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Capacity-Related Driver Behavior on Modern Roundabouts Built on High-Speed Roads

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CAPACITY-RELATED DRIVER BEHAVIOR ON MODERN ROUNDABOUTS

BUILT ON HIGH-SPEED ROADS

A Thesis

Submitted to the Faculty

of

Purdue University

by

Shaikh Ahmad

In Partial Fulfillment of the

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For my wife and son

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TABLE OF CONTENTS

Page

LIST OF TABLES vi
LIST OF FIGURES vii
LIST OF ABBREVIATIONS viii
ABSTRACT ix
CHAPTER 1. INTRODUCTION 1
1.1 Overview 1
1.2 Problem Statement 2
1.3 Research Scope and Objectives 3
1.4 Thesis Organization 4
CHAPTER 2. CAPACITY AND INLUENCING FACTORS 5
2.1 Overview 5
2.2 Current Roundabout Capacity Models 6
2.2.1 UK Empirical Capacity Model 7
2.2.2 Gap-Acceptance Capacity Models 9
2.2.3 HCM 2010 Capacity Model 12
2.2.4 Simulation Methods 14
2.3 Previous Studies on Gap Acceptance Parameters 15
2.4 Factors Influencing Driver Gap-Acceptance Behavior 17
2.4.1 Heavy Vehicles 17
2.4.2 Lighting Conditions 22
2.4.3 Congestion 22
2.4.4 Other Factors 24
2.5 Critical Headway Estimation Methods 24
2.5.1 Tradeoff between the MLM and the Binary Probit Method 28
CHAPTER 3. RESEARCH METHODOLOGY 31
3.1 General Approach 31
3.2 Binary Probit Method 33
3.3 Maximum Likelihood Method (MLM) 36
3.4 Simulation 37

CHAPTER 4. DATA 39
4.1 Data Collection 39
4.2 Data Extraction 42
CHAPTER 5. RESULTS AND DISCUSSION 50
5.1 Results 50
5.1.1 Binary Probit Model for Critical Headways 50
5.1.2 MLM Results for Critical Headways 53
5.1.3 Follow-up Headways 54
5.2 Discussion 55
5.2.1 Capacity Factors 55
5.2.2 Indiana Conditions vs. HCM 2010 61
5.2.3 Model Evaluation 65
CHAPTER 6. CONCLUSIONS 68
6.1 Conclusions 68
6.2 Recommendations 70
6.3 Research Limitations 70
REFERENCES 71
Appendix A Descriptive Statistics 75
Appendix B Intermediate Results from SAS Binary Probit Models 77

LIST OF TABLES

Table Page

2-1 Summary of Critical and Follow-up Headways for U.S. Roundabouts (Average Values in Parentheses) (Source: NCHRP Report 572) ... 15

2-2 Gap-Acceptance Parameters for Selected Countries ... 17

4-1 Studied Roundabouts ... 42

4-2 Sample Size and Date of Data Collection ... 47

4-3 Sample Size by Studied Factors ... 48

4-4 Variables Available to Estimate Critical Headways ... 48

4-5 Data Inventory Format ... 49

5-1 Binary Probit Model for Critical Headway Estimation ... 50

5-2 Effects of the Influencing Factors on Critical Headways ... 51

5-3 Estimated Critical Headways: MLM, Probit Method and NCHRP 572 Findings ... 52

5-4 Summary of Estimated Critical Headways Based on MLM ... 53

5-5 Summary of Estimated Follow-up Headways (sec) for the Studied Conditions (Standard Deviations in Parentheses) ... 55

5-6 Effects of 10% Heavy Vehicles on the Entry Capacity Based on Service Time, HCM, SIDRA, and Volume-Weighted Methods for Indiana Conditions ... 59

5-7 Estimated Critical Headways ... 65

5-8 Simulation Results to Evaluate Different Methodological Assumptions for Critical Headway Estimