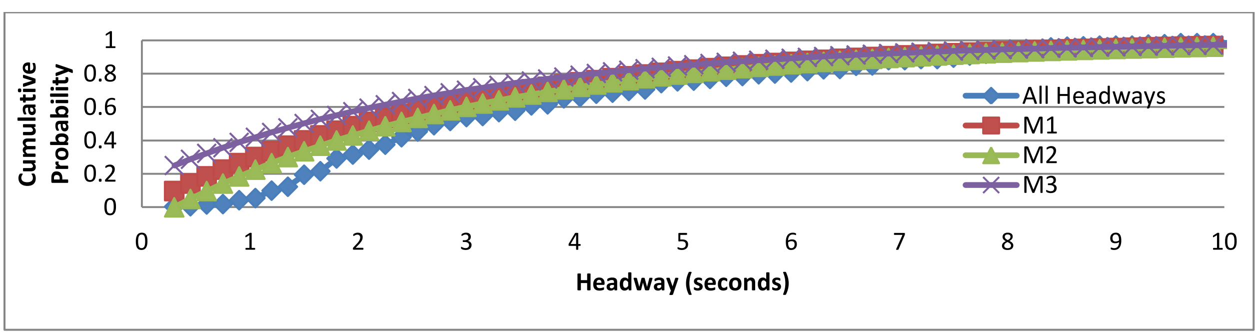
(a) Car/car headways



(b) Car/truck headways



(c) Truck/car headways



(d) Combined headways

Figure 5-1. Headway Distributions at the Brattleboro Roundabout.

Although the headway distributions for the car/truck and truck/car cases were slightly different from the car/car case, they had a minimal effect on the combined headway distribution. Thus, the combined headway distributions were obtained (without considering vehicle types) for all other roundabouts where the car-car case was dominant. Headway distributions for all roundabouts are shown in Appendix D.

It was found that the M2 distribution had the lowest root-mean-square error (RMSE) for the car/car, car/truck and combined cases, and the M1 distribution had the lowest RMSE for the truck/car case. However, the distributions of the observed headways were generally similar to the M1, M2 and M3 distributions. This indicates that the assumptions of headway distribution in the existing capacity models (Equations 2.7 – 2.10) are valid.

5.2 Free-flow Speed

The average free-flow speeds for cars and trucks at each roundabout are shown in Table 5-1. For all the roundabouts, cars travelled at a higher free-flow speed than trucks. This is because trucks require a larger turning radius and they tend to travel slower along the curved path of a circulatory roadway. The truck's slower free-flow speed than the car's free-flow speed indicates that trucks are more likely to obstruct the circulating flow. This indicates that trucks tend to decrease the circulating flow and increases the likelihood of available gaps for the entering vehicles. In Table 5-1, the *percentage of speed difference* was calculated as follows:

$$\%\text{speed difference} = \frac{(\text{car speed} - \text{truck speed})}{\text{car speed}} \cdot 100 \tag{5.1}$$

Truck's free-flow speed was lower than car's free-flow speed by 14-31% within roundabouts.

Table 5-1. Observed Average Free-flow Speed

Roundabout	Free-flow speed		
	Car speed (km/hr)	Truck speed (km/hr)	Average % speed difference
Brattleboro	29	20	30.1%
Waterloo	39	30	22.8%
32&57	31	24	21.9%
78&92	33	23	30.8%
42&43	33	25	24.3%
Vanguard	33	25	24.4%
Bennett	37	29	22.5%
Moorland North	22	17	19.1%
Moorland South	22	19	14.3%
Thompson North	39	29	25.1%
Thompson South	37	29	19.4%

5.3 Critical Headway

The gap acceptance/rejection data were collected for each entry leg separately first. However, it was found that the distributions of the accepted and rejected gaps were not significantly different among different entry legs. Thus, the gap data for each leg were combined for each roundabout.

It was also observed that some vehicles, particularly trucks, aggressively entered the roundabout even when a sufficient gap was not available and forced the circulating vehicles to yield to the entering vehicle. This type of gap-forcing behavior obstructed the circulating flow. For the Brattleboro roundabout, it was found that during one 5-minute period, 5 out of 57 cars (9%) which entered the roundabout obstructed the circulating flow. During one 15-minute period, 26 out of 52 trucks (50%) which entered the roundabout obstructed the circulating flow. This shows that trucks are more likely to obstruct the circulating flow than cars at this roundabout. This is because trucks need longer time gaps to enter a roundabout than cars, but longer time gaps are less likely to be available in the circulating flow. Thus, truck drivers are more likely to be impatient as they wait for available gaps for longer period of time. This circumstance may have forced trucks to enter the roundabout even when sufficient gaps are not available. Similar truck gap-forcing behaviour was observed at all other roundabouts.

The critical headway was estimated using the gap acceptance/rejection data and the methods discussed in Section 2.1.3. The results of the graphical method are shown in Appendix E. There was an insufficient amount of data points to determine the critical headways for trucks for the 78&92, Thompson North and Thompson South roundabouts.

However, determining the critical headway using the graphical method is highly subjective since the intersection point of the cumulative accepted and rejected gap curves depends on the selected time intervals of the gap. For more objective determination of the critical headway, an alternative mathematical method was used. In this regard, the critical headway was calculated using the probability equilibrium method. The calculation was performed in the Excel spreadsheet provided by Dr. Ning Wu – a developer of the method. A sample calculation of the critical headway for trucks at the 32&57 roundabout is shown in Appendix F. The maximum likelihood method was not used due to the limitations as explained in Section 2.1.3.

The critical headways for all roundabouts are shown in Table 5-2. Generally, the critical headways estimated using the graphical and probability equilibrium methods were similar. An average of the two critical headways was used as a representative critical headway for each roundabout. As expected, the critical headway for trucks was longer than of the critical headway for cars at all the roundabouts.

Table 5-2. Observed Roundabout Critical Headways Summary

Roundabout	Graphical		Probability Equilibrium		Average	
	$t_{c,cars}$ (s)	$t_{c,trucks}$ (s)	$t_{c,cars}$ (s)	$t_{c,trucks}$ (s)	$t_{c,cars}$ (s)	$t_{c,trucks}$ (s)
Brattleboro	3.8	5.2	3.9	5.3	3.9	5.3
Waterloo	4.0	6.0	4.2	5.3	4.1	5.7
32&57	3.2	4.2	3.7	4.7	3.5	4.5
78&92	5.0	-*	5.4	-	5.2	-
42&43	3.8	5.0	4.0	6.0	3.9	5.5
Vanguard	4.1	4.5	4.0	4.6	4.1	4.6
Bennett	4.4	6.6	5.1	5.6	4.8	6.1
Moorland North	4.1	4.5	4.5	5.6	4.3	5.1
Moorland South	4.1	4.5	4.5	4.7	4.3	4.6
Thompson North	3.9	-*	4.4	-	4.2	-
Thompson South	4.2	-	4.9	-	4.6	-

*Due to lack of entering trucks, critical headways could not be estimated.

In addition to the critical headway, the gap acceptance/rejection data were used to find the minimum headway for each roundabout. The minimum headway for each roundabout is shown in Table 5-3. All minimum headways was relatively short (shorter than 1 sec) because some headways were taken for the vehicle following the lead vehicle in the adjacent lane at two-lane roundabouts or one-lane roundabouts with larger width of circulatory roadway.

Table 5-3. Observed Roundabout Minimum Headways

Roundabout	Minimum headway (s)
Brattleboro	0.3
Waterloo	0.9
32&57	0.3
78&92	0.5
42&43	0.5
Vanguard	0.3
Bennett	0.4
Moorland North	0.3
Moorland South	0.5
Thompson North	0.5
Thompson South	0.8

5.4 Follow-up Time

Follow-up times for different vehicle-following conditions are shown in Table 5-4. Similar to the critical headway, there was not enough truck volume to collect the follow-up time for all vehicle-following cases at some roundabouts. It was found that the follow-up time was longer for the cases where a truck was the lead vehicle and/or the following vehicle. The follow-up time for the truck/car case was longer than the follow-up time for the car/truck case since it took longer time for the lead truck to enter the roundabout than the lead car. Although a truck could rarely follow another truck using the same gap at the entry leg of most roundabouts, it was found that the follow-up time for the truck-truck case was the longest due to the lead truck's slow entry and the following truck's low acceleration.

Table 5-4. Observed Roundabout Follow-up Time

Roundabout	Follow-up time			
	$t_{f,cc}$ (s)	$t_{f,ct}$ (s)	$t_{f,tc}$ (s)	$t_{f,tt}$ (s)
Brattleboro	2.1	4.2	5.3	8.5
Waterloo	2.3	5.0	6.8	7.4
32&57	2.1	3.3	5.3	-
78&92	1.6	2.6	-	-
42&43	2.3	2.8	5.5	7.8
Vanguard	2.2	2.7	5.4	-
Bennett	2.2	3.5	5.5	5.7
Moorland North	2.3	3.1	4.5	-
Moorland South	2.0	3.5	5.2	-
Thompson North	-*	-	-	-
Thompson South	-	-	-	-

*Due to lack of queued entering trucks, follow-up times could not be estimated.

5.5 Geometric Factors

To evaluate the effect of road geometry on driver gap-acceptance behaviour, critical headways and follow-up times were related to 8 geometric factors shown in Table 4-2 using a linear regression. Conventionally geometric factors were related to the entry capacity (e.g. Rodegerdts et al., 2007), but they have not been related to gap acceptance parameters. The correlation among the geometric factors was checked to avoid multicollinearity problem. The correlation analysis shows that some factors were highly correlated, as shown in Table 5-5.

Table 5-5. Correlation among Geometric Factors

	inscribed circle diameter (m)	inner island diameter (m)	truck apron (m)	entry width (m)	exit width (m)	circulatory roadway width (m)	splitter island width (m)	entry angle (deg)
inscribed circle diameter (m)	**1**							
inner island diameter (m)	**0.763**	**1**						
truck apron (m)	0.349	-0.164	**1**					
entry width (m)	**0.655**	0.420	0.305	**1**				
exit width (m)	**0.569**	0.283	0.111	**0.727**	**1**			
circulatory roadway width (m)	**0.537**	0.294	0.216	**0.879**	**0.865**	**1**		
splitter island width (m)	**0.573**	0.397	0.294	0.162	-0.101	-0.153	**1**	
entry angle (deg)	-0.297	-0.269	-0.136	0.184	0.125	0.212	**-0.571**	**1**

Many geometric factors were correlated with the inscribed circle diameter, because the inscribed circle diameter represents overall roundabout size. For example, the inscribed circle diameter is most highly correlated with the inner island diameter, because the difference between these two variables is the width of the circulatory roadway, which is normally constant for a given number of circulating lanes. Similarly, the inscribed circle diameter is correlated to the circulatory roadway width because larger roundabouts are more likely to have multiple lanes, and have wider circulatory roadways. The same logic can be used to explain why entry width, exit width, and splitter island width are correlated with the inscribed circle diameter.

Entry width, exit width and circulatory roadway width are all correlated with each other because all vehicles which enter a roundabout must also be able to exit it in similar geometric conditions (i.e. the same number of lanes). Splitter island width and entry angle are negatively correlated, because a wider splitter island forces vehicles to enter at a smaller entry angle.

It was found that relationships between the critical headway and all geometric factors were not statistically significant at a 95% confidence level. However, relationships between the follow-up time and some geometric factors were statistically significant at a 95% confidence level (see Appendix G for linear regression results). For instance, the relationship between the follow-up time and the central island diameter was significant for the car/car and car/truck cases at a 95% confidence level. Figure 5-3 shows that as the central island diameter increases, the follow-up time increases. This is potentially because if the roundabout is larger, it takes longer for the driver to perceive how to navigate the roundabout (e.g. check which lane he/she should enter) (Rodegerdts et al., 2007). Thus, trucks tend to follow cars more slowly at a larger roundabout.

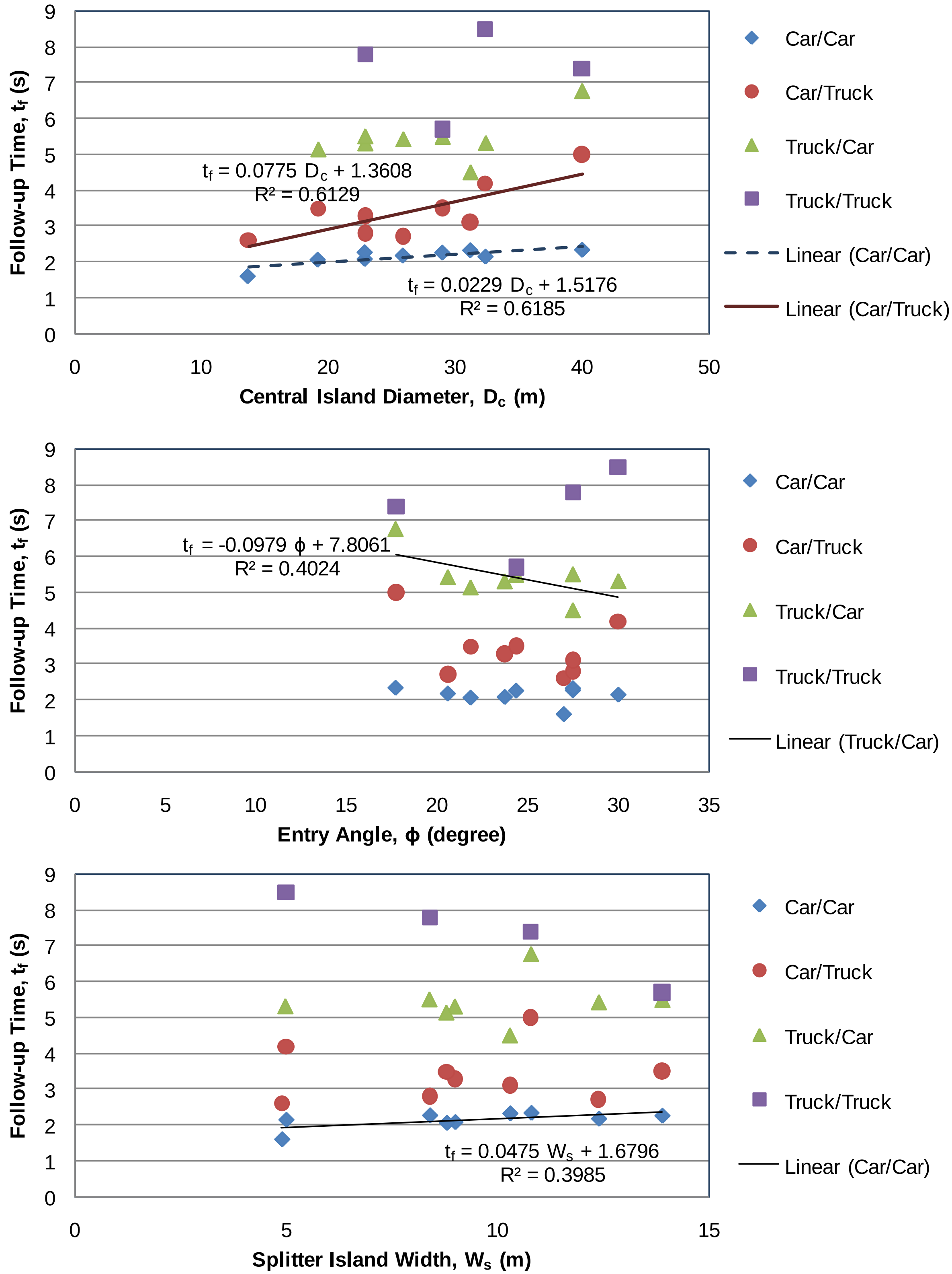


Figure 5-2. Relationships between Follow-up Times and Geometric Factors.

Given that sample size for these linear regression models was low (8 to 11 data points), some relationships that were significant at a 90% confidence level were also examined. As shown in Figure 5-3, car's follow-up time decreases when it follows trucks as the entry angle increases. This indicates that when it takes longer for trucks to negotiate sharper curve to enter the roundabout, cars tend to follow trucks more closely. Finally, the car/car follow-up time increases as the width of splitter island increases. This shows that larger width of the splitter island significantly increases the car/car follow-up time.

The regression models with multiple variables were also estimated but not all variables were statistically significant a 95% confidence level. Thus, these models were not considered further.

5.6 Capacity Estimation for Existing Conditions

Capacities of the Brattleboro, Waterloo and 32&57 roundabouts were estimated using the adjusted gap-acceptance parameters (Equations 3.1 and 3.2) and the existing macroscopic analytical capacity models. The percentage of trucks in each roundabout was calculated based on the car and truck counts in all entry legs. The percentages for the Brattleboro, Waterloo and 32&57 roundabouts were 11%, 19% and 5%, respectively. Since the term $t_{f,tt}$ could not be determined for the 32&57 roundabout due to lack of data, it was assumed to be equal to $t_{f,tc}$.

Capacities were also estimated using the two computerized models, SIDRA and VISSIM. The SIDRA model was run using three sets of 5-minute entry flow for each approach (right turn, through, and left turn). After running the model, the circulating flows were collected for each approach, and the per-lane capacity for each approach lane was averaged to determine the per-approach capacity. The approach for northbound US Route 5 was not included since the entry flow did not have conflict with the circulating flow.

In order to validate the VISSIM model, the free-flow times in the simulation were compared to the observed free-flow times for each approach. In general, average observed and simulated travel times for each approach were similar. However, due to low frequency of certain vehicle approach, the difference in standard deviation between the observed and simulated data was high. In general, standard deviations of travel time were lower in the simulated data than the observed data, especially for trucks. This is potentially because drivers choose the speed within a specified range of speed in the simulation, and their speeds in a give approach are less likely to vary than the actual conditions. Also, in reality, truck drivers are required to make a sharp turn to avoid various barriers such as a central island and a splitter island. Thus, some truck drivers are more cautious when they enter the roundabout regardless of traffic conditions. This will significantly increase their free-flow travel times and the variation in travel time will also increase.

Table 5-6. Comparison of Observed and Simulated Free-flow Travel Times

Approach			Observed (s)	Simulated (s)
SE to NE (right turn)	Cars	Mean	3.1	3.3
		Standard deviation	0.51	0.51
		Number	14	28
	Trucks	Mean	4.4	4.5
		Standard deviation	1.24	0.52
		Number	5	11
NE to SW (through)	Cars	Mean	3.9	3.7
		Standard deviation	0.45	0.27
		Number	37	7
	Trucks	Mean	5.7	5.6
		Standard deviation	0.93	0.67
		Number	9	6
NE to SE (left turn)	Cars	Mean	9.2	8.5
		Standard deviation	0.50	0.30
		Number	6	6
	Trucks	Mean	12.4	12.1
		Standard deviation	1.86	0.34
		Number	3	4

The capacities were estimated for different circulating flows using various capacity models and compared with the observed capacity as shown in Figure 5-3. It was found that the observed capacity was lower for the roundabout with higher truck percentage. This is because vehicles are more likely to wait for longer gaps (i.e. longer critical headway) and it takes longer for two vehicles to enter the roundabout using the same gap (i.e. longer follow-up time).

It should be noted that the observed capacity was less sensitive to the circulating flow at the Brattleboro and Waterloo roundabouts which have relatively higher truck percentages than the 32&57 roundabout. This reflects that the rate of reduction in the number of the entering vehicles with an increase in the circulating flow is lower when there are more trucks. This finding is intuitive in a sense that as available gaps approaches to the minimum acceptable gaps for trucks due to higher circulating flow, it becomes more difficult for trucks to enter the roundabout than cars. When gaps are shorter than the minimum acceptable gaps for trucks (but longer than the minimum acceptable gaps for cars), the number of entering trucks is less likely to be affected by an increase in the circulating flow than the number of entering cars.

Most capacity models closely reflected this trend as shown in Figure 5-4. In particular, Troutbeck's model estimated the capacity for the 32&57 roundabout most accurately by considering more sensitive change in the capacity to change in the circulating flow when truck percentage is lower.

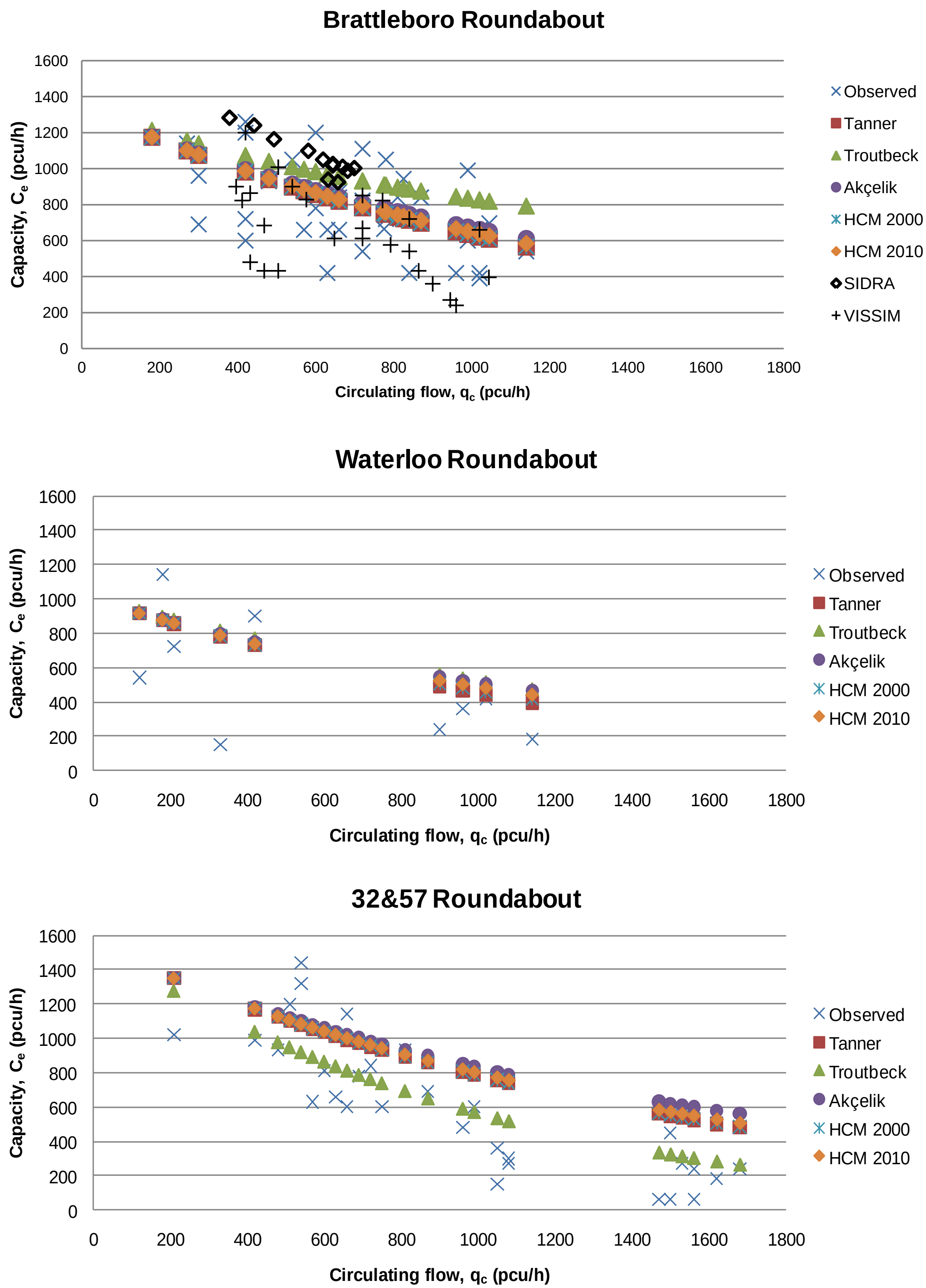


Figure 5-3. Comparison of Estimated Capacities for Three Roundabouts (capacity adjusted for trucks).

The capacity estimated using SIDRA was slightly higher than the capacities estimated by the other models for the Brattleboro roundabout (Figure 5-3 (a)). This is likely because a single-lane roundabout with a wider circulating lane width was treated similar to a two-lane roundabout in the model. On the other hand, the capacity estimated using VISSIM was generally lower than the other models. This is likely because VISSIM reflects that the circulating vehicles slow down to avoid potential conflicts and this reduces gaps for the entering vehicles. This variation in speed of the circulating flow will ultimately lower the capacity. However, a large fluctuation in the capacity estimated by VISSIM for a given circulating flow was similar to the observed data.

To evaluate the effectiveness of the adjusted gap-acceptance parameters, the capacities estimated using the adjusted and unadjusted parameters were compared with each other. Since cars are dominant in entry flow, if the difference in gap-acceptance behaviour between cars and trucks is not considered, the gap-acceptance parameters will be similar to the parameters for cars only. The accuracy of each capacity model was evaluated using the root-mean-square errors (RMSE) as shown in Figure 5-4. It was found that RMSE were lower for the capacity models with the adjusted parameters than the capacity models with the unadjusted parameters. It was also found that the percentage reduction in RMSE was greater for the roundabout with higher truck percentage. This indicates that gap-acceptance parameters need to be adjusted for trucks to estimate capacity for the roundabouts more accurately and the accuracy is more likely to be improved for the roundabouts with higher truck percentage.

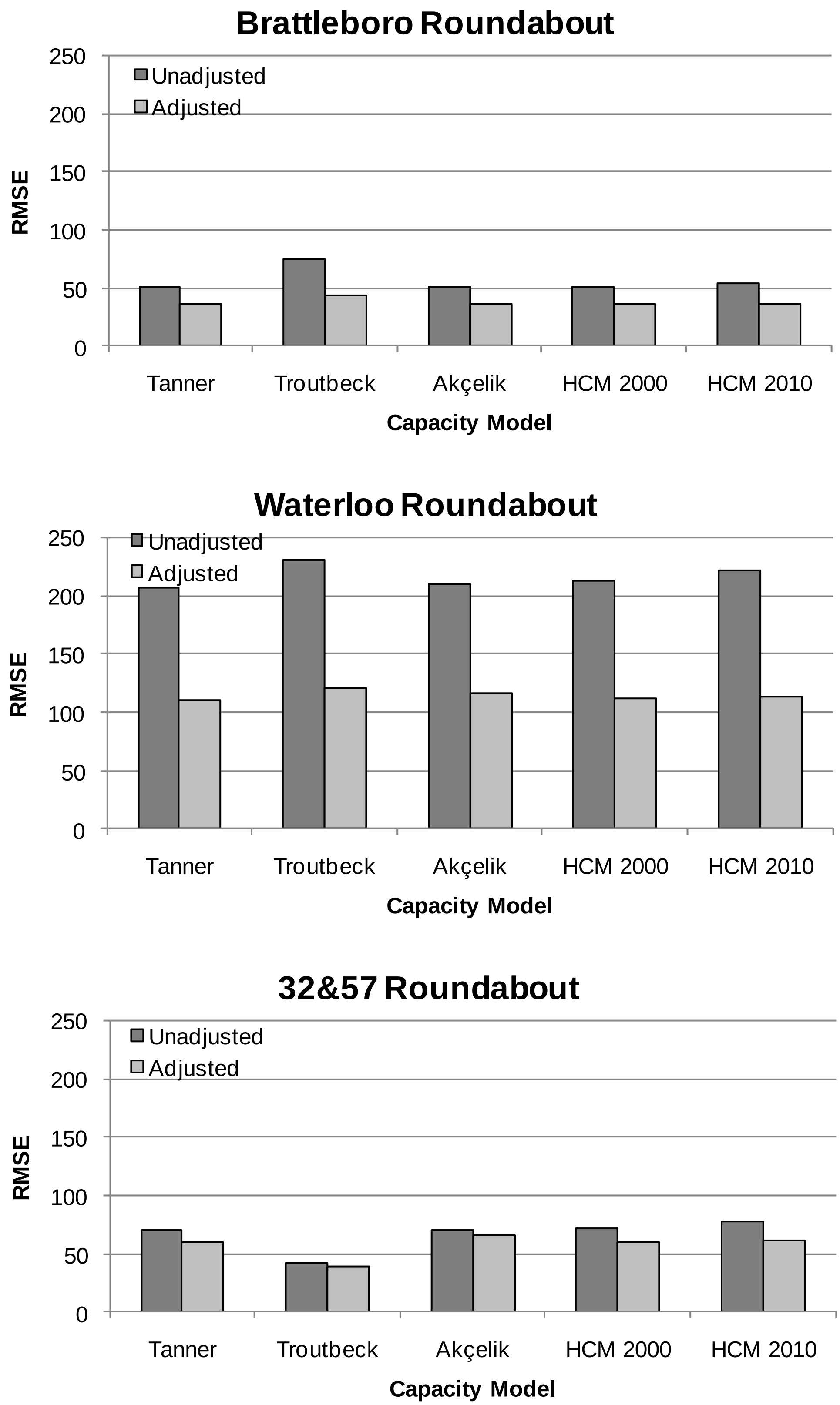


Figure 5-4. Comparison of Estimation Errors for Three Roundabouts.

The capacity models derived from the M3 distribution (Troutbeck's and Akçelik's models) generally provided a good fit to the observed capacities for all three roundabouts. However, the accuracy of estimation mainly depends on the proportion of free vehicles (α) that is described in a function of the circulating flow. For instance, Akçelik's function showed lower error for the roundabouts with higher truck percentage and Troutbeck's function showed lower error for the roundabout with lower truck percentage.

5.7 Capacity Estimation for Hypothetical Cases of Truck Percentage

For demonstration purpose, Troutbeck's model was applied to the Brattleboro, Waterloo and 32&57 roundabouts to better understand the general trend of capacity affected by truck percentage. Troutbeck's model was chosen due to relatively low RMSE of the estimated capacity for these roundabouts. Capacities were estimated with five hypothetical truck percentages (0, 5, 10, 15 and 20%) and the circulating flow in the range of 0-1,800 pcu/h as shown in Figure 5-5.

It was assumed that critical headways for cars and trucks, and follow-up times for all vehicle-following cases are not affected by change in truck percentage. Thus, only the adjusted critical headways and follow-up times change as truck percentage changes.

The results showed that capacity decreases as truck percentage increases, but the amount of capacity reduction is less at higher circulating flow. The results also show that the rate of capacity reduction with an increase in circulating flow is lower at higher truck percentage.

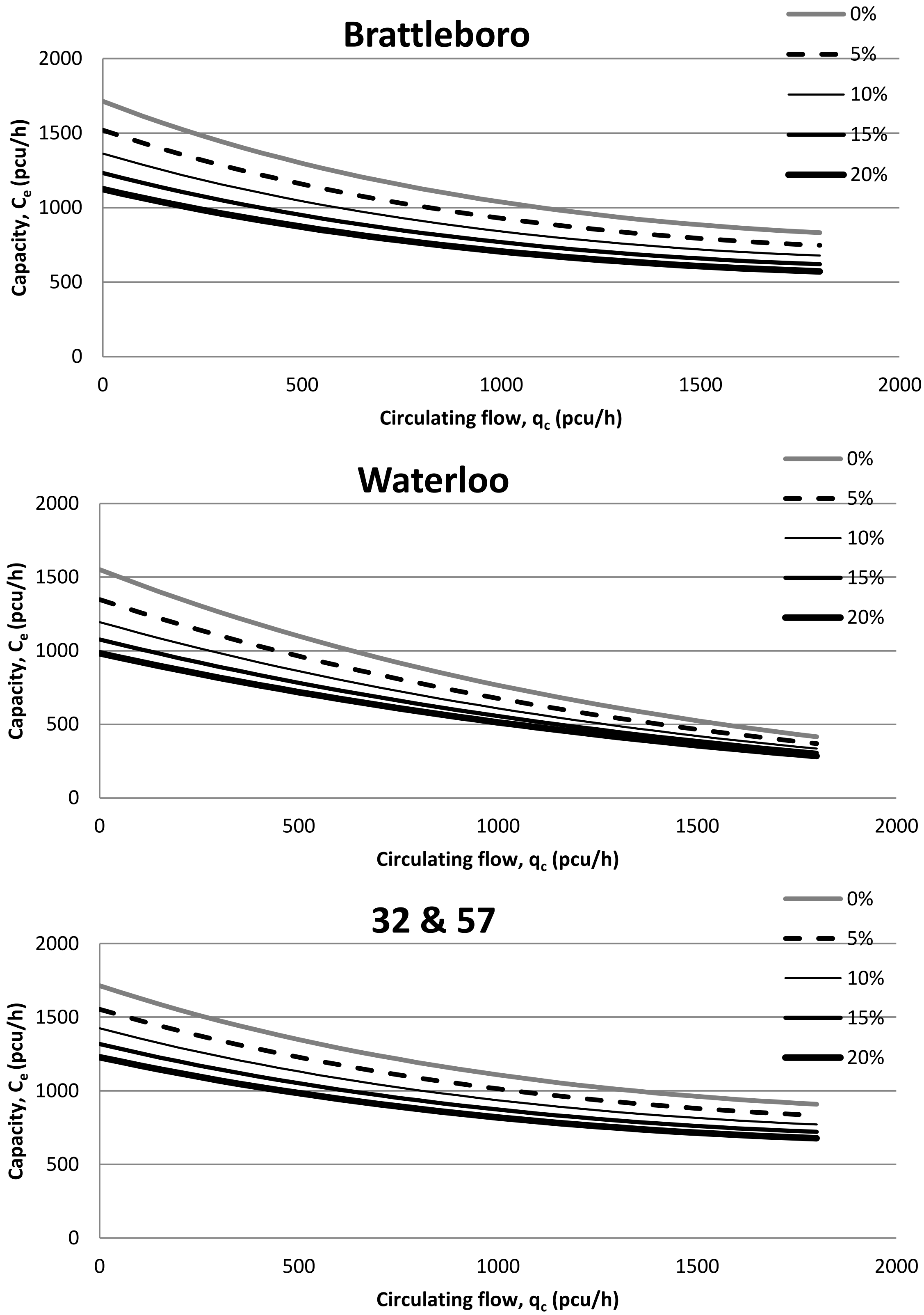


Figure 5-5. Change in Capacity with Various Truck Percentages.

This effect is most noticeable at the Waterloo roundabout which has longer adjusted critical headway and follow-up time, as shown in Figure 5-6. This indicates that change in the circulating flow is less likely to affect capacity as truck percentage increases when the adjusted gap-acceptance parameters are higher.

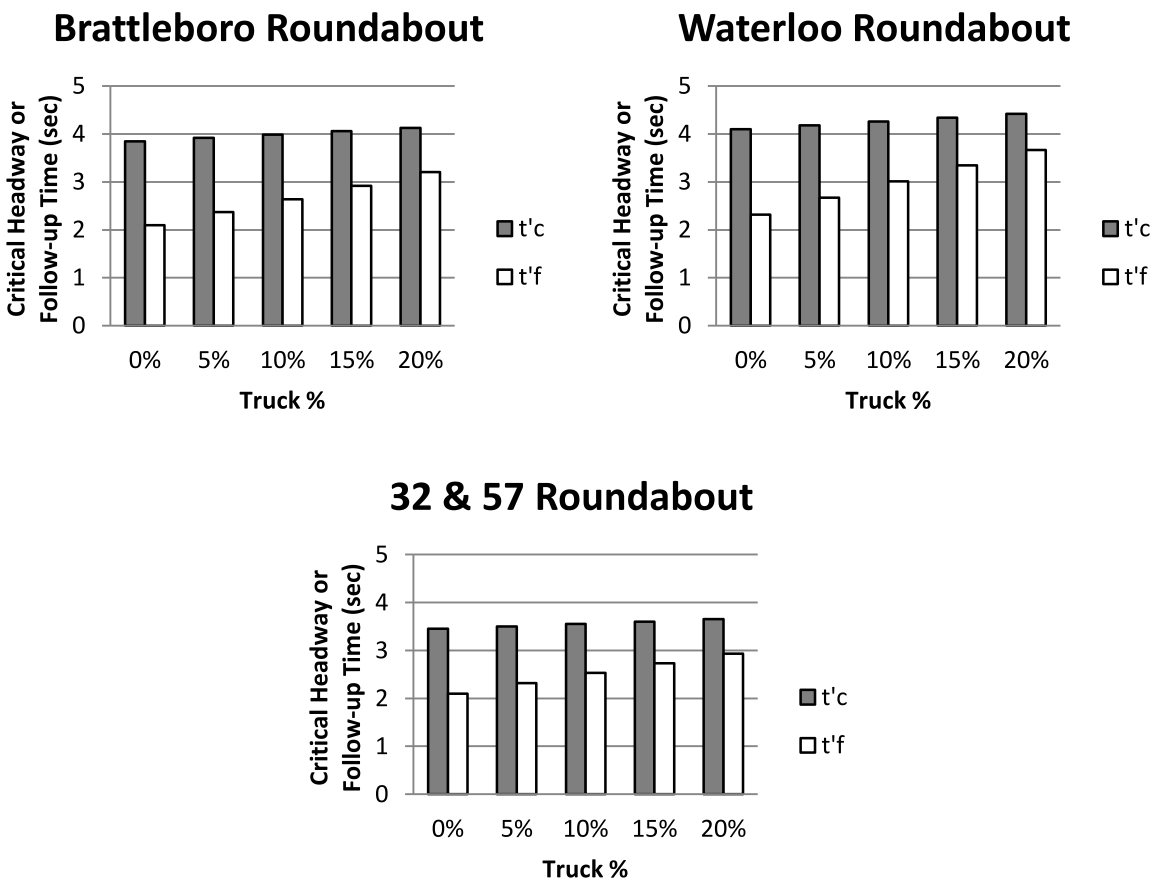


Figure 5-6. Adjusted Gap-acceptance Parameters with Various Truck Percentages.

Capacities were also estimated as a function of truck percentage for given circulating flows – 600, 800 and 1000 pcu/h. As shown in Figure 5-7, capacity decreases at higher rate for lower circulating flow as truck percentage increases. This trend helps estimate the amount of reduction in capacity with an increase in truck percentage, which can be used to improve the roundabout design. In particular, the capacity is affected to a greater extent for the Waterloo roundabout even when truck percentage is low. This is because car and truck gap-acceptance parameters are higher for this roundabout.

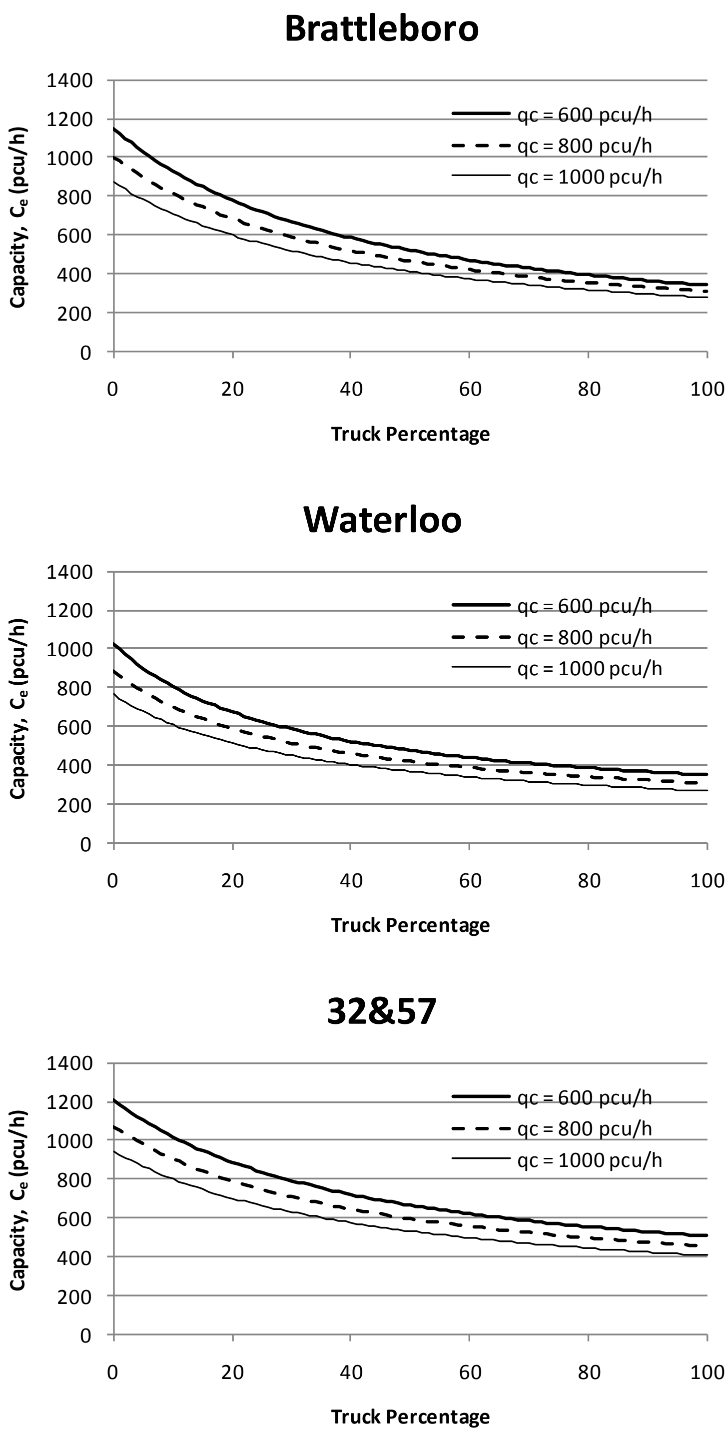


Figure 5-7. Change in Capacity due to Truck Percentage with Various Circulating Volumes.

6 CONCLUSIONS AND RECOMMENDATIONS

As a growing number of roundabouts are built in the areas with high truck volume, a more accurate method of estimating the entry capacity is needed. In this regard, this study proposes the method of adjusting gap-acceptance parameters for trucks considering truck's slower speed and larger radius required for turning. The study assumes that the ratio of truck-car critical headway is not always equal to the ratio of truck-car follow-up time unlike previous studies. Also, the follow-up time was assumed to be different for different vehicle-following cases.

To investigate the difference in gap-acceptance behaviour between cars and trucks, the movements of vehicles were observed at 11 roundabouts in Vermont, Ontario, and Wisconsin. The critical headway and follow-up time were estimated for cars and trucks separately. Capacity was estimated using various capacity models with the adjusted gap-acceptance parameters and compared with actual capacity observed from the field. The findings of the study are summarized as follows:

1. Critical headways were longer for trucks than cars. Follow-up times were longer in the order of a truck following a truck, a car following a truck, a truck following a car and a car following a car.

2. Truck's free-flow speed was lower than car's free-flow speed in a circulatory roadway. Thus, truck's entry caused obstruction of the circulating flow and had an effect on the likelihood of acceptable gaps for the entering vehicles on adjacent legs. It increases the likelihood of acceptable gaps in front of the truck but decreases the likelihood of acceptable gaps behind the truck.

3. Follow-up times for some truck-involved vehicle-following cases were associated with roundabout geometric factors. The follow-up time for a truck following a car increased as the central island diameter increased whereas the follow-up time for a car following a truck increased as the entry angle decreased.

4. The rate of reduction in the observed capacity with an increase in the circulating flow was lower at the roundabout with higher truck percentage. It was found that even small percentages of trucks had an immediate effect on roundabout operation.

5. The estimation errors of capacity were lower for the capacity models with the adjusted gap-acceptance parameter than the models with the unadjusted gap-acceptance parameters. This indicates the adjusted gap-acceptance parameters improve the accuracy of capacity estimation particularly for the roundabouts with high truck volume.

6. As truck percentage increased, the critical headway and the follow-up time for the roundabout increased and this resulted in lower capacities. The amount of reduction in capacity due to an increase in truck percentage helps improve the roundabout design in order to compensate for the loss of capacity.

7. Microscopic traffic simulation models such as VISSIM can realistically represent the effect of trucks on the circulating flow, such as gap forcing and obstruction. VISSIM can also reflect large variation in capacity for a given circulating flow similar to the observed capacity. However, the calibration and validation of the model are time-consuming and very complex. Instead, the macroscopic analytical models using the adjusted gap acceptance parameter can estimate the capacity at a reasonable accuracy with relatively less effort of calibration and validation.

These findings indicate that the effect of trucks on roundabout capacity cannot be solely reflected by converting the number of vehicles to passenger car unit (pcu) as the conventional method suggested. Since truck drivers' gap acceptance behavior is different from car drivers' behavior, their likelihood of entering the roundabout for a given circulating flow must also be different. Thus, gap-acceptance parameters used for capacity estimation need to be adjusted to account for the difference.

The capacity estimated using the adjusted gap-acceptance parameters can be effectively used for the design of roundabouts with high truck volume. The capacity can be estimated more accurately for a forecasted travel demand and percentage of trucks. Then the geometric factors can be determined such that they can accommodate travel demand. The adjusted gap-acceptance parameters can also be used to determine how to modify the existing roundabout design to increase the capacity. Since geometric factors affect truck's gap-acceptance behavior, the design can be improved to reduce the entry time for trucks and ultimately increase the capacity. For instance, a truck apron can also be included outside of the circulatory roadway to provide more room for a truck's wider turning and increase truck mobility.

Finally, the adjusted gap-acceptance parameters can show the general relationship between the capacity and truck percentage using simple mathematical equations unlike microscopic traffic simulation. This relationship helps engineers understand the sensitivity of the capacity to truck percentage and determine the critical truck percentage that will cause a significant reduction in the capacity. To avoid such flow breakdown, the method of controlling truck traffic can be considered.

In spite of some promising results, there are some limitations in this study. Due to a lack of trucks in the entry flow, the gap-acceptance parameters for trucks could not be determined for some roundabouts. Also, it was assumed that individual driver's gap-acceptance behaviour is independent from truck percentage change of the entire entry flow and the circulating flow. However, if they are correlated, the adjusted gap-acceptance parameters may provide the biased result. For instance, if truck percentage is high and the entering vehicles are required to wait longer, they are more likely to accept shorter gaps (Polus et al., 2003). Finally, the gap acceptance only depends on available gaps in the circulating flow. However, it's possible that gap acceptance is also affected by driver's sight and aggressiveness, and road surface conditions.

In future studies, more data need to be collected from roundabouts with a wide range of truck percentages to better understand general effect of truck percentage on capacity. It is also recommended to observe how individual car drivers and truck drivers behave differently at roundabouts under various geometric, traffic and weather conditions. For instance, the variation in driver's gap acceptance behaviour by time of day and driver's cautious behaviour in adverse weather conditions needs to be considered. The effects of other vehicle types (e.g. bus) on the capacity also need to be investigated. It is expected that the critical headway and follow-up time are different for different vehicle types and the entry capacity is affected by the vehicle composition. Finally, in spite of advantages of roundabouts, the construction of roundabouts is not always a feasible option to replace the existing intersections (e.g. signalized or stop-controlled intersections) due to limited space. Thus, it is recommended traffic engineers evaluate differential effects of trucks on the capacity among different intersection types.

REFERENCES

Akçelik & Associates Pty Ltd. (2011). *SIDRA INTERSECTION 5.1*. Greythorn, Victoria, Australia.

Akçelik, R. (2011). An Assessment of the Highway Capacity Manual 2010 Roundabout Capacity Model. Proceeding of the 3rd International Conference on Roundabouts, Carmel, IN, May 18-20, 2011.

Akçelik, R. and E. Chung. (2003). Calibration of the Bunched Exponential Distribution of Arrival Headways. *Road Transport Research,* 3 (1), pp. 42-59.

Akçelik, R. (2003). Speed-Flow and Bunching Relationships for Uninterrupted Flows, 25th Conference of Australian Institute of Transport Research (CAITR 2003), University of South Australia, Adelaide, Australia, 3-5 December 2003.

Baldwin, G. (2005). *Too Many Trucks on the Road?* Statistics Canada — No. 11-621-MIE2005028,

Chey, R., Valdez, M., Duran, C., Archuleta, M., Ibarra, I., and Cheu, D. (2011) Performance Evaluation of an Intersection with Roundabout and Signalized Control. Proceeding of at the 3rd International Conference on Roundabouts, Carmel, IN, May 18-20, 2011.

Cowan, R. C. (1975). Useful Headway Models. *Transportation Research*, 9, pp. 371-375.

Dahl, J. and Lee, C. (2011). Factors Affecting for Capacity Estimation for Roundabouts with High Truck Volume. Proceeding of the 3rd International Conference on Roundabouts, Carmel, IN, May 18-20, 2011.

Fellendorf, M. and Vortisch, P. (2010). *Miscroscopic Traffic Flow Simulator VISSIM*. Fundamentals of Traffic Simulation, pp. 63-93.

Garder, P. (1998). *Little Falls, Gorham a Modern Roundabout.* University of Maine Orono. Orono, Maine.

Google Map (2011). http://maps.google.com. [accessed on August 2011]

Isebrands, H., Cicu, F., Illotta, P. F, and Bared, J. (2011). *VISSIM Calibration of Roundabouts Traffic Performance*. TRB Annual Meeting 2011

Kittleson & Associates. (2011) *Modern Roundabouts: The Web Site* http://roundabouts.kittelson.com/Roundabouts [accessed on August 2011]

Mayhew, D., Simpson, H. M., and Beirness, D. (2004). *Heavy Trucks and Road Crashes.* Traffic Injury Research Foundation

Mereszczak, Y., M. Dixon, M. Kyte, L. Rodegerdts, and M. Blogg. (2006). Including Exiting Vehicles in Capacity Estimation at Single-lane U.S. Roundabouts. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1988, Transportation Research Board of the National Academies, Washington, D.C., pp. 23-30.

Natural Resources Canada. (2007) *2005 Canadian Vehicle Survey Summary Report.*

Polus, A., S. S. Lazar, and M. Livneh. (2003). Critical Gap as a Function of Waiting Time in Determining Roundabout Capacity. *Journal of Transportation Engineering*, Vol. 129, No. 5, pp. 504-509.

PTV AG. (2011). *VISSIM 5.30-05 User Manua*l. Karlsruhe, Germany.

Qiu, T. Z. and Yin, D. (2011). *Comparison of Macroscopic and Microscopic Simulation Models in Modern Roundabout Analysis.* TRB Paper No: 11-2062. Submitted for presentation at the 90th Annual Meeting of Transportation Research Board and publication in Transportation Research Record: Journal of Transportation Research Board

Rasheed, S. (2010). *Survey of Canadian Roundabout.* Institute of Transportation Engineers (ITE)

Reddington, T. (2001). *Modern Roundabout, Global Warming, and Emissions Reductions: Status of Research and Opportunities for North America.* Canadian Transportation Research Forum, 2001. A Transportation Odyssey. Canadian Transportation Research Forum. Proceedings of the 36th Annual Conference.

Robinson, B. W., Rodegerdts, L., Troutbeck, R., Brilon, W., Bondzio, L., Courage, K., Kyte, M., Mason, J., Flannery, A., Myers, E., Bunker, J., and Jacquemart, G. (2000). *Roundabouts: An Informational Guide.* U.S. Department of Transportation. Federal Highway Administration. Publication No. FHWA-RD-00-067.

Rodegerdts, L., Bansen, J., Tiesler, C., Knudsen, J., Myers, E., Johnson, M., Moule, M., Persaud, B., Lyon, C., Hallmark, S., Isebrands, H., Crown, R. B., Guichet, B. and O'Brien, A. (2010) *Roundabouts: An Informational Guide Second Edition*. NCHRP Report 672, Transportation Research Board.

Rodegerdts, L., Blogg, M., Wemple, E., Myers, E., Kyte, M., Dixon, M., List, G., Flannery, A., Troutbeck, R., Brilon, W., Wu, N., Persaud, B., Lyon, C., Harkey, D., and Carter, D. (2007) *Roundabouts in the United States.* NCHRP Report 572, Transportation Research Board, Washington, D.C.

Statistics Canada, (2005). *Canadian Vehicle Survey, Annual 2003,* Catalogue no. 53-223-XIE, pages 26 and 30

Sullivan, D. P., and Troutbeck, R. (1994). "The use of Cowan's M3 distribution for modeling urban traffic flow." *Traffic Eng. Control*, 35(7–8), 445–450.

Tanner, J. C. (1967). The Capacity of Uncontrolled Intersection. *Biometrika*, 54 (3–4), pp.163–170.

Tanyel, S., Baran, T., and Özuysal, M. (2007) Applicability of Various Capacity Models for Single-lane Rondabouts in Izmir, Turkey. *Journal of Transportation Engineering*, Vol. 133, No. 12, pp. 647-653.

The Highways Agency, Transport Scotland, Welsh Assembly Government Llywodraeth Cynulliad Cymru, and The Department for Regional Development Northern Ireland. (2007). *Geometric Design of Roundabouts*. TD 16/07 Volume 6, Section 2, Part 3.

Transportation Research Board (TRB). (2000). *Highway Capacity Manual 2000*.

Transportation Research Board (TRB). (2010). *Highway Capacity Manual 2010*.

Troutbeck, R. J. and Kako, S. (1999). Limited Priority Merge at Unsignalized Intersections. *Transportation Research Part A*, 33, pp. 291-304.

Troutbeck, R. J. (1986). Average delay at Unsignalized Intersection with Two Major Streams Each Having Dichotomized Headway Distribution. *Transportation Science*, Vol. 20, No. 4, pp. 272-286.

Troutbeck, R. J. (1993). Effect of Heavy Vehicles at Australian Traffic Circles and Unsignalized Intersections. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1398, Transportation Research Board of the National Academies, Washington, D.C., pp. 54-60.

Troutbeck, R. J. (1991). Unsignalized Intersections and Roundabouts in Australia: Recent Developments. *Intersections without traffic signals II*, Bochum, Germany, pp. 238–257.

Trueblood, M. and Dale, J. (2003). *Simulating Roundabouts with VISSIM.* 2nd Urban Street Symposium (Anaheim, California) from July 28-30, 2003

Wei, T., Ambadipudi, R., and Shah, H. (2011). VISSIM Calibration for Modeling Roundabouts: Practical Guidelines. Presented at the 3rd International Conference on Roundabouts, Carmel, IN, May 18-20, 2011

Wu, N. (2006). A New Model of Estimating Critical Headway and Its Distribution at Unsignalized Intersections based on the Equilibrium of Probabilities. Proceeding of the 5th International Symposium on Highway Capacity and Quality of Service, Yokohama, Japan, July 25-29, 2006.

Zheng, D., Porters, B., Chitturi, M. V., Bill, A., and Noyce, D. A. (2011). Evaluating the Operational Characteristics at a Heavily Congested Roundabout. Presented at the 90th Transportation Research Board Annual Meeting, Washington, D.C., January 23-27, 2011.

APPENDIX A – GEOMETRIC DRAWINGS

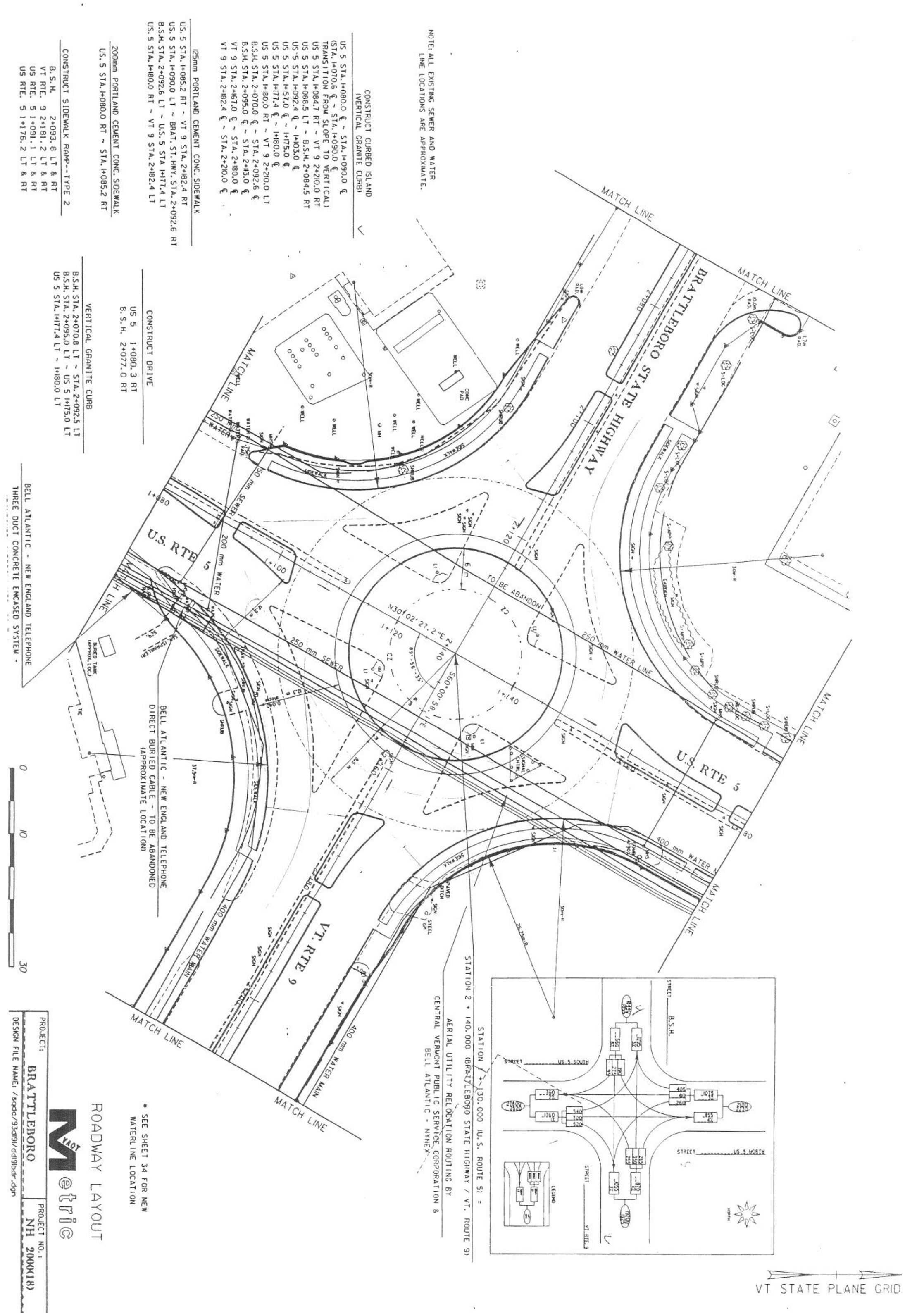


Figure A-1. Brattleboro Roundabout Geometry

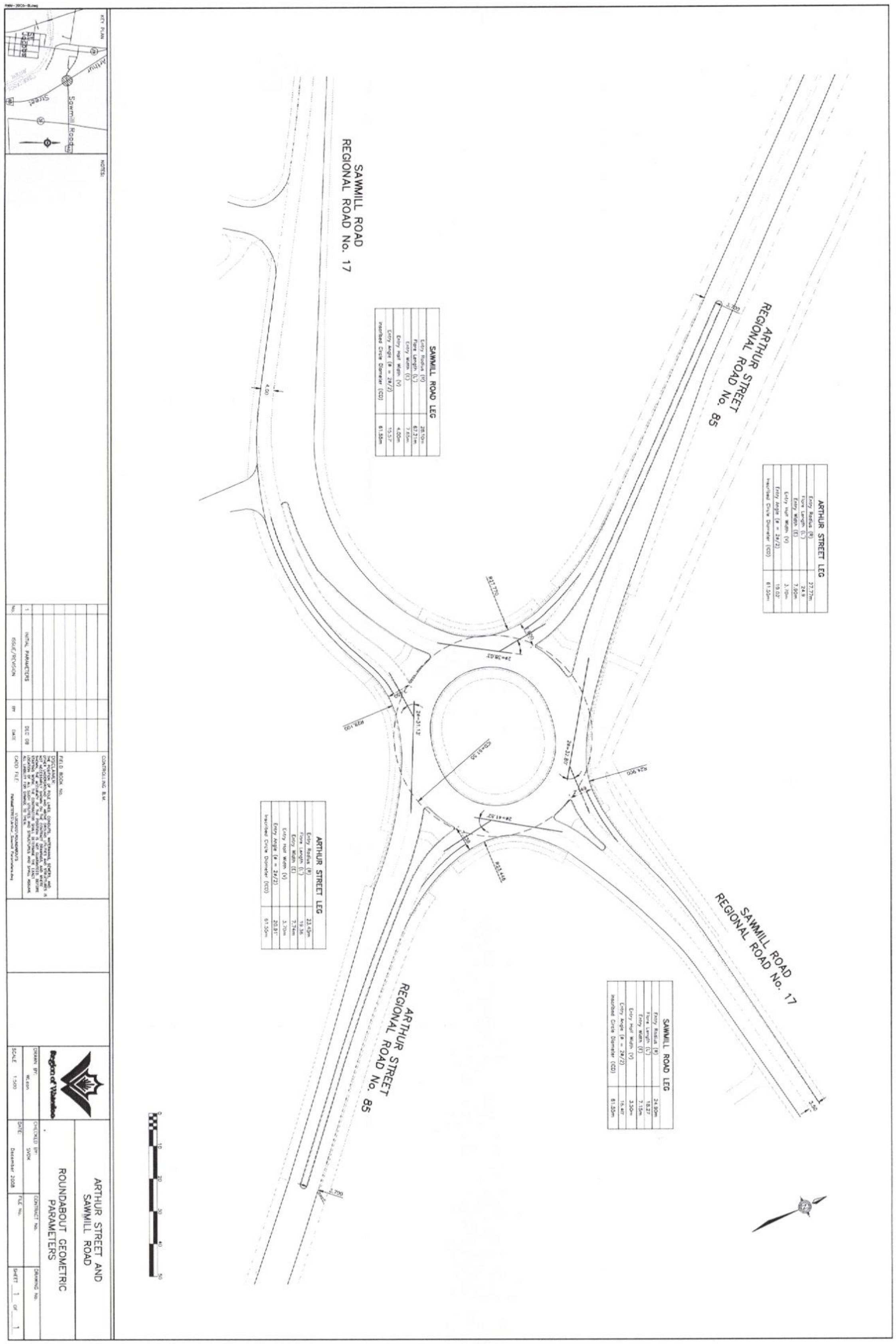


Figure A-2. Waterloo Roundabout Geometry

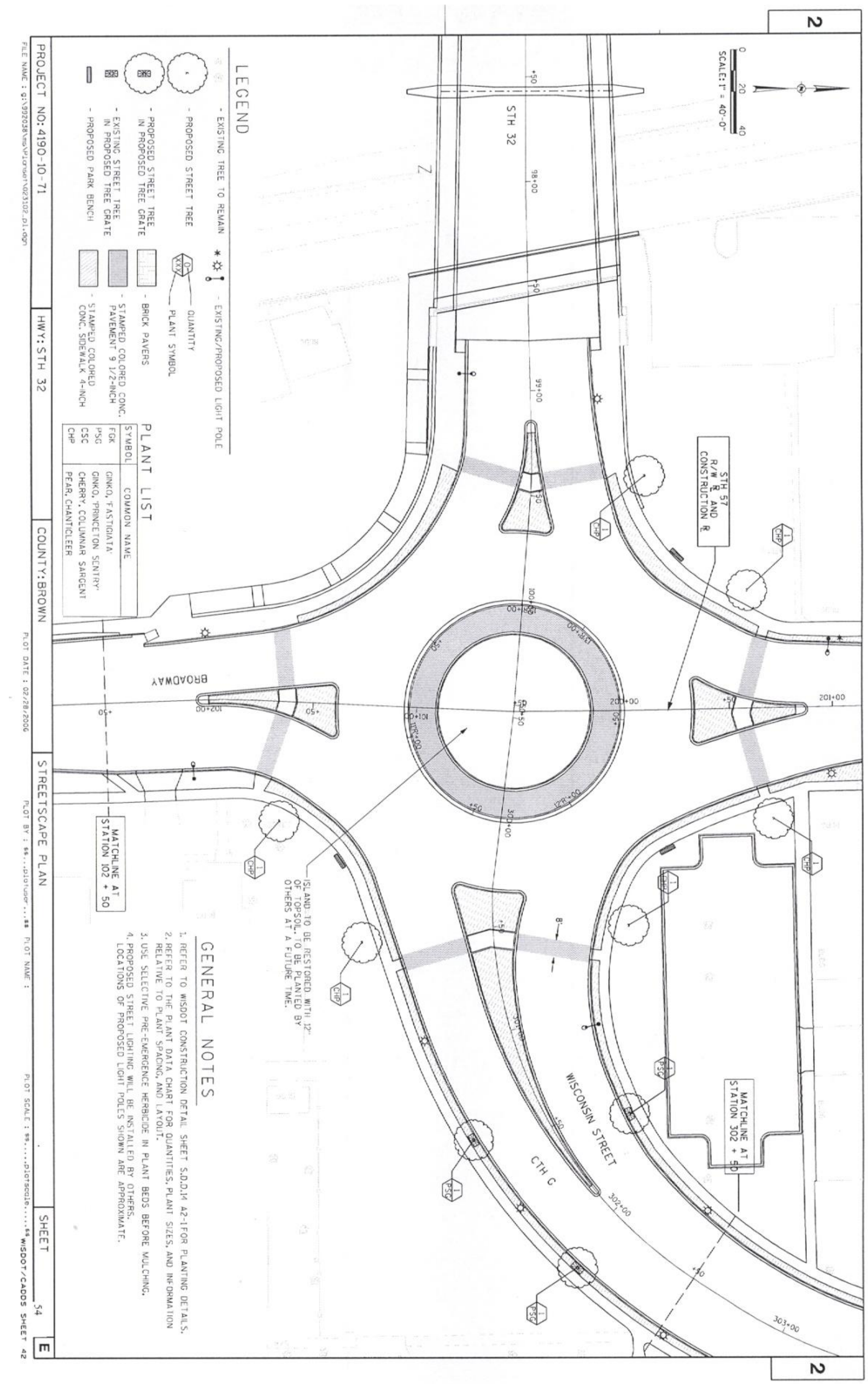


Figure A-3. 32 & 57 Roundabout Geometry

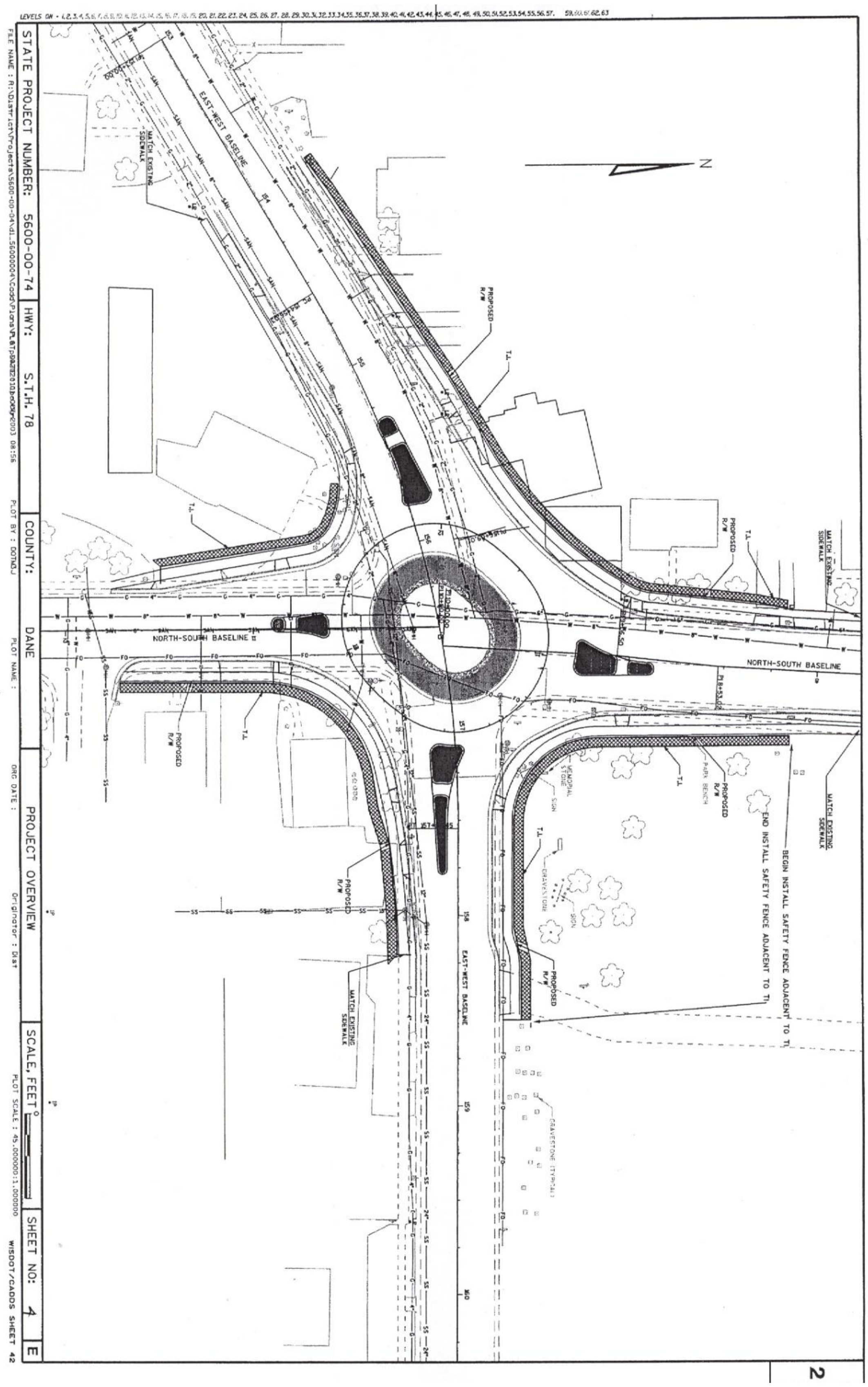


Figure A-4. 78 & 92 Roundabout Geometry

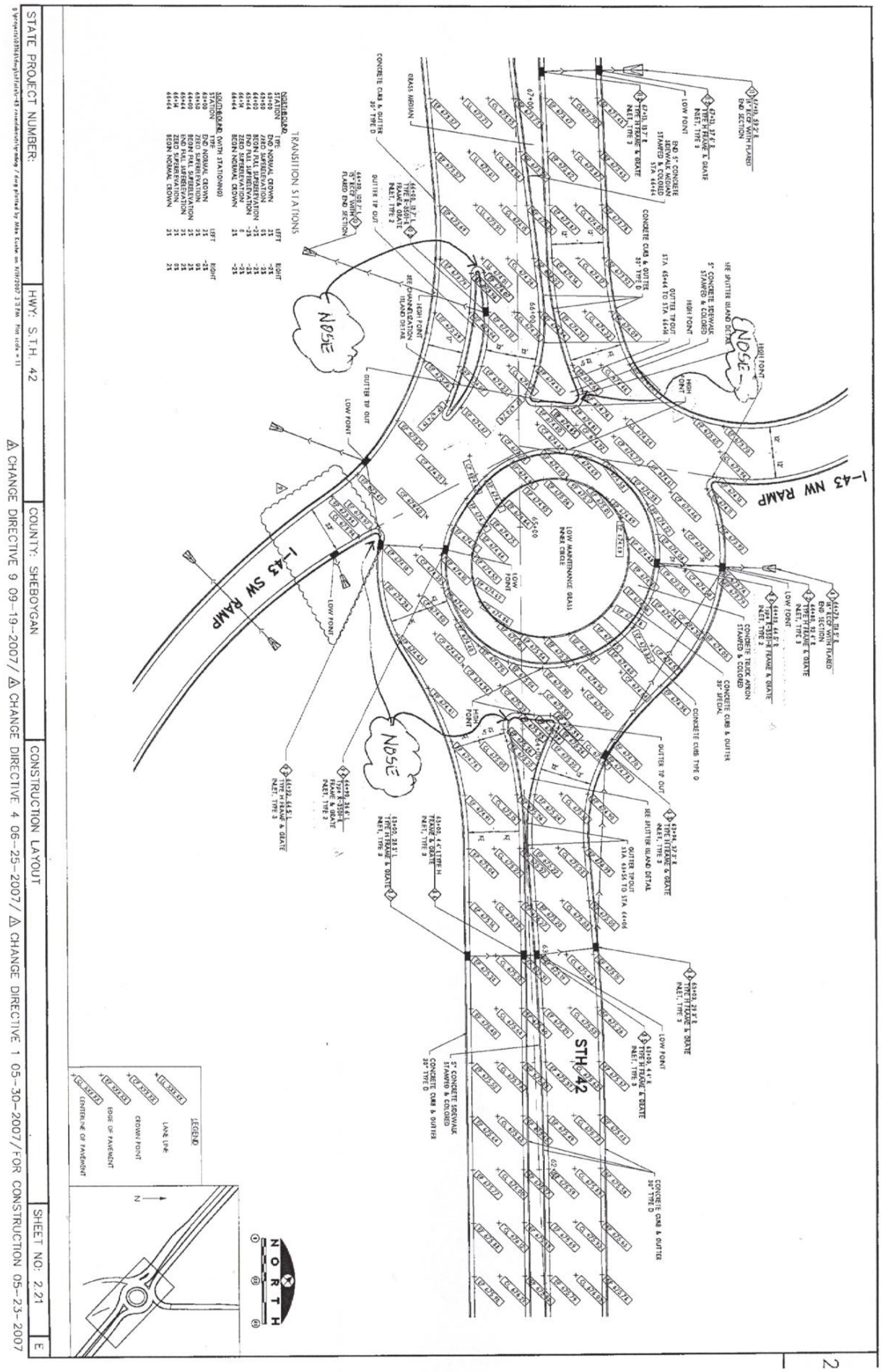


Figure A-5. 42 & 43 Roundabout Geometry

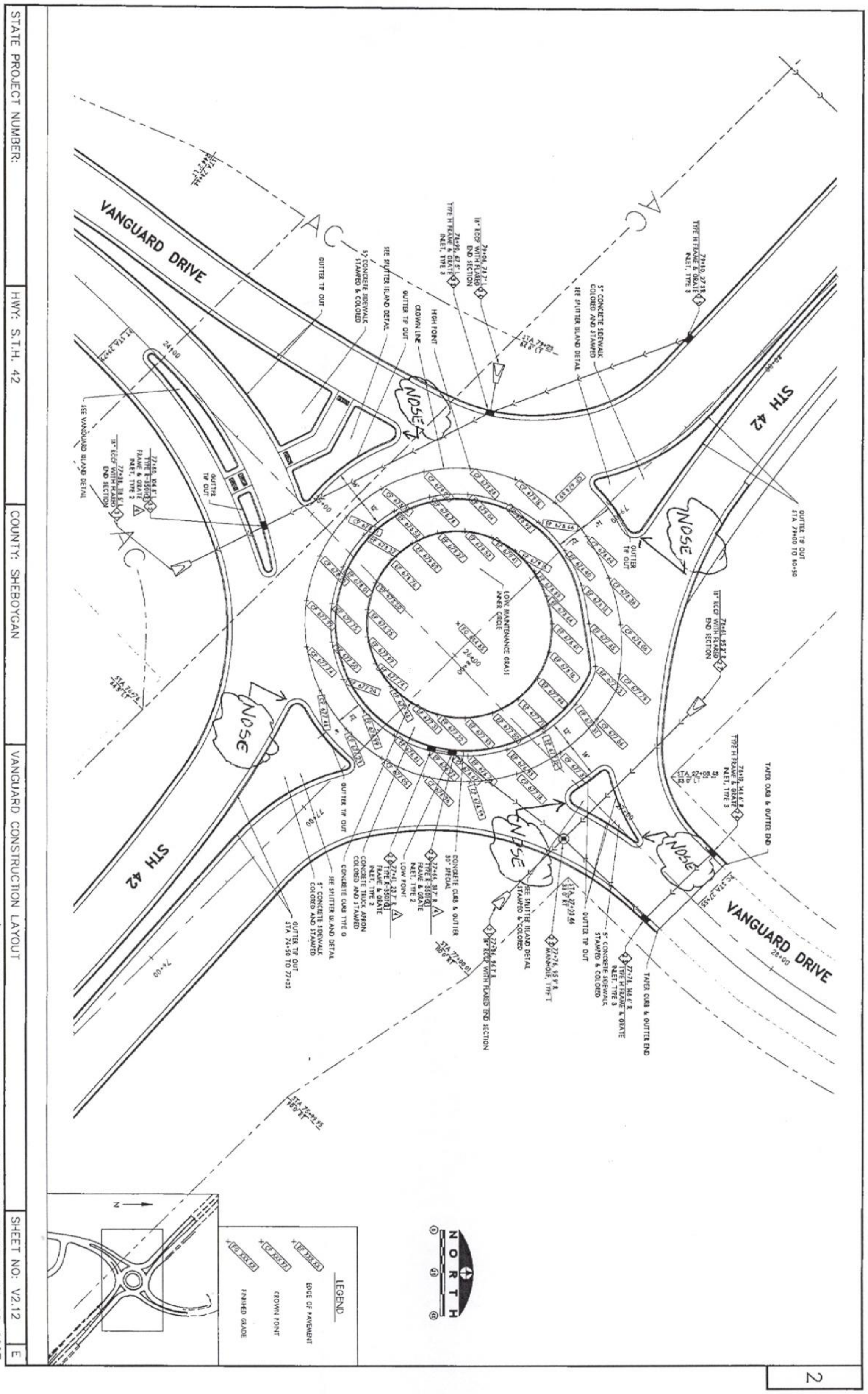


Figure A-6. Vanguard Roundabout Geometry

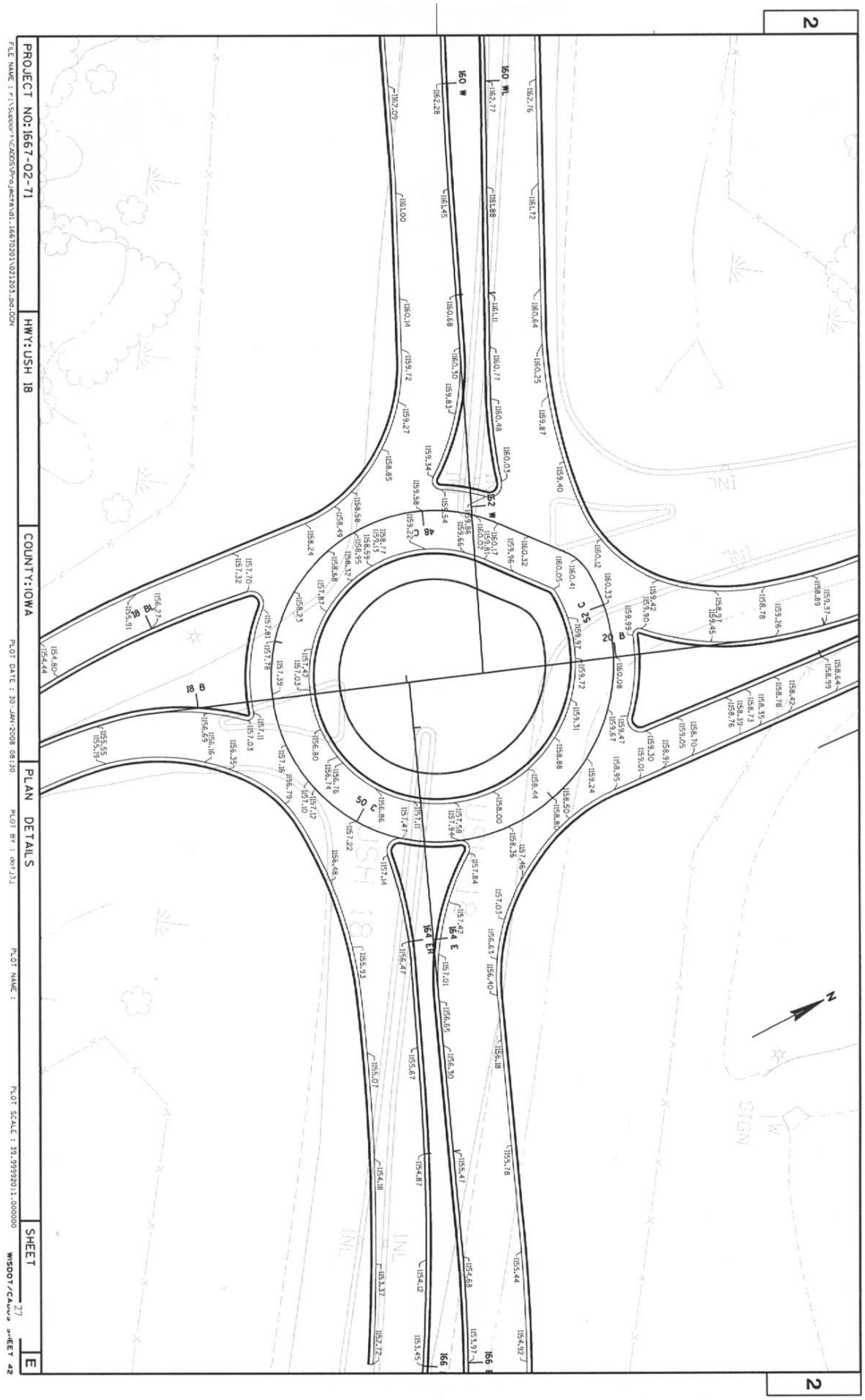


Figure A-7. Bennett Roundabout Geometry

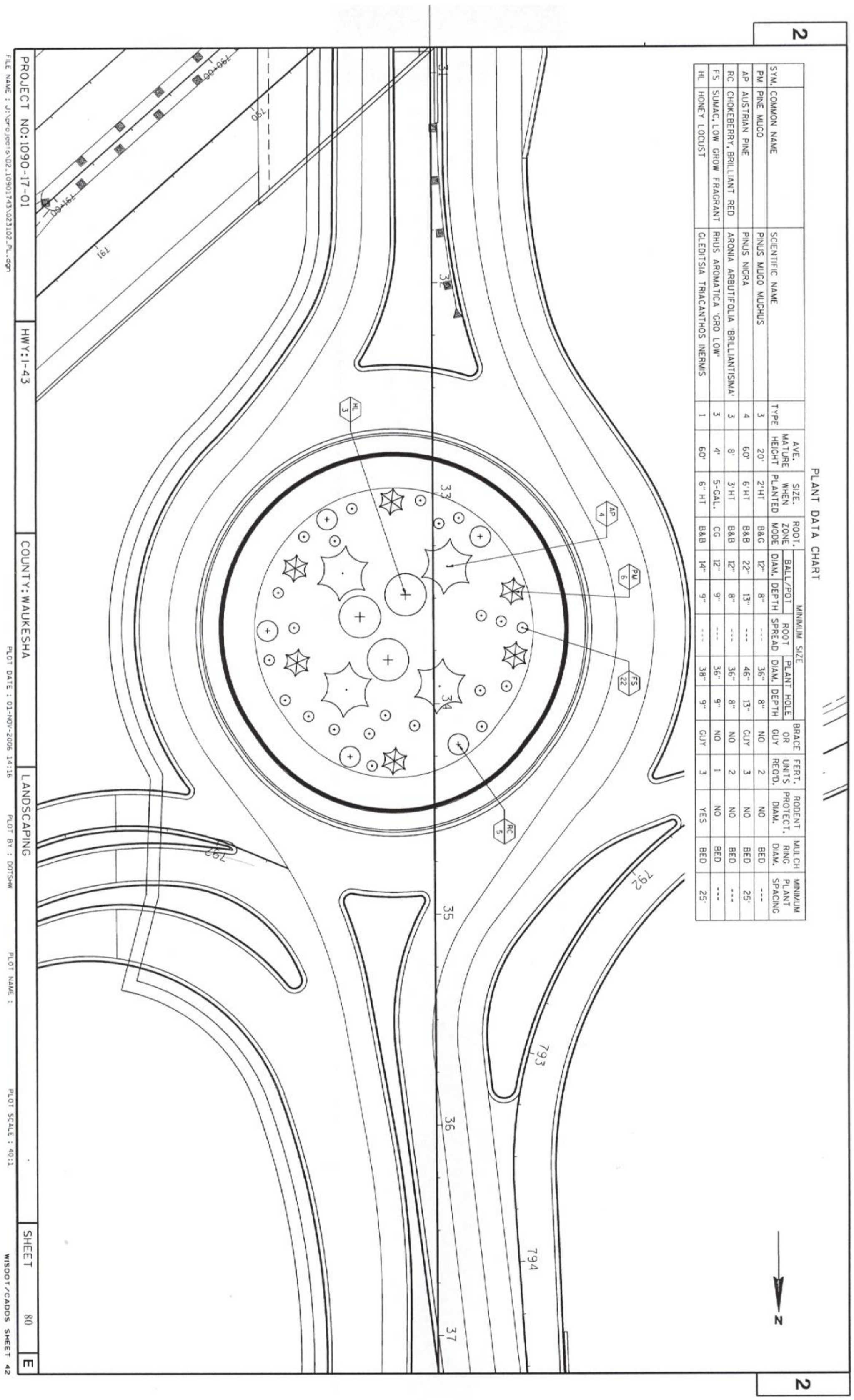


Figure A-8. Moorland North Roundabout Geometry

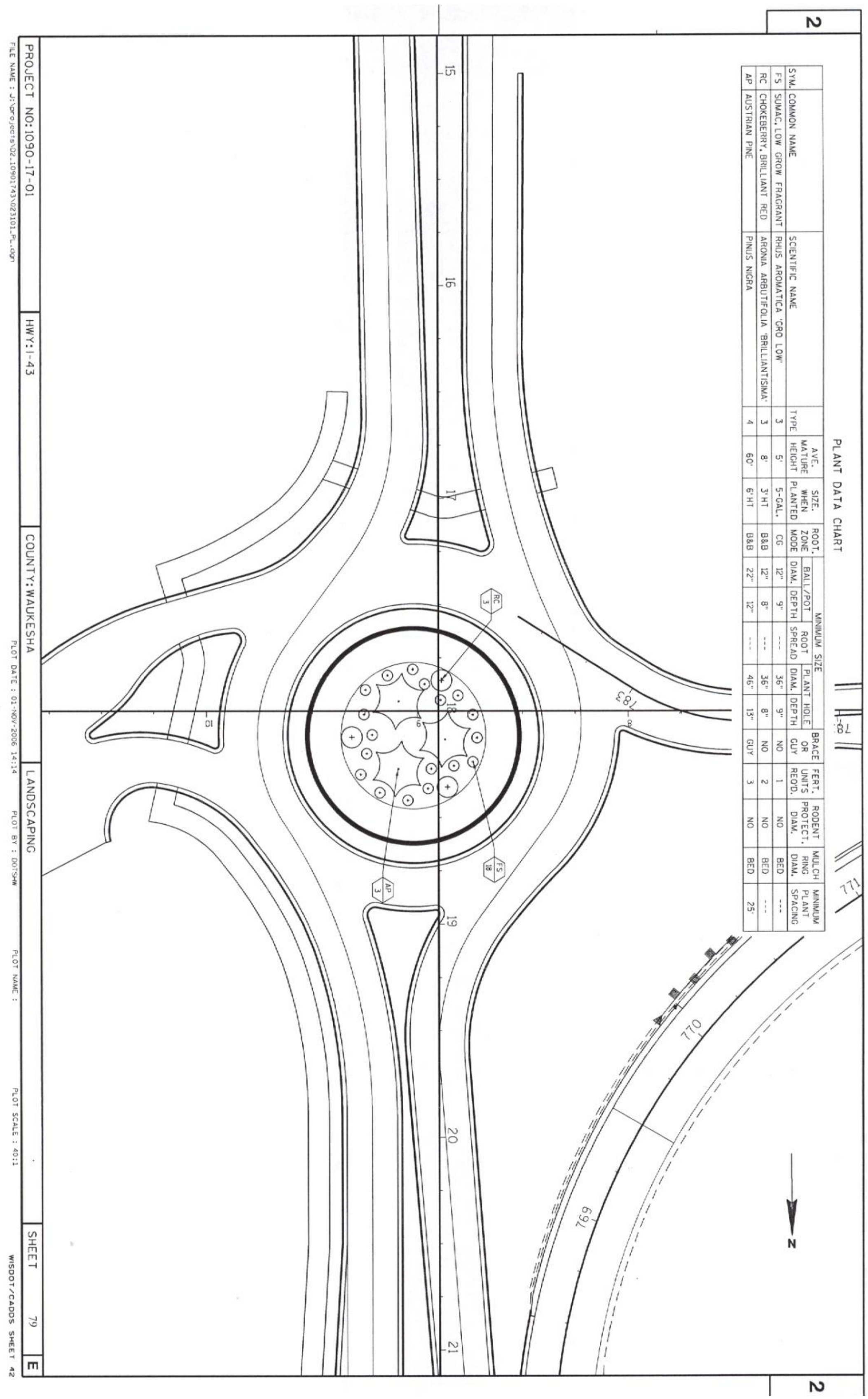


Figure A-9. Moorland South Roundabout Geometry

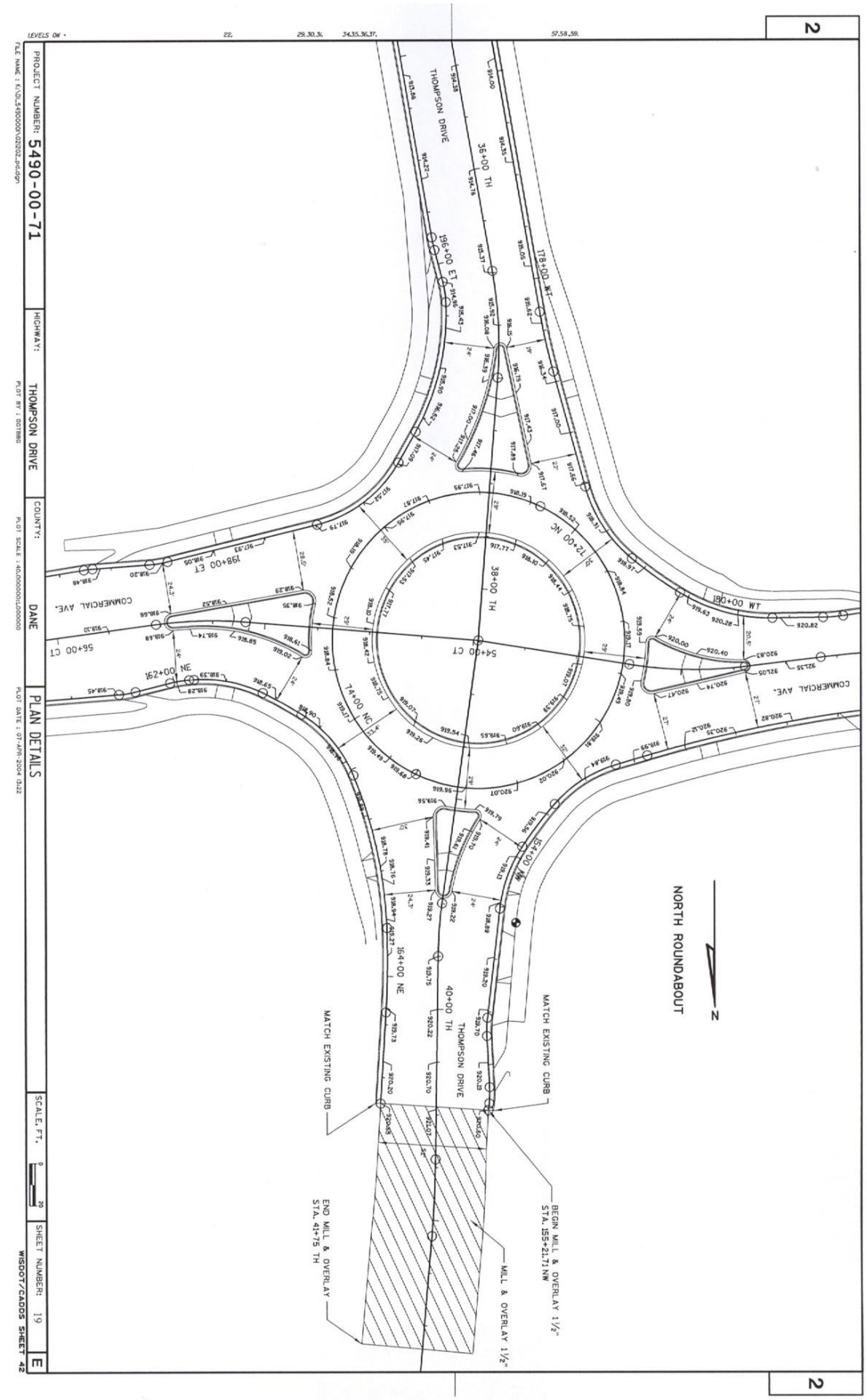


Figure A-10. Thompson North Roundabout Geometry

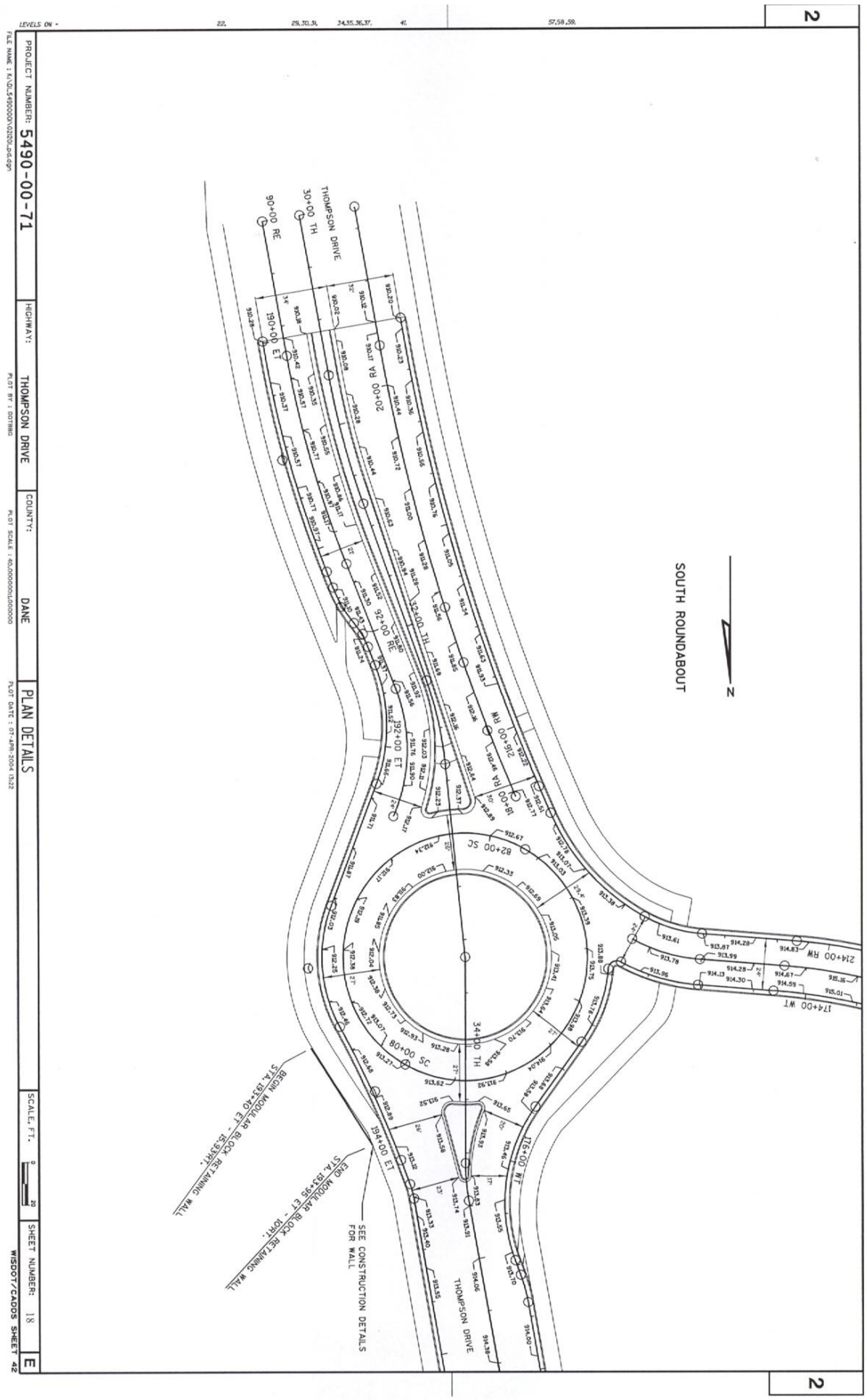


Figure A-11. Thompson South Roundabout Geometry

APPENDIX B – VIDEO SCREENSHOTS

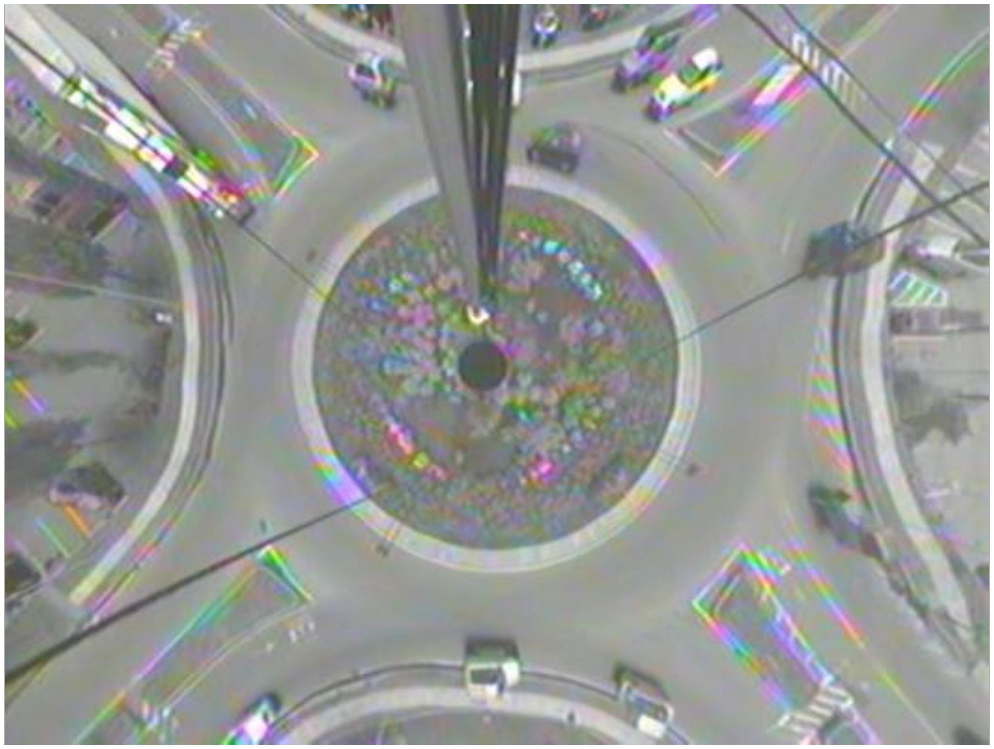


Figure B-1. Brattleboro Roundabout Screenshot

Figure B-2. Waterloo Roundabout Screenshot

Figure B-3. 32 & 57 Roundabout Screenshot

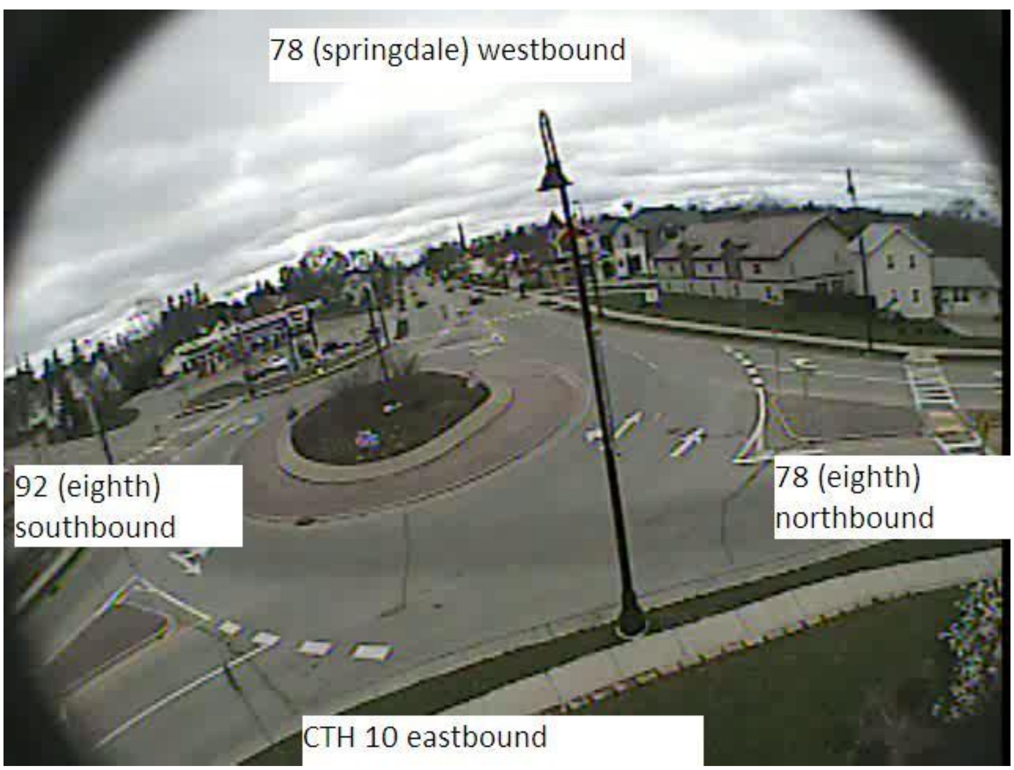


Figure B-4. 78 & 92 Roundabout Screenshot

Figure B-5. 42 & 43 Roundabout Screenshot

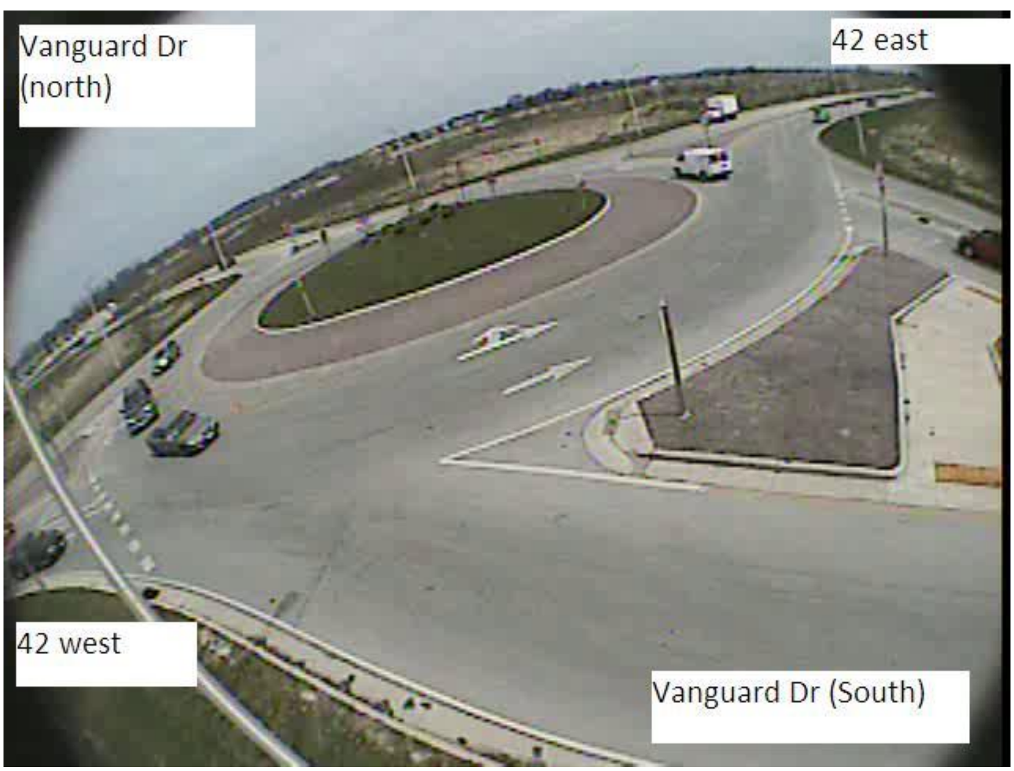


Figure B-6. Vanguard Roundabout Screenshot

Figure B-7. Bennett Roundabout Screenshot

Figure B-8. Moorland North Roundabout Screenshot

Figure B-9. Moorland South Roundabout Screenshot

Figure B-10. Thompson North Roundabout Screenshot

Figure B-11. Thompson South Roundabout Screenshot

APPENDIX C – GAP ACCEPTANCE DATA (32&57 Roundabout)

Table C-1. Gap Acceptance Data

Time Instance	Start Direction	Gap Length (sec)		Accepted/Rejected	Additional notes
And disc number	0-BL 1-BR 2-TR 3-TL	Cars	Trucks	0=reject 1=accept	Queue/Flow/Driver Characteristics
01-0100-08-48					
0m7s	0	8.8		1	
0m39s	0	4.2		0	
	0	7.5		1	
0m49s	0	3.4		1	
1m27s	0	2.3		0	
	0	1.1		0	
	0	0.8		0	
	0	2.2		0	
	0	4.2		0	
	0	5.5		1	
1m30s	0	5.5		1	
1m44s	0	11.1		1	
2m22s	0	0.9		0	
2m22s	0	0.9		0	
	0	7		1	
	0	7		1	
2m37s	0	4.7		1	
2m42s	0	1.6		0	
	0	2.4		0	
	0	2.9		0	
	0	2.7		0	
	0	1.6		0	
	0	23		1	
3m20s	0	4.3		1	
3m25s	0	17		1	
3m42s	0	2.9		0	
	0	1.6		0	
	0	5.8		1	
4m15s	0	9.5		1	
4m38s	0	0.8		0	
	0	1.6		0	
	0	2.3		1	
4m43s	0	2.5		0	
	0	4.6		1	
4m46s	0		4.4	0	

Table C-1. Gap Acceptance Data (continued)

Time Instance	Start Direction	Gap Length (sec)		Accepted/Rejected	Additional notes
And disc number	0-BL 1-BR 2-TR 3-TL	Cars	Trucks	0 reject 1 accept	Queue/Flow/Driver Characteristics
	0		0.6	0	
	0		14.8	1	
5m8s	0	7		0	
	0	7.5		1	
5m20s	0	3		0	
5m20s	0	3		1	
5m25s	0	3		1	
	0	1		0	
	0	2		0	
	0	1.2		0	
	0	0.8		0	
	0	0.7		0	
	0	1		0	
	0	2.4		0	
	0	0.3		0	
	0	2		0	
	0	0.9		0	
	0	2.3		0	
	0	3.5		0	
	0	1.2		0	
	0	1		0	
	0	3.2		0	
	0	6.9		1	
6m3s	0	5.8		1	
6m3s	0	5.8		1	
6m9s	0	5.8		1	
6m15s	0	4.3		0	
	0	1.1		0	
	0	3.6		1	
6m20s	0		0.8	0	
	0		3.6	0	
	0		9.9	1	Gap forcing
6m40s	0	7.1		1	
6m50s	0	1.8		0	
	0	0.9		0	
	0	1.2		0	
	0	2.4		0	
	0	0.7		0	

Table C-1. Gap Acceptance (continued)

Time Instance	Start Direction	Gap Length (sec)		Accepted/Rejected	Additional notes
And disc number	0-BL 1-BR 2-TR 3-TL	Cars	Trucks	0 reject 1 accept	Queue/Flow/Driver Characteristics
	0	2.6		0	
	0	4.8		1	
7m	0	1.9		0	
	0	4.5		1	
7m7s	0	0.9		0	
7m7s	0	0.9		0	
	0	1.3		0	
	0	1.3		0	
	0	1		0	
	0	1		0	
	0	1.6		0	
	0	1.6		0	
	0	11		1	
	0	11		1	
7m47s	0	1.2		0	
	0	6.8		1	
8m19s	0	3.5		1	
8m24s	0	1.7		0	
8m24s	0	1.7		0	
	0	6.3		1	
	0	6.3		1	
8m32s	0	10.8		1	
8m32s	0	6.2		0	
	0	6.5		1	
8m58s	0	3.4		0	
8m58s	0	3.4		0	
	0	4.1		1	
	0	4.1		1	
9m33s	0	1.7		0	
	0	3.9		0	
	0	3		1	
9m41s	0	4.2		0	
9m41s	0	4.2		0	
	0	4.2		1	
	0	4.2		0	
	0	3.9		0	
	0	1.8		0	
	0	2.6		1	

Table C-1. Gap Acceptance Data (continued)

Time Instance	Start Direction	Gap Length (sec)		Accepted/Rejected	Additional notes
And disc number	0-BL 1-BR 2-TR 3-TL	Cars	Trucks	0 reject 1 accept	Queue/Flow/Driver Characteristics
9m47s	0	7.2		1	
9m55s	0	1.6		0	
	0	3.1		0	
	0	2.8		1	
0m38s	3	36.6		1	
1m15s	3		30	1	
1m15s	3	30		1	
2m5s	3	3.7		0	
	3	15.3		1	
2m12s	3	12		1	
2m25s	3	5.2		1	
2m25s	3	5.2		1	
2m31s	3	29		1	
2m31s	3	29		1	
4m31s	3	12		1	
4m31s	3	12		1	
4m45s	3	71		1	
5m56s	3		6.5	1	
5m56s	3	6.5		1	
6m3s	3	3.9		1	
6m3s	3	3.9		0	
	3	22.2		1	
6m8s	3	22.2		1	
6m40s	3	33		1	
6m40s	3	33		1	
7m16s	3	3		0	
7m16s	3	3		0	
	3	24		1	
	3	24		1	
7m51s	3	3.3		1	
7m55s	3	4.3		1	
8m	3	12.2		1	
8m12s	3	6.9		1	
8m12s	3	6.9		1	
8m19s	3	26		1	
8m19s	3	26		1	
1m	2	28		1	
1m27s	2	1.3		0	

Table C-1. Gap Acceptance Data (continued)

Time Instance	Start Direction	Gap Length (sec)		Accepted/Rejected	Additional notes
And disc number	0-BL 1-BR 2-TR 3-TL	Cars	Trucks	0 reject 1 accept	Queue/Flow/Driver Characteristics
	2	1.3		0	
	2	2.5		0	
	2	0.3		0	
	2	1.7		0	
	2	8.9		1	
1m34s	2	0.3		0	
	2	1.7		0	
	2	8.9		1	
1m50s	2	4		1	
1m54s	2	3.1		0	
	2	34		1	
2m43s	2	1.3		0	
	2	2		0	
	2	7		1	Rolling entrance
3m7s	2	2.3		0	
	2	1		0	
	2	0.9		0	
	2	1.6		0	
	2	1.5		0	
	2	9.1		1	
4m5s	2		1.6	0	
	2		2.6	0	
	2		1.1	0	
	2		3.9	0	
	2		0.6	0	
	2		3.7	0	
	2		4.3	0	
	2		8	1	
4m32s	2	3.7		0	
	2	8.6		1	
4m45s	2	7.7		1	
4m53s	2	2.3		0	
	2	4.2		0	
	2	3.4		1	
5m2s	2	2.9		0	
	2	1.4		0	
	2	1		0	
	2	8.2		1	

Table C-1. Gap Acceptance Data (continued)

Time Instance	Start Direction	Gap Length (sec)		Accepted/Rejected	Additional notes
And disc number	0-BL 1-BR 2-TR 3-TL	Cars	Trucks	0 reject 1 accept	Queue/Flow/Driver Characteristics
5m22s	2	11.9		1	
5m35s	2	17.3		1	
5m52s	2	0.7		0	
	2	1.9		0	
	2	10.2		1	
6m45s	2	3.4		0	
	2	1.1		0	
	2	3.5		1	
6m58s	2		3.2	0	
	2		4.2	0	
	2		12.3	1	
6m58s	2	3.2		0	
	2	4.2		0	
	2	12.3		1	
7m18s	2	3.5		0	
	2	1.9		0	
	2	1.5		0	
	2	2.4		0	
	2	1		0	
	2	1		0	
	2	1.4		0	
	2	0.4		0	
	2	1.4		0	
	2	0.6		0	
	2	1.2		0	
	2	0.3		0	
	2	2		0	
	2	1		0	
	2	4.9		1	
7m23s	2	1.5		0	
	2	2.4		0	
	2	1		0	
	2	1		0	
	2	1.4		0	
	2	0.4		0	
	2	1.4		0	
	2	0.6		0	
	2	1.2		0	

Table C-1. Gap Acceptance Data (continued)

Time Instance	Start Direction	Gap Length (sec)		Accepted/Rejected	Additional notes
And disc number	0-BL 1-BR 2-TR 3-TL	Cars	Trucks	0 reject 1 accept	Queue/Flow/Driver Characteristics
	2	0.3		0	
	2	2		0	
	2	1		0	
	2	4.9		1	
7m57s	2	1.9		0	
	2	2.4		0	
	2	1.5		0	
	2	1.6		0	
	2	4		1	
8m10s	2	2		0	
	2	3.7		1	
8m31s	2	4.4		0	
	2	1.8		0	
	2	3.7		1	
8m49s	2	1.6		0	
	2	2.4		0	
	2	8.8		1	
8m54s	2	8.8		1	
9m31s	2	2.3		0	
	2	12.6		1	
10m37s	1	1.8		0	
	1	3.9		1	
17m18s	2		2.3	0	
	2		1.9	0	
	2		4	0	
	2		3.1	0	
	2		1.6	0	
	2		6.2	1	Gap forcing
17m42s	2		12	1	
25m14s	0		3.8	0	
	0		9	1	
27m06s	0		5.3	0	
	0		9.7	1	
30m46s	0		0.7	0	
	0		3.3	0	
	0		2.5	0	
	0		2	0	
	0		1.8	0	

Table C-1. Gap Acceptance Data (continued)

Time Instance	Start Direction	Gap Length (sec)		Accepted/Rejected	Additional notes
And disc number	0-BL 1-BR 2-TR 3-TL	Cars	Trucks	0 reject 1 accept	Queue/Flow/Driver Characteristics
	0		6.6	1	Gap forcing
31m3s	2		1.5	0	
	2		2	0	
	2		1.4	0	
	2		1.6	0	
	2		5.1	0	
	2		11.2	1	
36m02s	3		36	1	
43m33s	3		2.4	0	
	3		1.2	0	
	3		54	1	
54m45s	2		1.3	0	
	2		1.7	0	
	2		1.4	0	
	2		1	0	
	2		4	0	
	2		4.1	0	
	2		6.2	1	
56m17s	0		4.1	0	
	0		7.1	1	Gap forcing
01-01-01-08-52					
5m45s	3		4.8	0	
	3		23	1	
11m6s	0		10.2	1	
11m13s	1		1.6	0	
	1		2.5	0	
	1		2.1	0	
	1		2.1	0	
	1		2	0	
	1		1.8	0	
	1		1.4	0	
	1		1.6	0	
	1		1	0	
	1		4.4	1	
16m14s	2		4.3	0	
	2		3.9	0	
	2		3.3	0	
	2		3.7	0	

Table C-1. Gap Acceptance Data (continued)

Time Instance	Start Direction	Gap Length (sec)		Accepted/Rejected	Additional notes
And disc number	0-BL 1-BR 2-TR 3-TL	Cars	Trucks	0 reject 1 accept	Queue/Flow/Driver Characteristics
	2		3.9	0	
	2		2.5	0	
	2		0.7	0	
	2		1.4	0	
	2		3.1	0	
	2		12.6	1	Gap forced
16m48s	1		1.8	0	
	1		1.4	0	
	1		1.5	0	
	1		0.8	0	
	1		2.2	0	
	1		0.7	0	
	1		5.8	1	
17m10s	0		2.9	0	
	0		0.4	0	
	0		0.9	0	
	0		4	0	
	0		8.2	1	Gap forced; multiple exiting vehicles
18m9s	2		0.8	0	
	2		3.9	0	
	2		4.2	0	
	2		7.7	1	
22m18s	0		13.8	1	
26m26s	3		4.1	0	
	3		35	1	

Exit Conditions	
Δcars	Δtrucks
2.3	3

Minimum Headway
0.3

APPENDIX D – ROUNDABOUT HEADWAY DISTRIBUTIONS

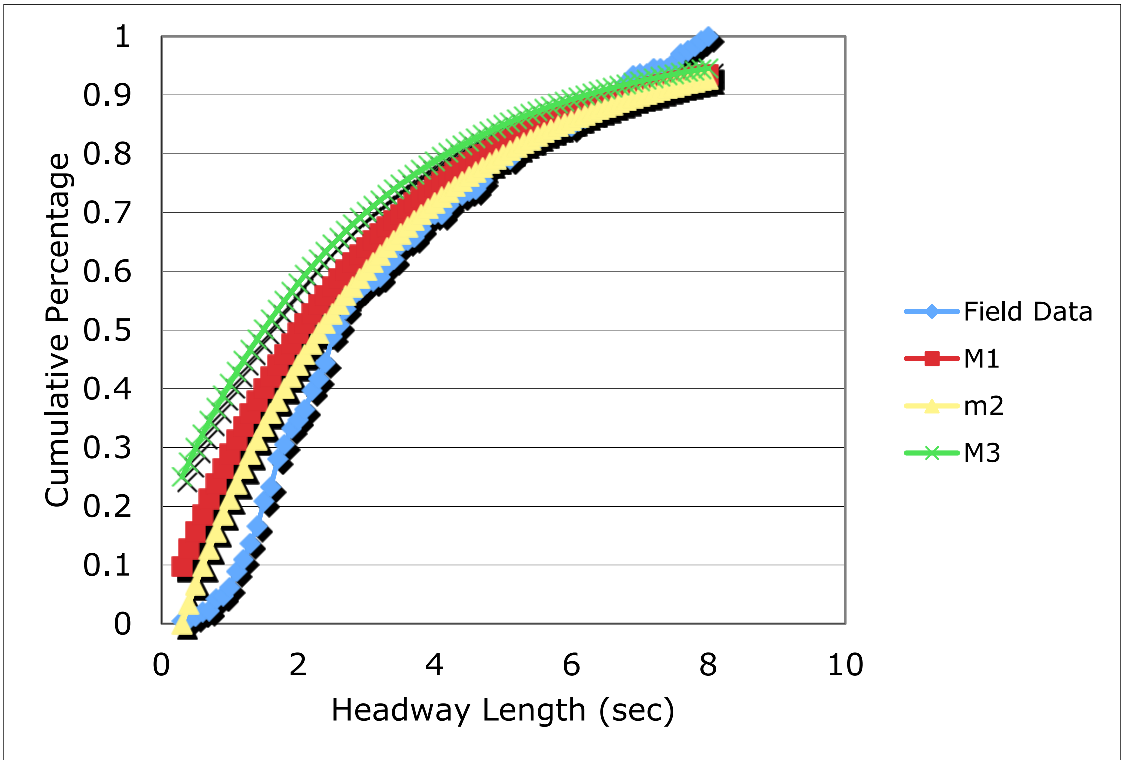


Figure D-1. Headway Distribution for Brattleboro Roundabout

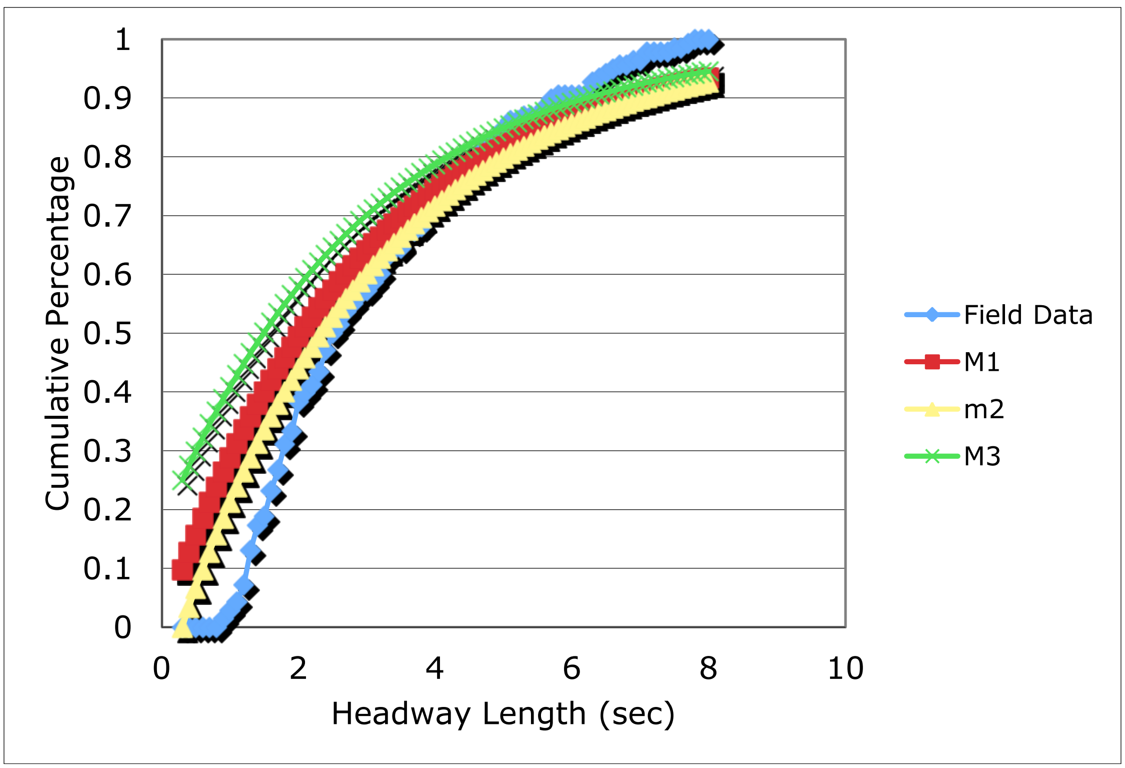


Figure D-2. Headway Distribution for Waterloo Roundabout

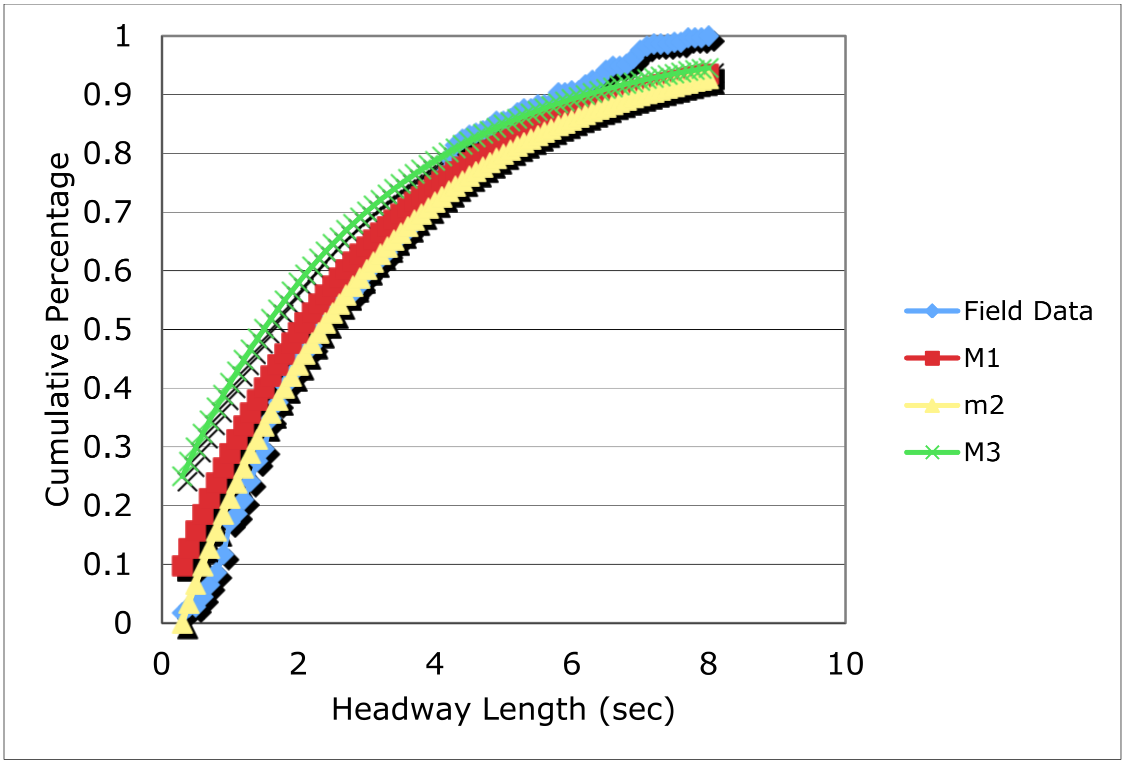


Figure D-3. Headway Distribution for 32&57 Roundabout

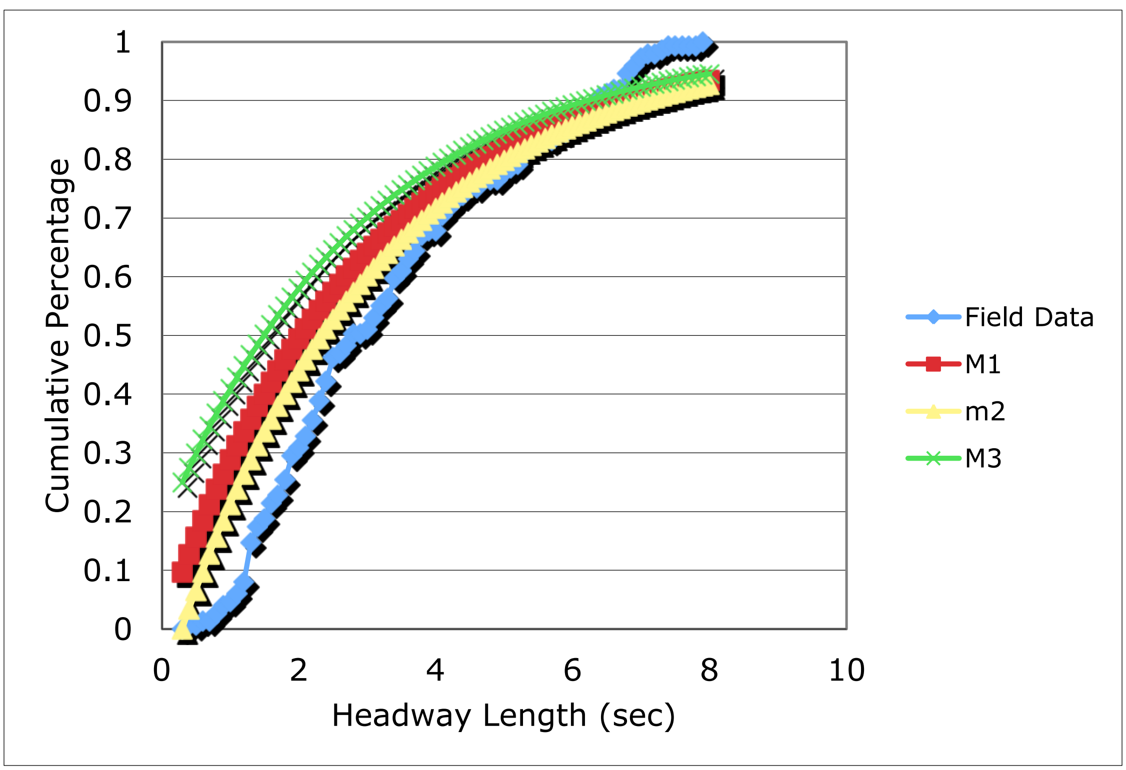


Figure D-4. Headway Distribution for 78 & 92 Roundabout

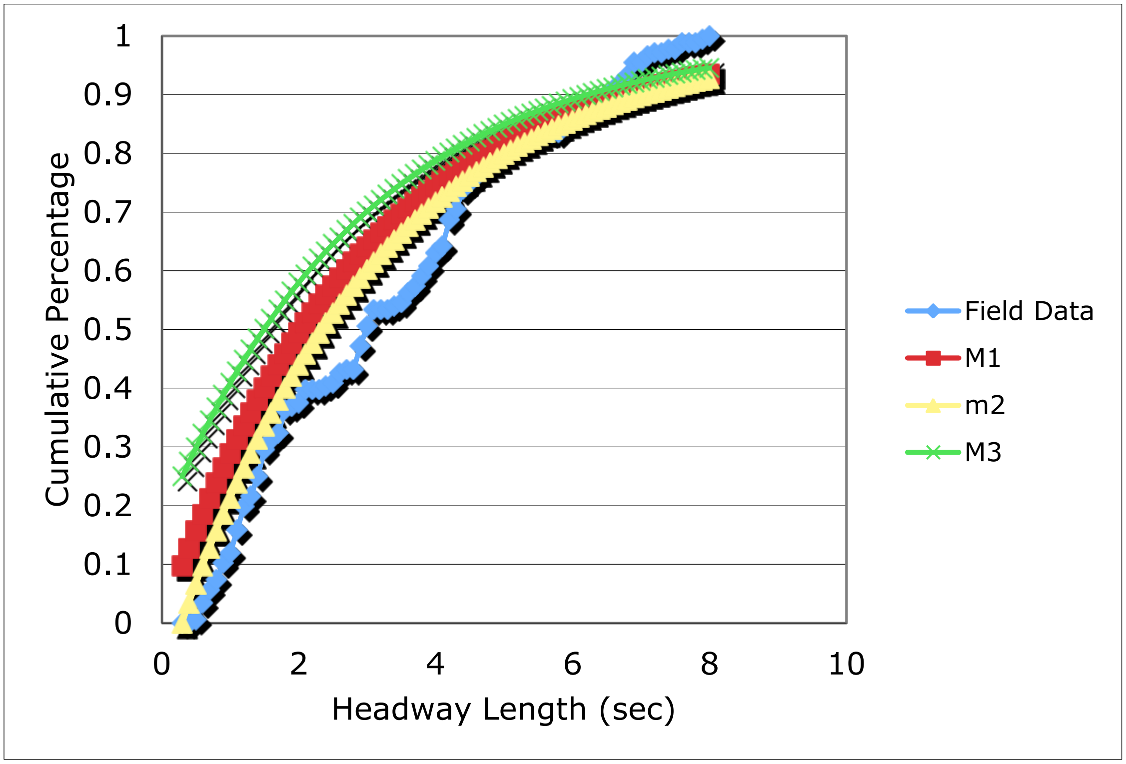


Figure D-5. Headway Distribution for 42 & 43 Roundabout

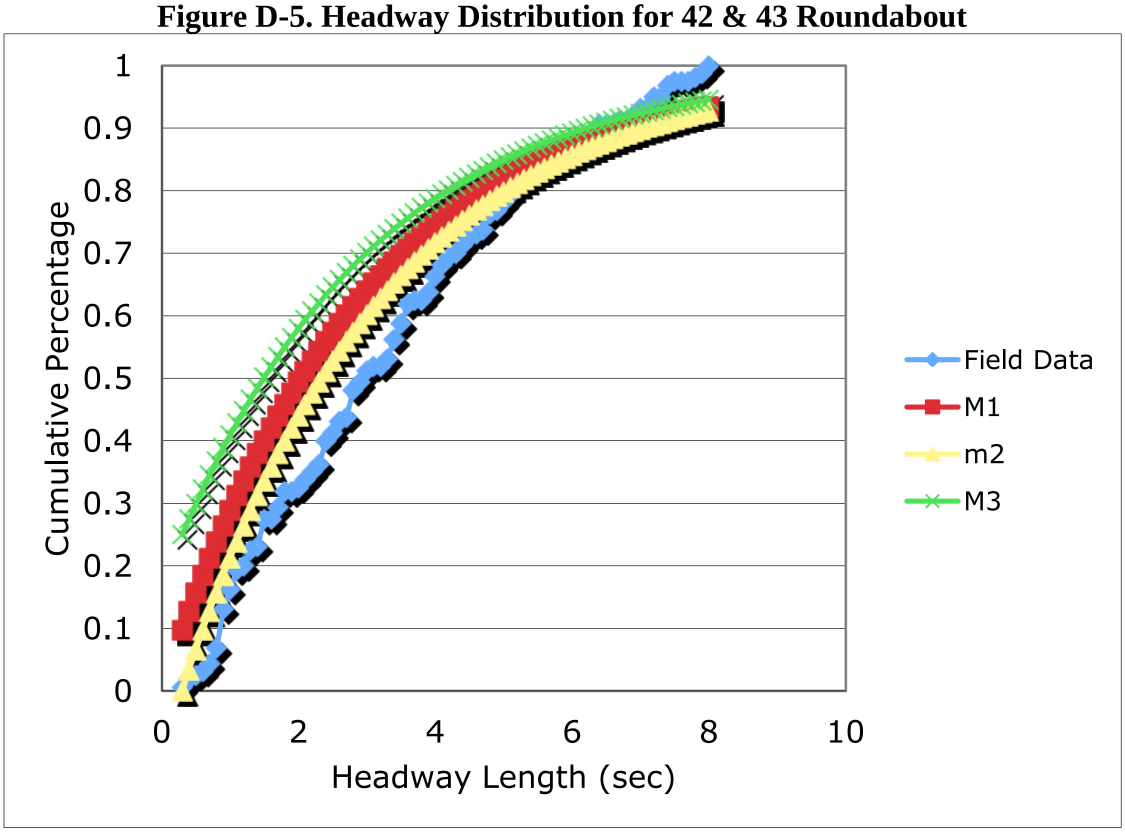


Figure D-6. Headway Distribution for Vanguard Roundabout

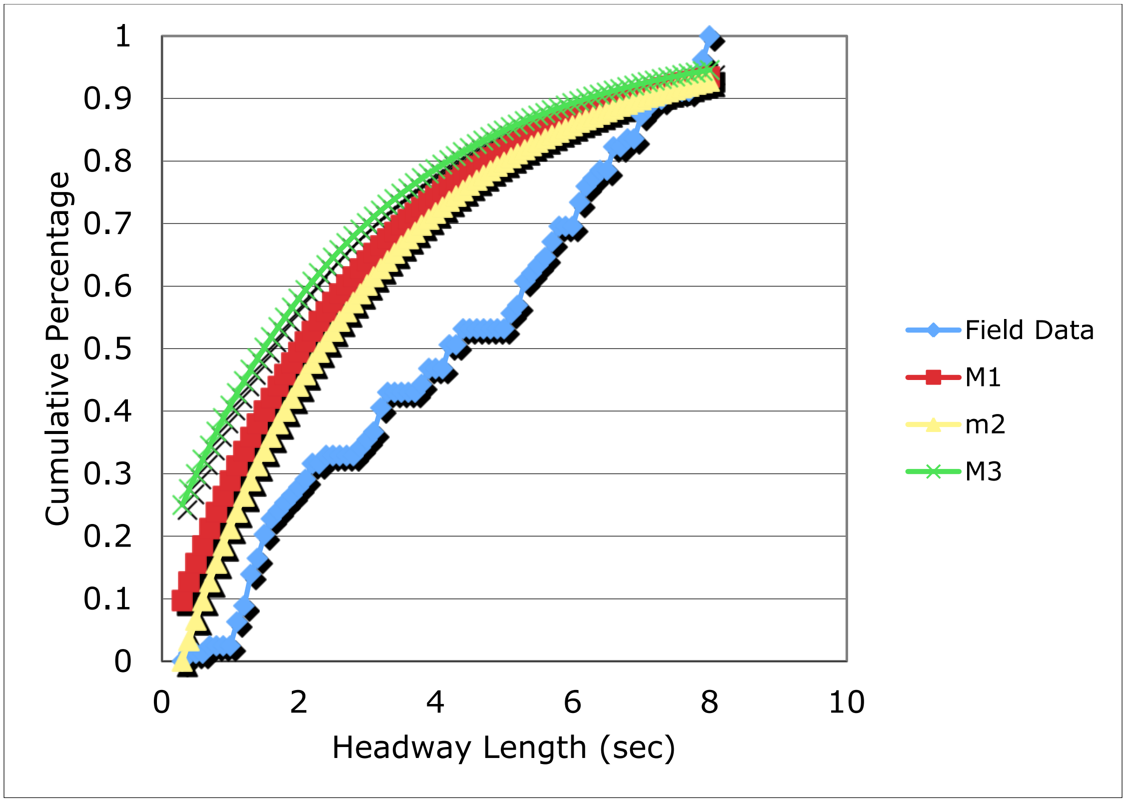


Figure D-7. Headway Distribution for Bennett Roundabout

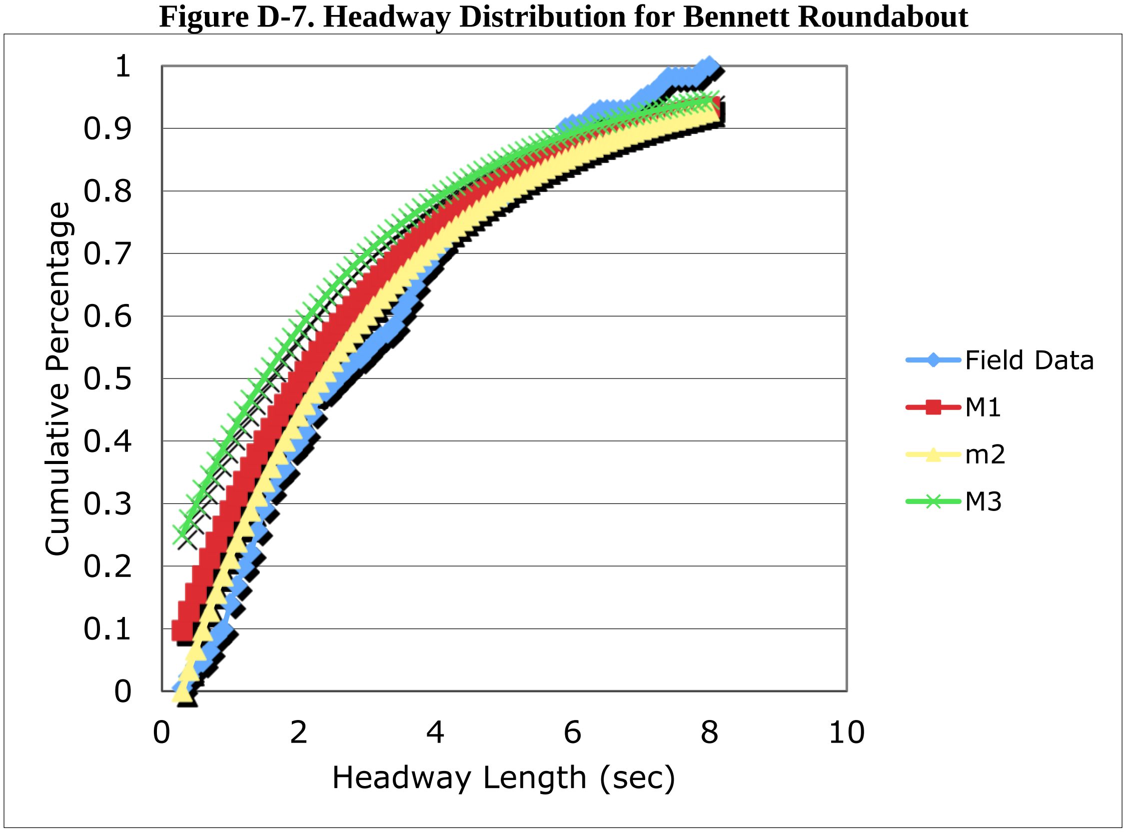


Figure D-8. Headway Distribution for Moorland North Roundabout

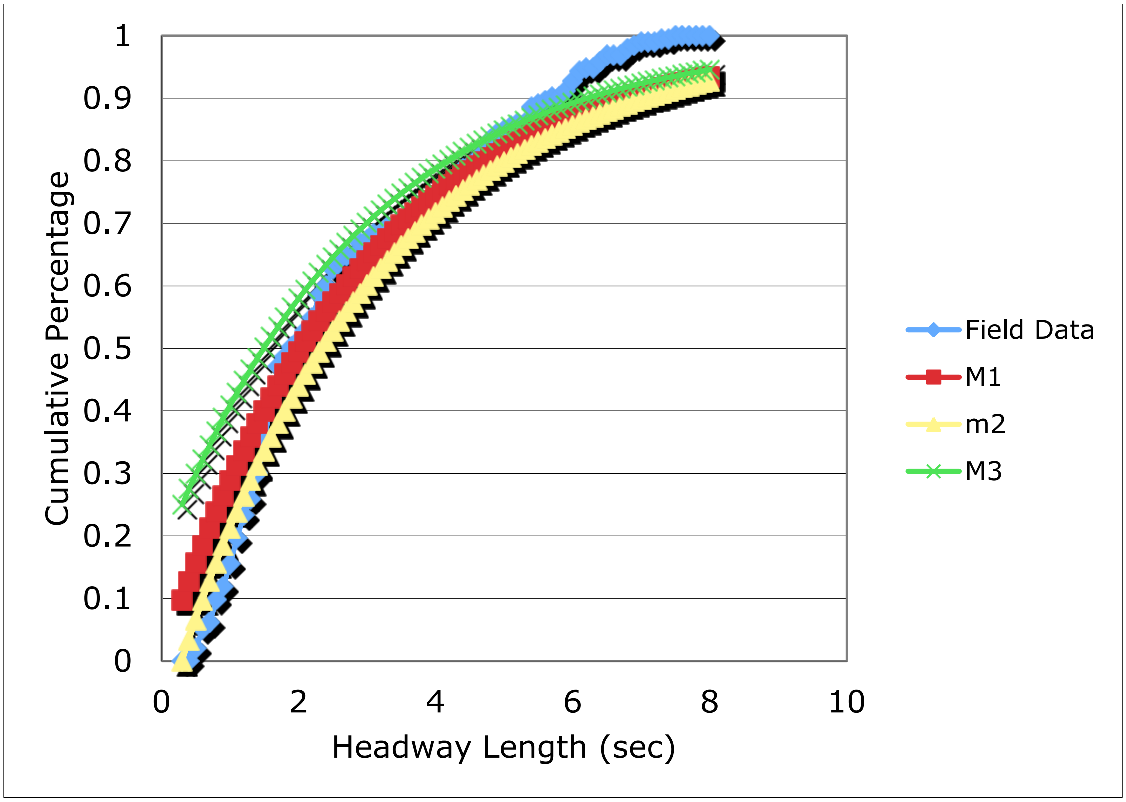


Figure D-9. Headway Distribution for Moorland South Roundabout

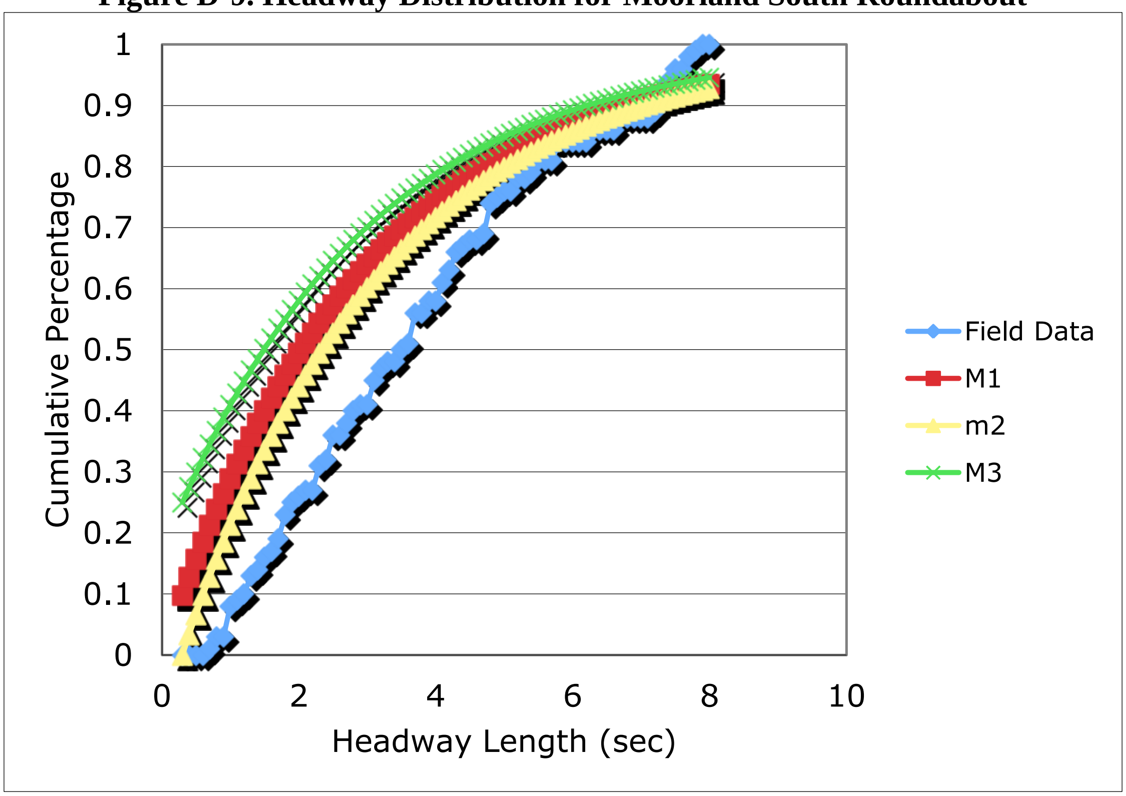


Figure D-10. Headway Distribution for Thompson North Roundabout

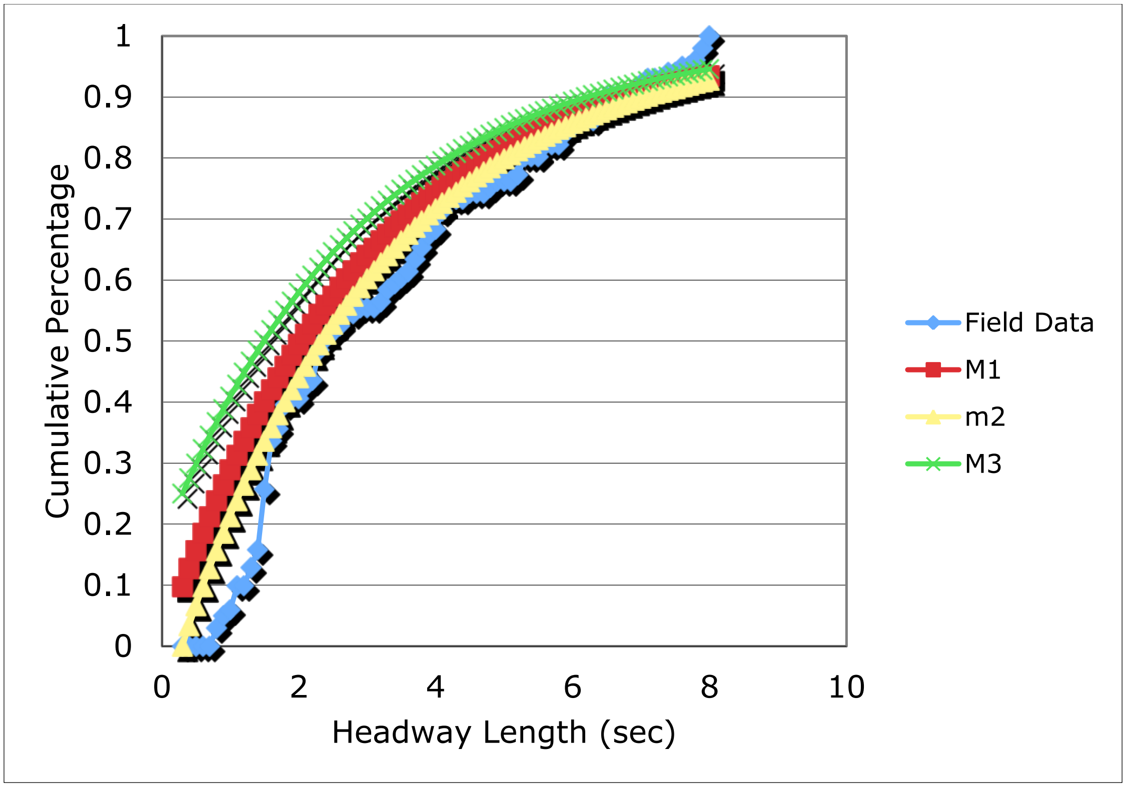


Figure D-11. Headway Distribution for Thompson South Roundabout

APPENDIX E – CRITICAL HEADWAY GRAPHICAL METHOD

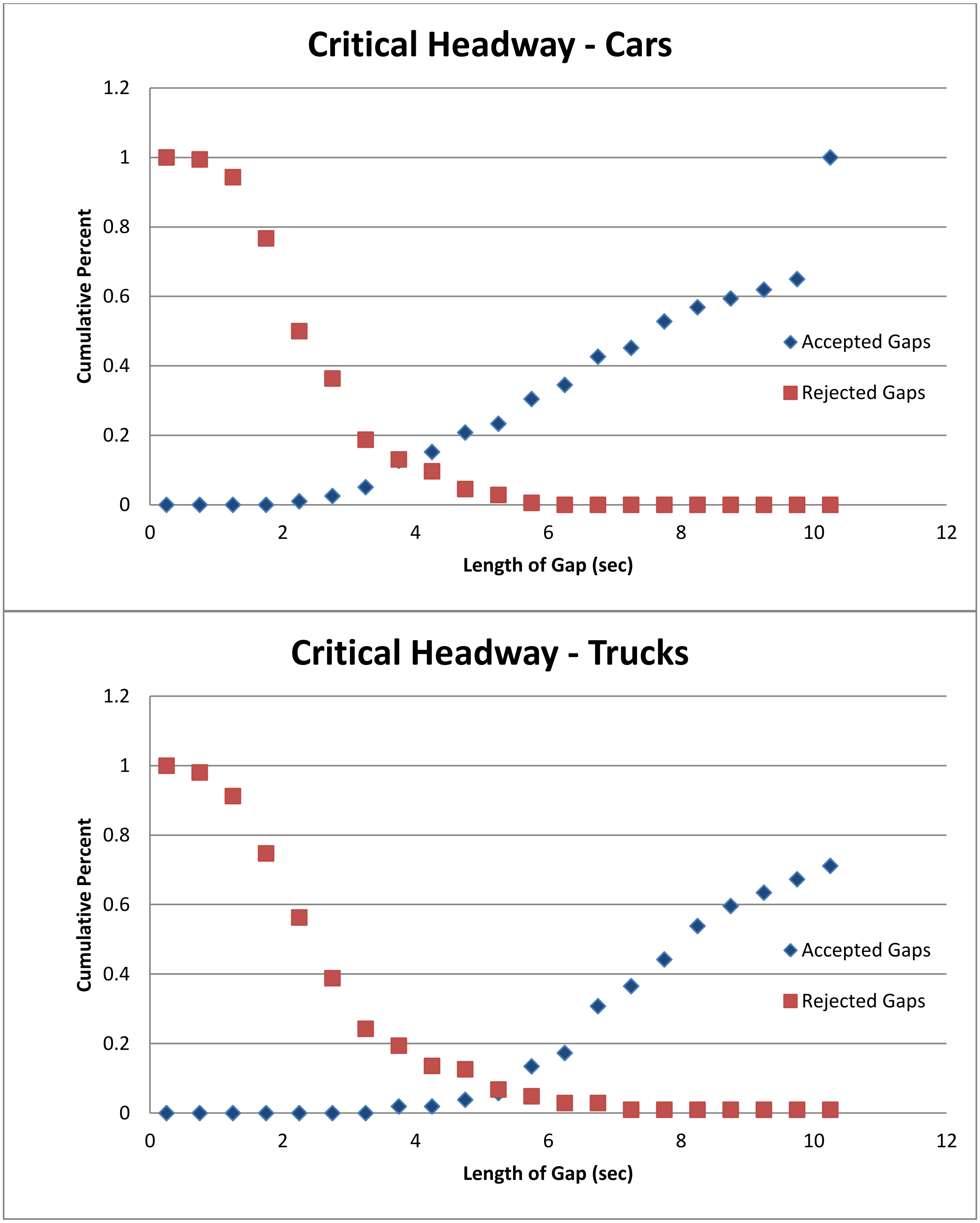


Figure E-1. Critical Headways for Brattleboro Roundabout

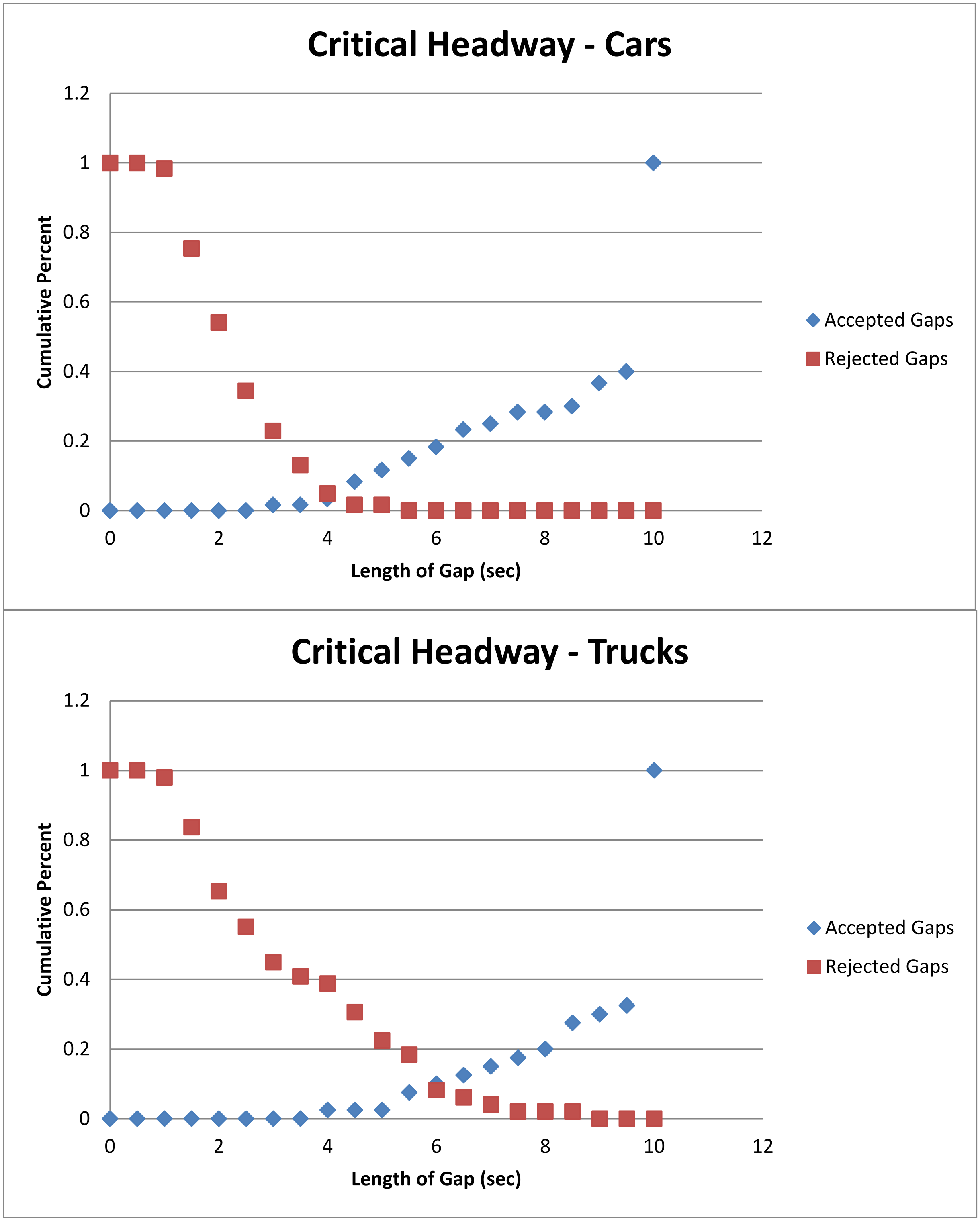
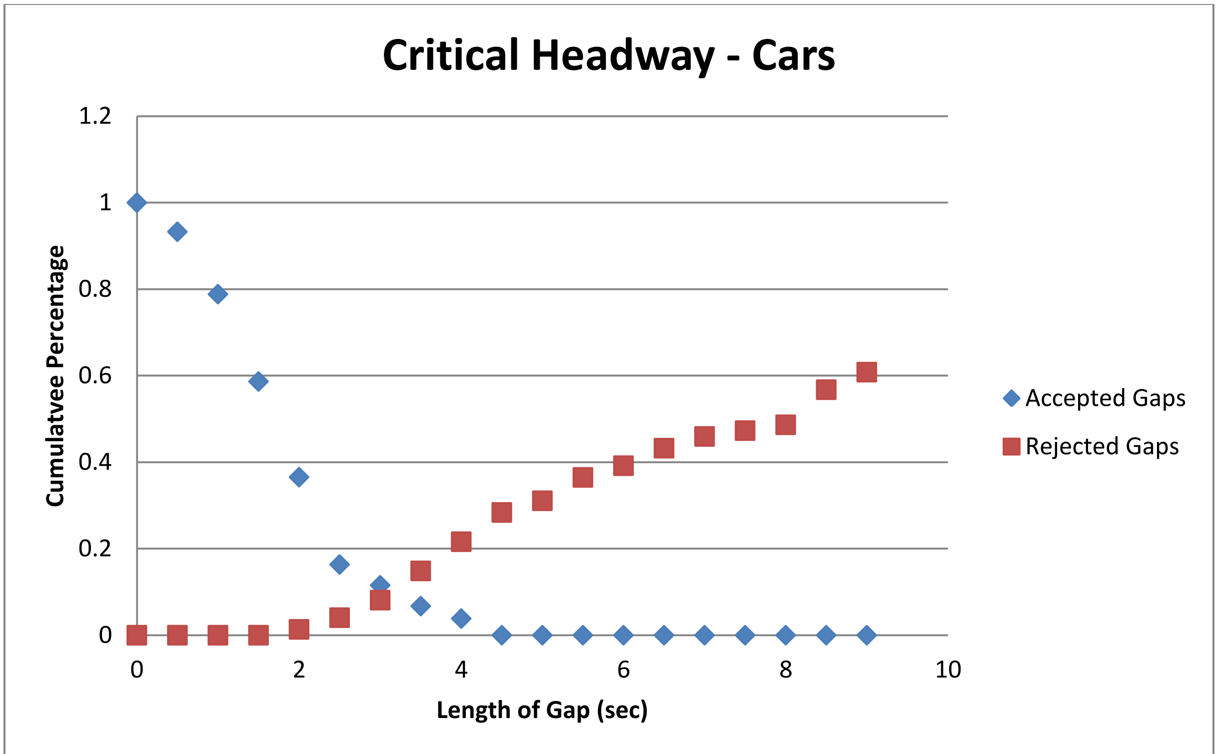


Figure E-2. Critical Headways for Waterloo Roundabout



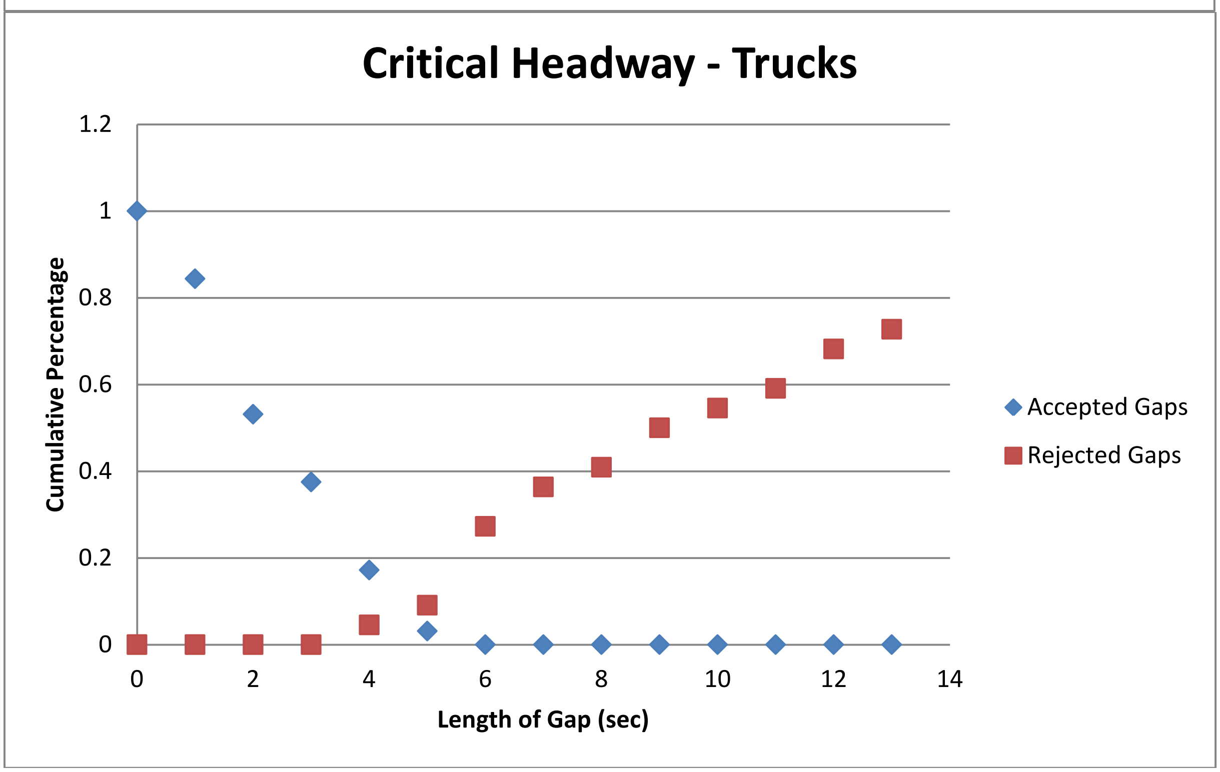


Figure E-3. Critical Headways for 32 & 57 Roundabout

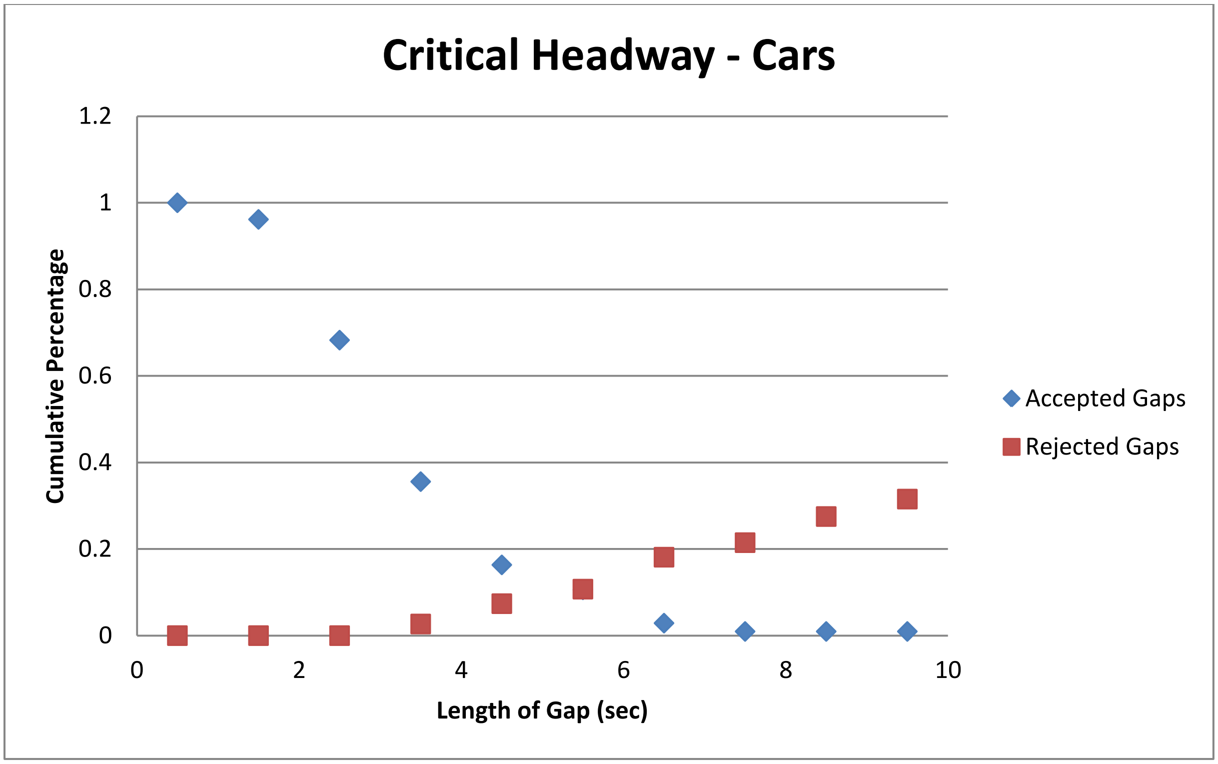
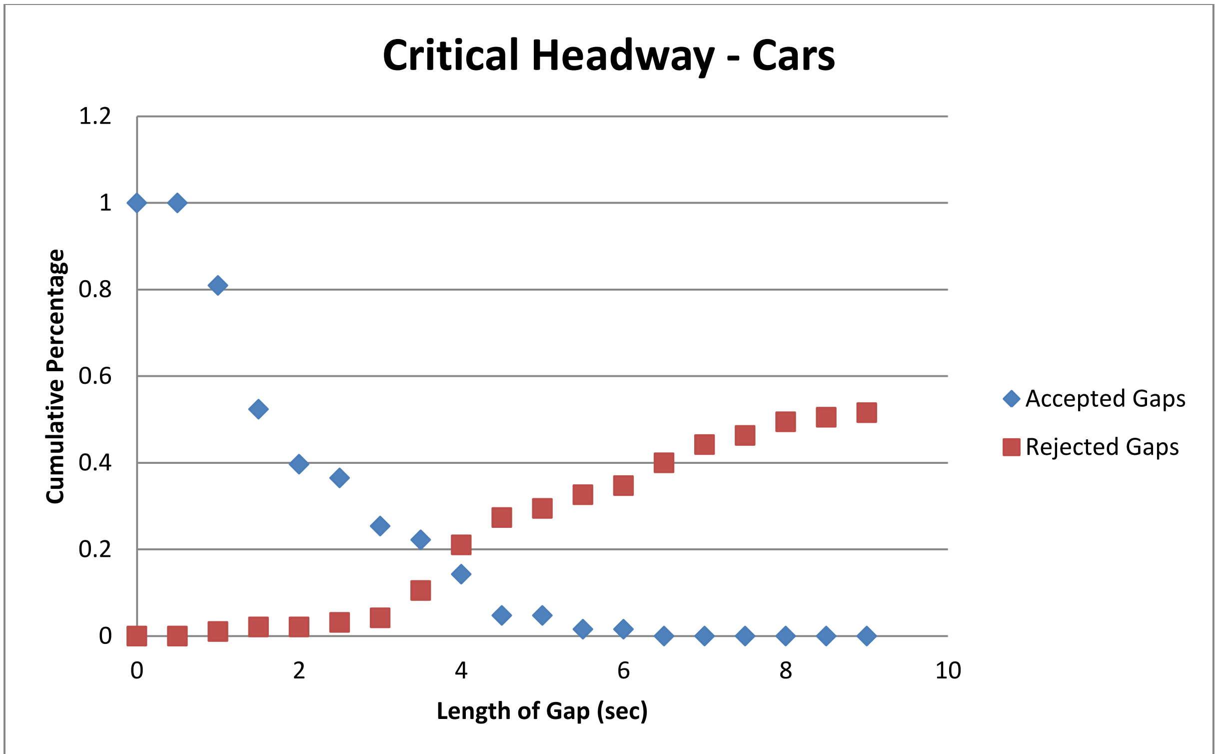


Figure E-4. Critical Headway (Cars) for 78 & 92 Roundabout

There was an insufficient amount of data points to determine the critical headways for trucks for the 78&92 (above), Thompson North (Figure F-10) and Thompson South (Figure F-11) roundabouts.



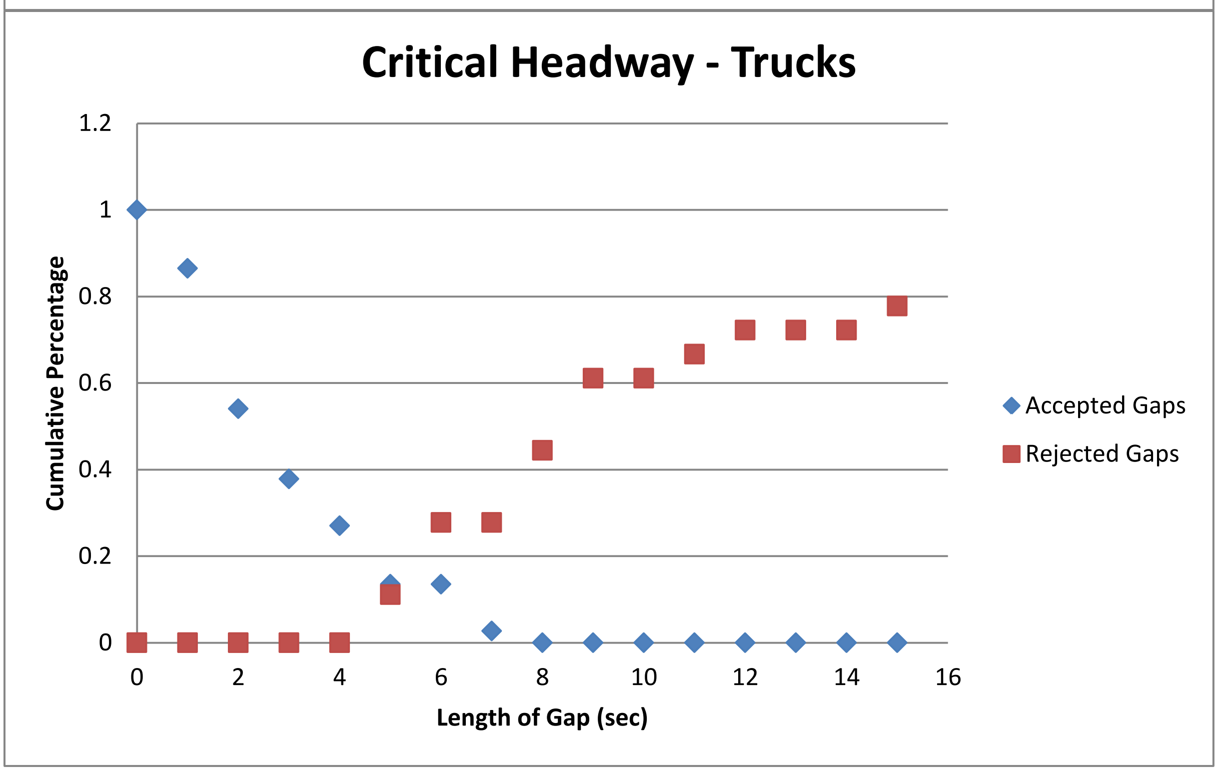


Figure E-5. Critical Headways for 42 & 43 Roundabout

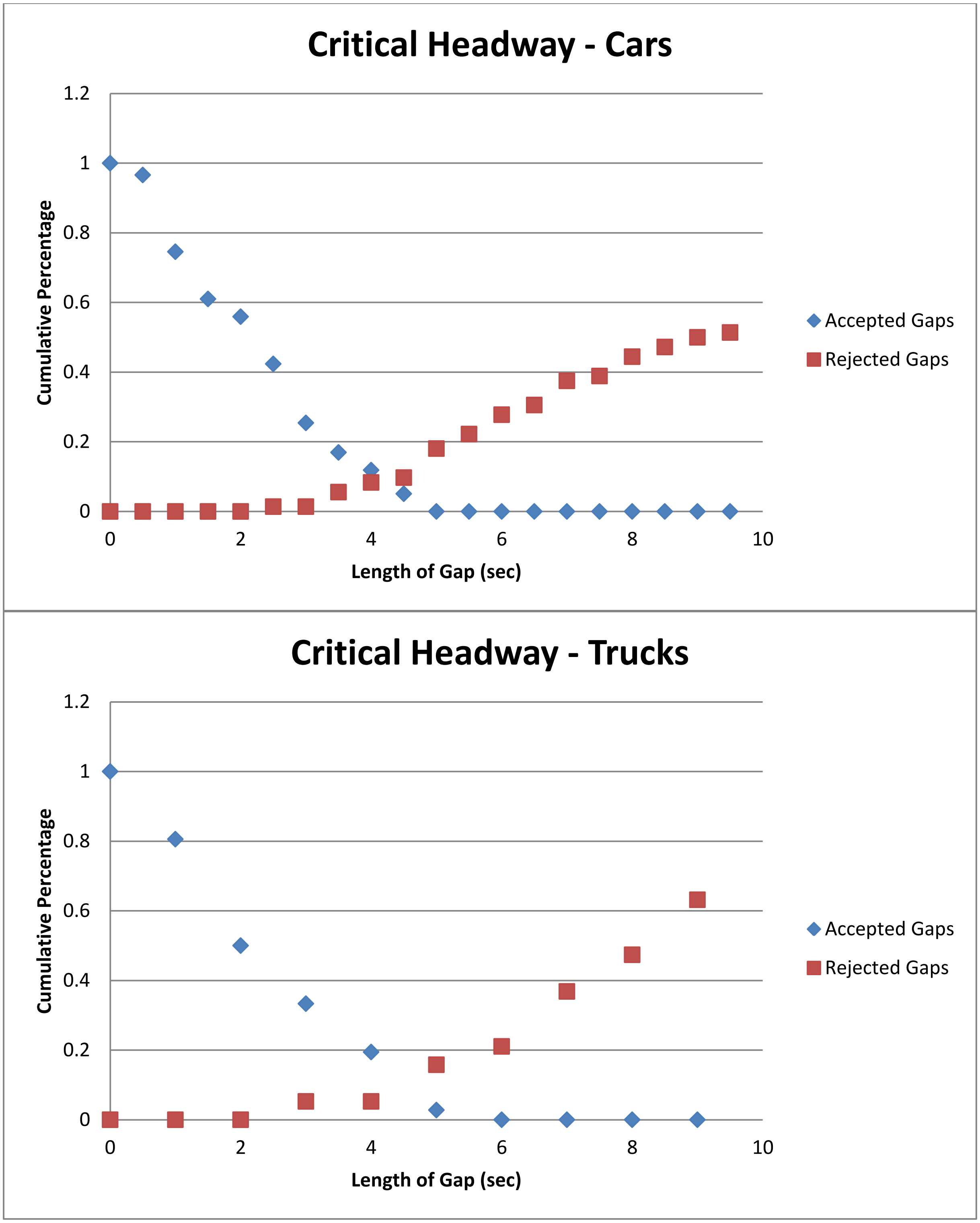


Figure E-6. Critical Headways for Vanguard Roundabout

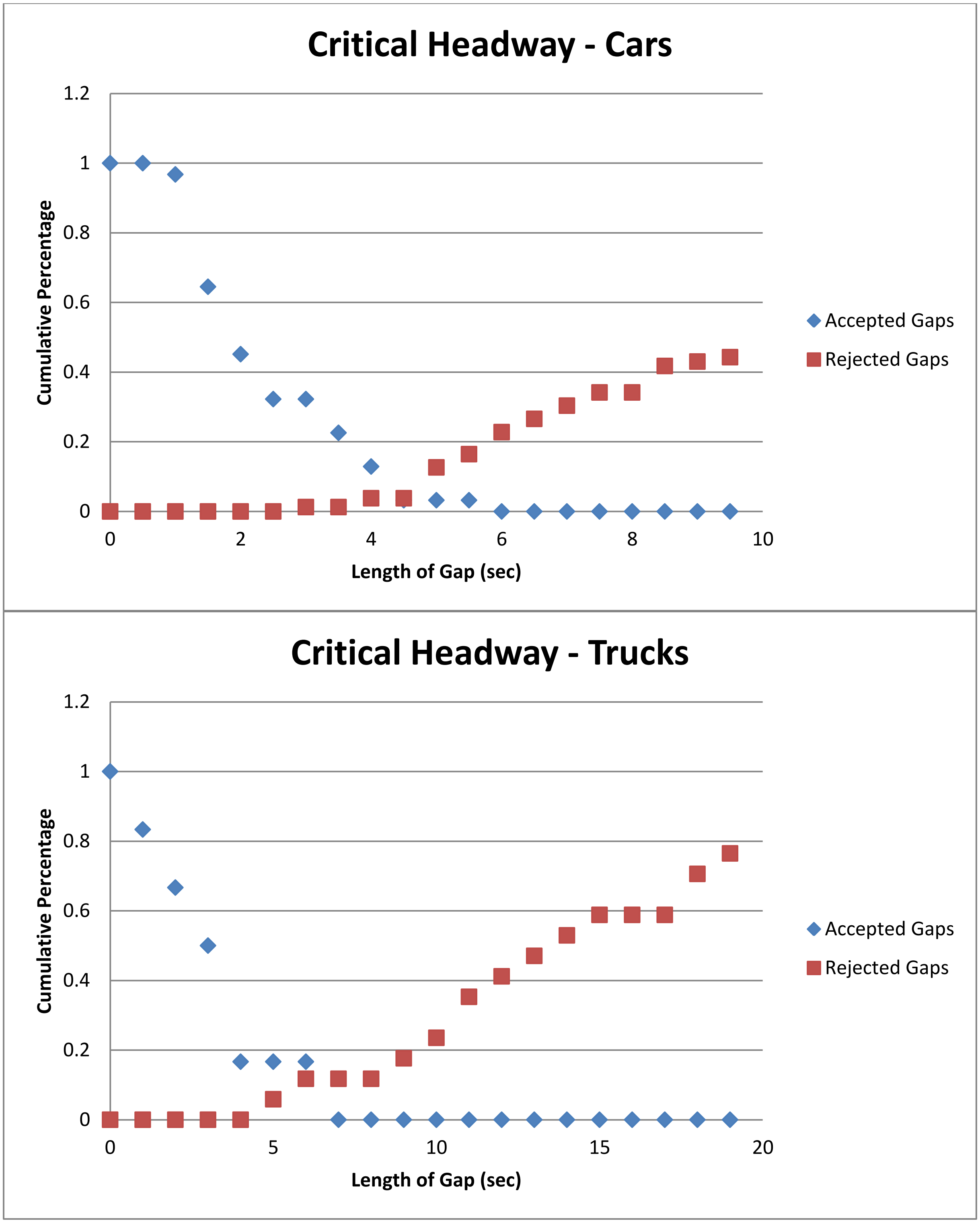
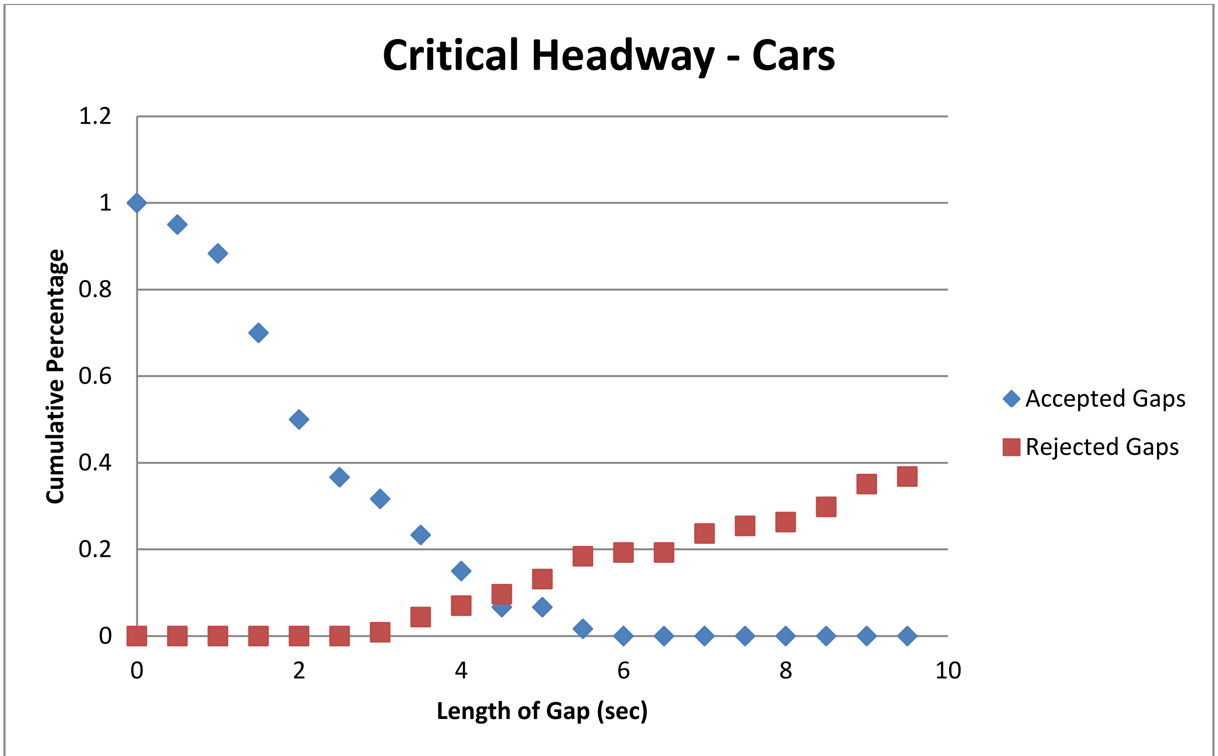


Figure E-7. Critical Headways for Bennett Roundabout



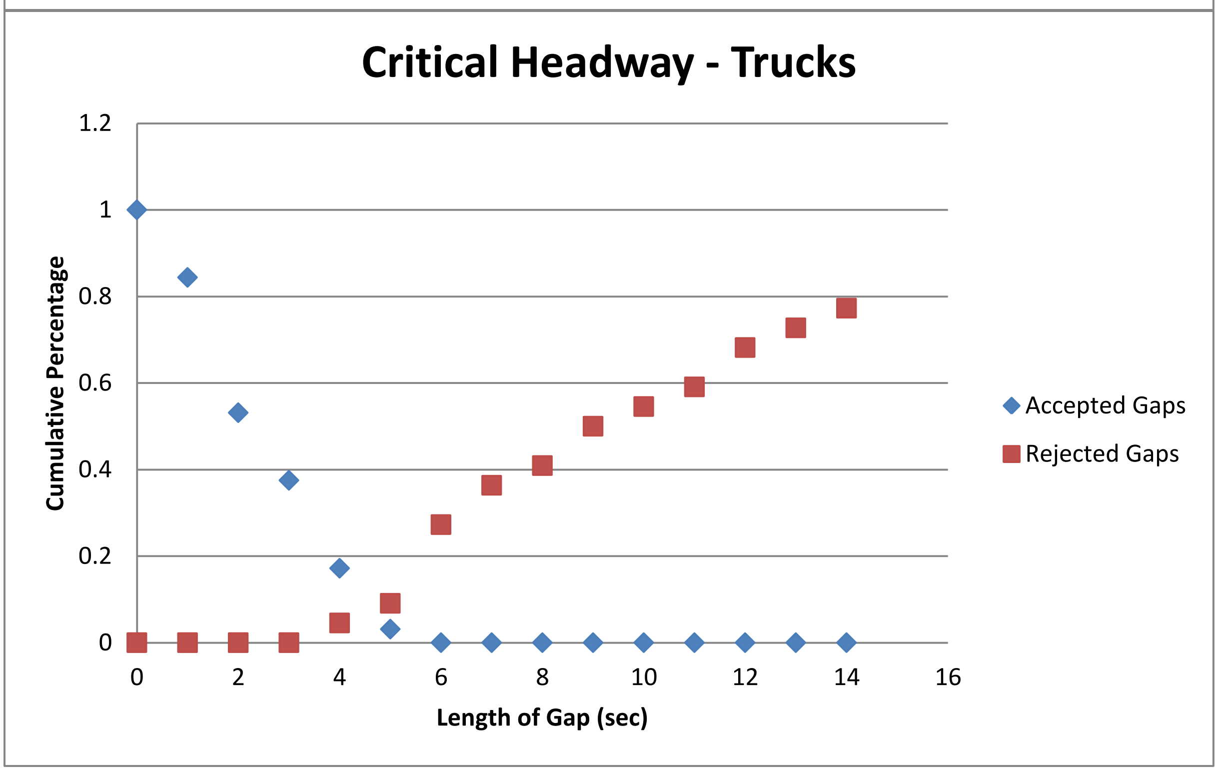
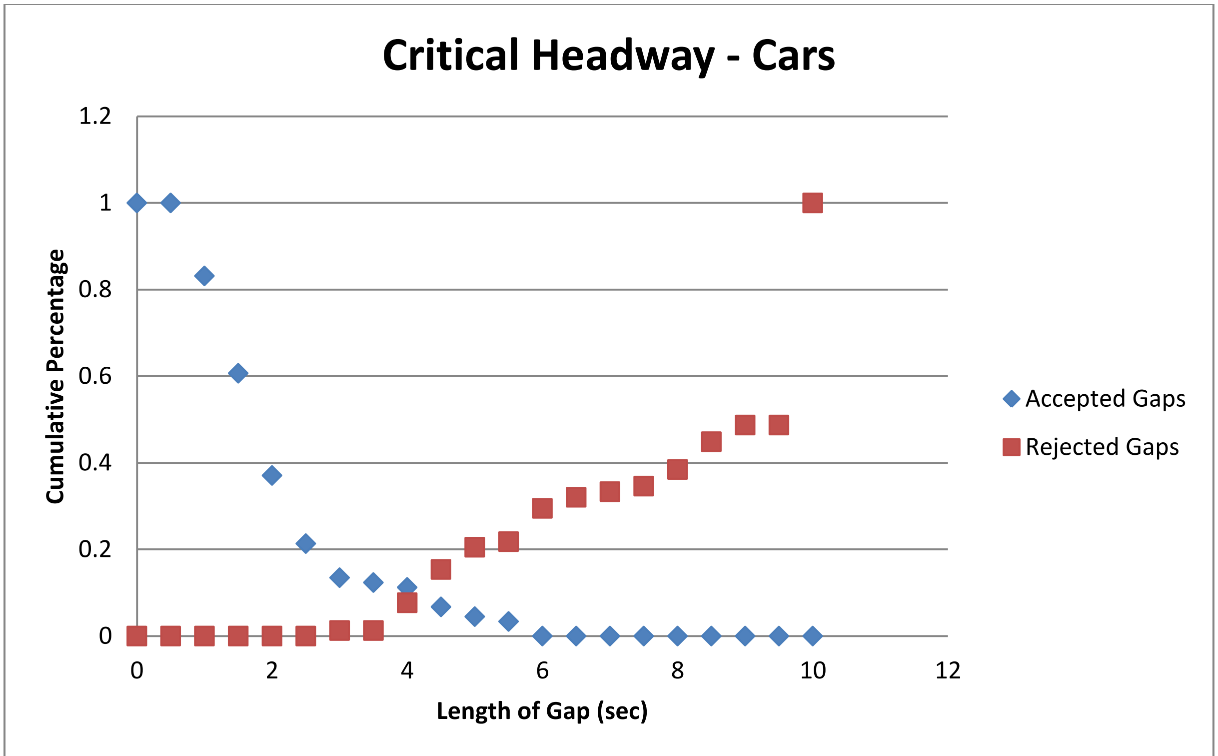


Figure E-8. Critical Headways for Moorland North Roundabout



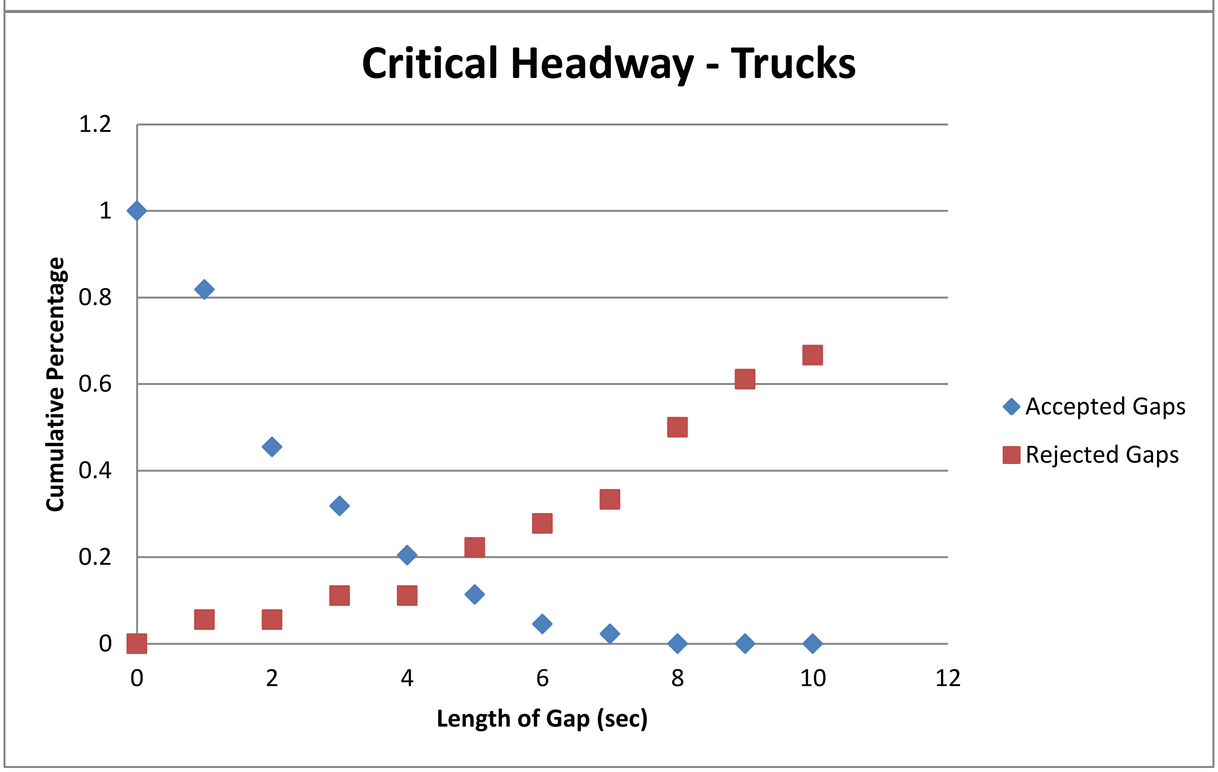


Figure E-9. Critical Headways for Moorland South Roundabout

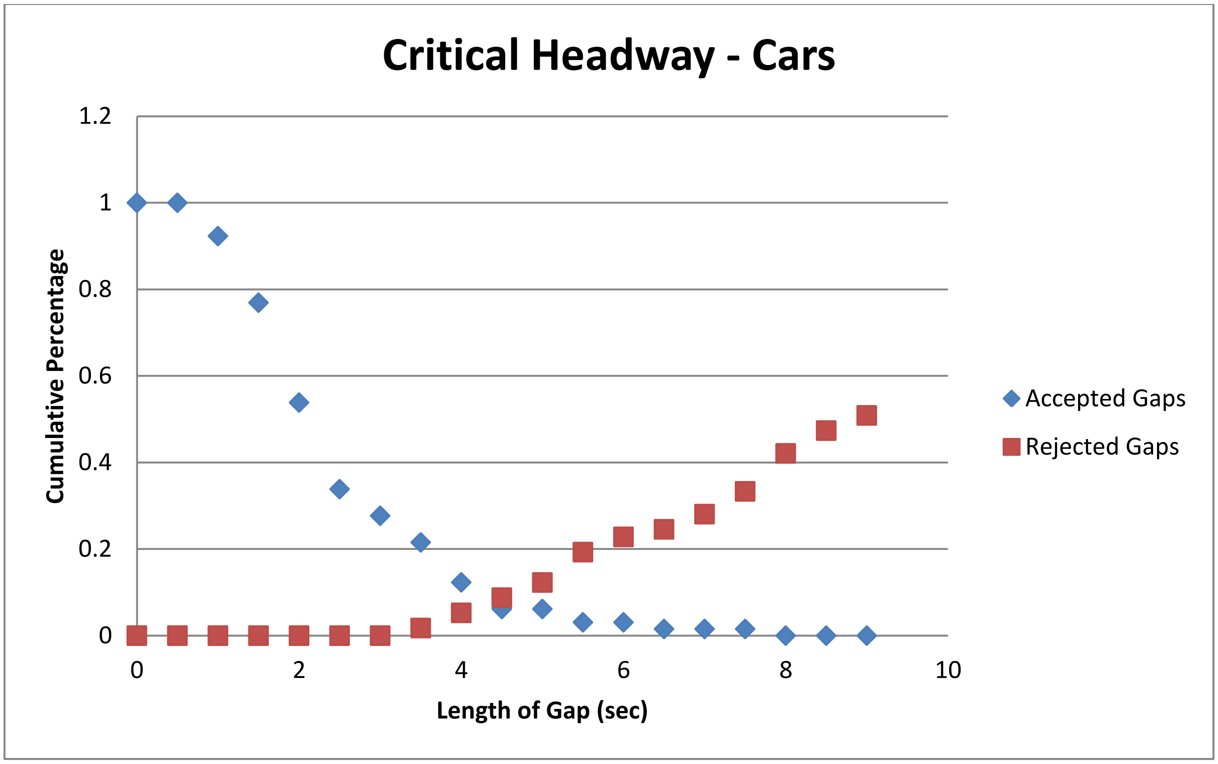


Figure E-10. Critical Headway (Cars) for Thompson North Roundabout

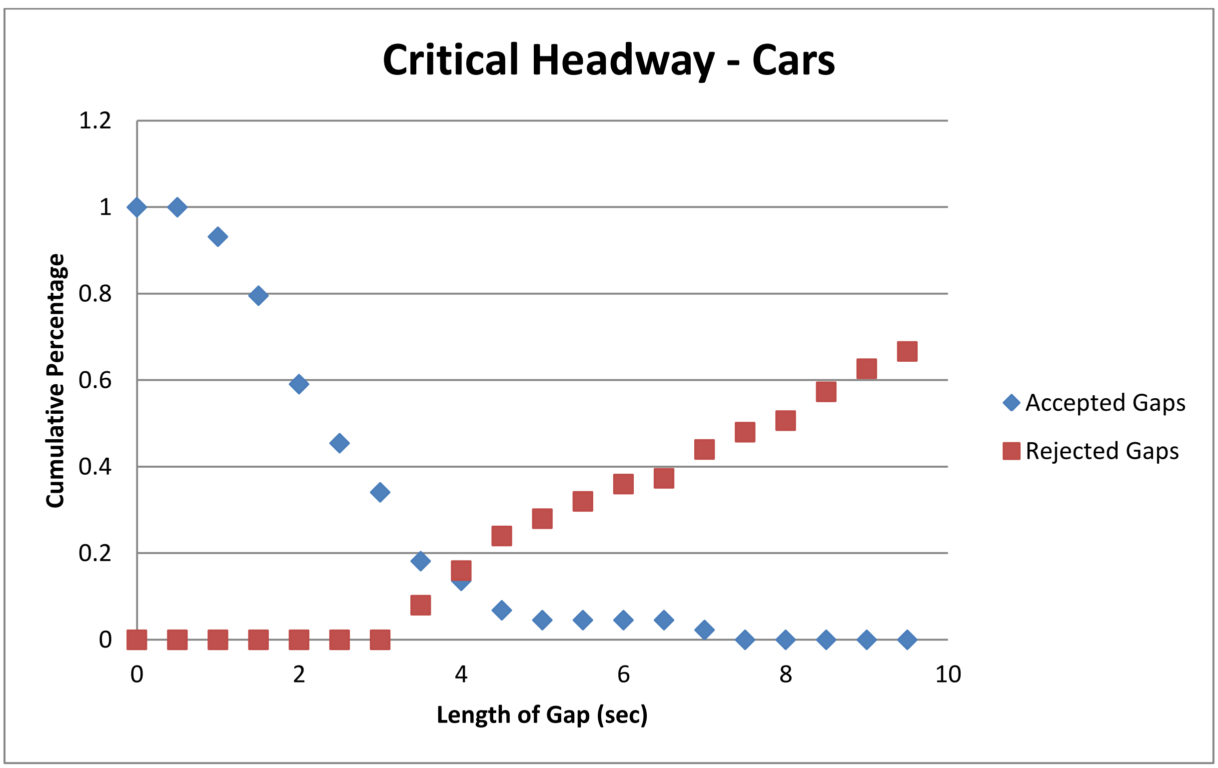


Figure E-11. Critical Headway (Cars) for Thompson South Roundabout

APPENDIX F –PROBABILITY EQUILIBRIUM METHOD (32&57 Roundabout)

Table F-1. Probability Equilibrium Method Information and Procedure

Kombination von Nebenstrom und bevorrechtigten Strömen:		
Bad Nauheim	(Nichtl eere)	
Knoten1		
16/07/1997		
15.00		angen. Lücken
18.00		
betrachtete NS-Datei: 3rechts.d, Korrekturwert: 0 sec		
HS-Datei 1: Gerade2.d, Korrekturwert: 0,4 sec		
Die Spalten bedeuten der Reihe nach:		
Lücke (in Zehntelsek.)		
procedure:	1	take the accepted gaps and mark them with "a"
	2	take the (maximal) rejected gaps and mark them with "r"
	3	put all r- and a-gaps into the same colume alone withe their marks in the second colume
ohne lap	4	sort the gaps accently
	5	accumulating if(mark="r";nrj=nrj+1;nrj), nr0=0
	6	accumulating if(mark="a";naj=naj+1;naj), na0=0
	7	build F(r)=nrj/nrmax
	8	build F(a)=naj/namax
	9	calculating F(tg)=F(a)/(F(a)+1-F(r))
	10	calculaton p(tg)=F(tg),j-F(tg),j-1 with dt=tj-tj-1
	11	tg,averge=sum(p(tg)*(t-dt/2))
advantage:		no assuption of distribution of for tc is required
		no consistent or homogen behavior is requird
		straightforeward calculation (no iteration is required)
		taking account all rejected gaps possible
		easier in datahandling

Table F-2. Probability Equilibrium Method using Truck Gap Acceptance Data from 32&57

			var	7.17		var	0.34		var	10.23		var	1.31
		97	t(all)	5.26		tg(int)	4.71	25	t(a)	13.43	72	t(r)	2.42
t x10		all N(all)	all F(all)	all f(all)	macro Ftc	macro Ftc	macro ptc	a N(a)	a Fa	a Fa	r Fr	r Fr	r Fr
4	r	1	0.010	0.010	1	0	0	0	0	0	1	0.014	0.014
6	r	2	0.021	0.010	1	0	0	0	0	0	2	0.028	0.014
6	r	3	0.031	0.010	1	0	0	0	0	0	3	0.042	0.014
7	r	4	0.041	0.010	1	0	0	0	0	0	4	0.056	0.014
7	r	5	0.052	0.010	1	0	0	0	0	0	5	0.069	0.014

Table F-2. Probability Equilibrium Method using Truck Gap Acceptance Data from 32&57 (continued)

t x10		all N(all)	all F(all)	all f(all)	macro Ftc	macro Ftc	macro ptc	a N(a)	a Fa	a Fa	r Fr	r Fr	r Fr
7	r	6	0.062	0.010	1	0	0	0	0	0	6	0.083	0.014
8	r	7	0.072	0.010	1	0	0	0	0	0	7	0.097	0.014
8	r	8	0.082	0.010	1	0	0	0	0	0	8	0.111	0.014
8	r	9	0.093	0.010	1	0	0	0	0	0	9	0.125	0.014
9	r	10	0.103	0.010	1	0	0	0	0	0	10	0.139	0.014
10	r	11	0.113	0.010	1	0	0	0	0	0	11	0.153	0.014
10	r	12	0.124	0.010	1	0	0	0	0	0	12	0.167	0.014
11	r	13	0.134	0.010	1	0	0	0	0	0	13	0.181	0.014
12	r	14	0.144	0.010	1	0	0	0	0	0	14	0.194	0.014
13	r	15	0.155	0.010	1	0	0	0	0	0	15	0.208	0.014
14	r	16	0.165	0.010	1	0	0	0	0	0	16	0.222	0.014
14	r	17	0.175	0.010	1	0	0	0	0	0	17	0.236	0.014
14	r	18	0.186	0.010	1	0	0	0	0	0	18	0.250	0.014
14	r	19	0.196	0.010	1	0	0	0	0	0	19	0.264	0.014
14	r	20	0.206	0.010	1	0	0	0	0	0	20	0.278	0.014
15	r	21	0.216	0.010	1	0	0	0	0	0	21	0.292	0.014
15	r	22	0.227	0.010	1	0	0	0	0	0	22	0.306	0.014
16	r	23	0.237	0.010	1	0	0	0	0	0	23	0.319	0.014
16	r	24	0.247	0.010	1	0	0	0	0	0	24	0.333	0.014
16	r	25	0.258	0.010	1	0	0	0	0	0	25	0.347	0.014
16	r	26	0.268	0.010	1	0	0	0	0	0	26	0.361	0.014
16	r	27	0.278	0.010	1	0	0	0	0	0	27	0.375	0.014
17	r	28	0.289	0.010	1	0	0	0	0	0	28	0.389	0.014
18	r	29	0.299	0.010	1	0	0	0	0	0	29	0.403	0.014
18	r	30	0.309	0.010	1	0	0	0	0	0	30	0.417	0.014
18	r	31	0.320	0.010	1	0	0	0	0	0	31	0.431	0.014
19	r	32	0.330	0.010	1	0	0	0	0	0	32	0.444	0.014
20	r	33	0.340	0.010	1	0	0	0	0	0	33	0.458	0.014
20	r	34	0.351	0.010	1	0	0	0	0	0	34	0.472	0.014
20	r	35	0.361	0.010	1	0	0	0	0	0	35	0.486	0.014
21	r	36	0.371	0.010	1	0	0	0	0	0	36	0.500	0.014
21	r	37	0.381	0.010	1	0	0	0	0	0	37	0.514	0.014
22	r	38	0.392	0.010	1	0	0	0	0	0	38	0.528	0.014
23	r	39	0.402	0.010	1	0	0	0	0	0	39	0.542	0.014
24	r	40	0.412	0.010	1	0	0	0	0	0	40	0.556	0.014
25	r	41	0.423	0.010	1	0	0	0	0	0	41	0.569	0.014
25	r	42	0.433	0.010	1	0	0	0	0	0	42	0.583	0.014
25	r	43	0.443	0.010	1	0	0	0	0	0	43	0.597	0.014
26	r	44	0.454	0.010	1	0	0	0	0	0	44	0.611	0.014
29	r	45	0.464	0.010	1	0	0	0	0	0	45	0.625	0.014
31	r	46	0.474	0.010	1	0	0	0	0	0	46	0.639	0.014
31	r	47	0.485	0.010	1	0	0	0	0	0	47	0.653	0.014
32	r	48	0.495	0.010	1	0	0	0	0	0	48	0.667	0.014
33	r	49	0.505	0.010	1	0	0	0	0	0	49	0.681	0.014
33	r	50	0.515	0.010	1	0	0	0	0	0	50	0.694	0.014

Table F-2. Probability Equilibrium Method using Truck Gap Acceptance Data from 32&57 (continued)

t x10		all N(all)	all F(all)	all f(all)	macro Ftc	macro Ftc	macro ptc	a N(a)	a Fa	a Fa	r Fr	r Fr	r Fr
36	r	51	0.526	0.010	1	0	0	0	0	0	51	0.708	0.014
37	r	52	0.536	0.010	1	0	0	0	0	0	52	0.722	0.014
37	r	53	0.546	0.010	1	0	0	0	0	0	53	0.736	0.014
38	r	54	0.557	0.010	1	0	0	0	0	0	54	0.750	0.014
39	r	55	0.567	0.010	1	0	0	0	0	0	55	0.764	0.014
39	r	56	0.577	0.010	1	0	0	0	0	0	56	0.778	0.014
39	r	57	0.588	0.010	1	0	0	0	0	0	57	0.792	0.014
39	r	58	0.598	0.010	1	0	0	0	0	0	58	0.806	0.014
40	r	59	0.608	0.010	1	0	0	0	0	0	59	0.819	0.014
40	r	60	0.619	0.010	1	0	0	0	0	0	60	0.833	0.014
40	r	61	0.629	0.010	1	0	0	0	0	0	61	0.847	0.014
41	r	62	0.639	0.010	1	0	0	0	0	0	62	0.861	0.014
41	r	63	0.649	0.010	1	0	0	0	0	0	63	0.875	0.014
41	r	64	0.660	0.010	1	0	0	0	0	0	64	0.889	0.014
42	r	65	0.670	0.010	1	0	0	0	0	0	65	0.903	0.014
42	r	66	0.680	0.010	1	0	0	0	0	0	66	0.917	0.014
43	r	67	0.691	0.010	1	0	0	0	0	0	67	0.931	0.014
43	r	68	0.701	0.010	1	0	0	0	0	0	68	0.944	0.014
44	r	69	0.711	0.010	1	0	0	0	0	0	69	0.958	0.014
44	a	70	0.722	0.010	0.510	0.490	0.490	1	0.04	0.04	69	0.958	0.000
48	r	71	0.732	0.010	0.410	0.590	0.100	1	0.04	0.00	70	0.972	0.014
51	r	72	0.742	0.010	0.258	0.742	0.152	1	0.04	0.00	71	0.986	0.014
53	r	73	0.753	0.010	0	1	0.258	1	0.04	0.00	72	1.000	0.014
58	a	74	0.763	0.010	0	1	0	2	0.08	0.04	72	1	0
62	a	75	0.773	0.010	0	1	0	3	0.12	0.04	72	1	0
62	a	76	0.784	0.010	0	1	0	4	0.16	0.04	72	1	0
65	a	77	0.794	0.010	0	1	0	5	0.20	0.04	72	1	0
66	a	78	0.804	0.010	0	1	0	6	0.24	0.04	72	1	0
71	a	79	0.814	0.010	0	1	0	7	0.28	0.04	72	1	0
77	a	80	0.825	0.010	0	1	0	8	0.32	0.04	72	1	0
80	a	81	0.835	0.010	0	1	0	9	0.36	0.04	72	1	0
82	a	82	0.845	0.010	0	1	0	10	0.40	0.04	72	1	0
90	a	83	0.856	0.010	0	1	0	11	0.44	0.04	72	1	0
97	a	84	0.866	0.010	0	1	0	12	0.48	0.04	72	1	0
99	a	85	0.876	0.010	0	1	0	13	0.52	0.04	72	1	0
102	a	86	0.887	0.010	0	1	0	14	0.56	0.04	72	1	0
112	a	87	0.897	0.010	0	1	0	15	0.60	0.04	72	1	0
120	a	88	0.907	0.010	0	1	0	16	0.64	0.04	72	1	0
123	a	89	0.918	0.010	0	1	0	17	0.68	0.04	72	1	0
126	a	90	0.928	0.010	0	1	0	18	0.72	0.04	72	1	0
138	a	91	0.938	0.010	0	1	0	19	0.76	0.04	72	1	0
148	a	92	0.948	0.010	0	1	0	20	0.80	0.04	72	1	0
230	a	93	0.959	0.010	0	1	0	21	0.84	0.04	72	1	0
300	a	94	0.969	0.010	0	1	0	22	0.88	0.04	72	1	0
350	a	95	0.979	0.010	0	1	0	23	0.92	0.04	72	1	0

Table F-2. Probability Equilibrium Method using Truck Gap Acceptance Data from 32&57 (continued)

t x10		all N(all)	all F(all)	all f(all)	macro Ftc	macro Ftc	macro ptc	a N(a)	a Fa	a Fa	r Fr	r Fr	r Fr
360	a	96	0.990	0.010	0	1	0	24	0.96	0.04	72	1	0
540	a	97	1.000	0.010	0	1	0	25	1.00	0.04	72	1	0

tg(Ralf,Hart)=t(F(int)=0,5)=median

class mean tdj	ptc*tdj	r 1-F(r)
0	0	0.986
5	0	0.972
6	0	0.958
6.5	0	0.944
7	0	0.931
7	0	0.917
7.5	0	0.903
8	0	0.889
8	0	0.875
8.5	0	0.861
9.5	0	0.847
10	0	0.833
10.5	0	0.819
11.5	0	0.806
12.5	0	0.792
13.5	0	0.778
14	0	0.764
14	0	0.750
14	0	0.736
14	0	0.722
14.5	0	0.708
15	0	0.694
15.5	0	0.681
16	0	0.667
16	0	0.653
16	0	0.639
16	0	0.625
16.5	0	0.611
17.5	0	0.597
18	0	0.583
18	0	0.569
18.5	0	0.556
19.5	0	0.542
20	0	0.528
20	0	0.514

Table F-2. Probability Equilibrium Method using Truck Gap Acceptance Data from 32&57 (continued)

class mean tdj	ptc*tdj	r 1-F(r)
20.5	0	0.500
21	0	0.486
21.5	0	0.472
22.5	0	0.458
23.5	0	0.444
24.5	0	0.431
25	0	0.417
25	0	0.403
25.5	0	0.389
27.5	0	0.375
30	0	0.361
31	0	0.347
31.5	0	0.333
32.5	0	0.319
33	0	0.306
34.5	0	0.292
36.5	0	0.278
37	0	0.264
37.5	0	0.250
38.5	0	0.236
39	0	0.222
39	0	0.208
39	0	0.194
39.5	0	0.181
40	0	0.167
40	0	0.153
40.5	0	0.139
41	0	0.125
41	0	0.111
41.5	0	0.097
42	0	0.083
42.5	0	0.069
43	0	0.056
43.5	0	0.042
44	21.55	0.042
46	4.62	0.028
49.5	7.53	0.014
52	13.40	0
55.5	0	0
60	0	0
62	0	0
63.5	0	0
65.5	0	0
68.5	0	0
74	0	0

Table F-2. Probability Equilibrium Method using Truck Gap Acceptance Data from 32&57 (continued)

class mean tdj	ptc*tdj	r 1-F(r)
78.5	0	0
81	0	0
86	0	0
93.5	0	0
98	0	0
100.5	0	0
107	0	0
116	0	0
121.5	0	0
124.5	0	0
132	0	0
143	0	0
189	0	0
265	0	0
325	0	0
355	0	0
450	0	0
SUM	4.7	

APPENDIX G – LINEAR REGRESSION STATISTICS

Table G-1. Follow-up Time (Car/Car) and Inner Island Diameter Regression

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.786
R Square	0.618
Adjusted R Square	0.564
Standard Error	0.150
Observations	9

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.255	0.255	11.347	0.012
Residual	7	0.157	0.022		
Total	8	0.413			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*
Intercept	1.518	0.186	8.174	7.94E-05	1.079
inner island diameter (m)	0.023	0.007	3.368	0.012	0.007

Upper 95%	*Lower 95.0%*	*Upper 95.0%*
1.957	1.079	1.957
0.039	0.007	0.039

Table G-2. Follow-up Time (Car/Car) and Splitter Island Width Regression

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.631
R Square	0.398
Adjusted R Square	0.313
Standard Error	0.188
Observations	9

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.164	0.164	4.637	0.068
Residual	7	0.248	0.035		
Total	8	0.413			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*
Intercept	1.680	0.214	7.853	0.000	1.174
splitter island width (m)	0.047	0.022	2.153	0.068	-0.005

Upper 95%	*Lower 95.0%*	*Upper 95.0%*
2.185	1.174	2.185
0.100	-0.005	0.100

Table G-3. Follow-up Time (Car/Truck) and Inner Island Diameter Regression

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.783
R Square	0.613
Adjusted R Square	0.558
Standard Error	0.515
Observations	9

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	2.934	2.934	11.081	0.013
Residual	7	1.853	0.265		
Total	8	4.787			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*
Intercept	1.361	0.637	2.136	0.070	-0.146
inner island diameter (m)	0.077	0.023	3.329	0.013	0.022

Upper 95%	*Lower 95.0%*	*Upper 95.0%*
2.867	-0.146	2.867
0.133	0.022	0.133

Table G-4. Follow-up Time (Truck/Car) and Entry Angle Regression

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.634
R Square	0.402
Adjusted R Square	0.303
Standard Error	0.523
Observations	8

ANOVA

	df	SS	MS	F	Significance F
Regression	1	1.106	1.106	4.040	0.091
Residual	6	1.642	0.274		
Total	7	2.748			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%
Intercept	7.806	1.191	6.552	0.001	4.891
entry angle (deg)	-0.0979	0.049	-2.010	0.091	-0.217

Upper 95%	Lower 95.0%	Upper 95.0%
10.721	4.891	10.721
0.0212	-0.217	0.021

VITA AUCTORIS

NAME	Jason Dahl
PLACE OF BIRTH	Windsor, Ontario, Canada
YEAR OF BIRTH	1987
EDUCATION	Essex District High School Essex, Ontario, Canada 2001-2005 University of Windsor Windsor, Ontario, Canada B.A.Sc. Civil Engineering (Co-op) 2005-2009 University of Windsor Windsor, Ontario, Canada M.A.Sc. Civil Engineering 2009-2011
CONFERENCES	Presentation: 2nd Annual CITE Joint Toronto / Hamilton / Southwest Ontario Student Presentation Competition 2010 Presentation: ITE International Annual Meeting 2010 Presentation: Bringing Together Communities; Graduate Conference 2011 Presentation: 3rd International Conference on Roundabouts 2011 Paper Published: 3rd International Conference on Roundabouts 2011 Paper Submitted: Transportation Research Board Annual Meeting 2012 Workshop: VISSIM Roundabout Modeling Workshop 2011 Workshop: SIDRA Roundabout Training Workshop 2011
MEDIA	Interview: UWin Daily News 2010 Interview: CBC Radio 3 2010
AWARDS	2nd Annual CITE Joint Toronto / Hamilton / Southwest Ontario Student Presentation Competition; First Place in Graduate Category 2010 Canadian Institute of Transportation Engineers Student Presentation Award 2010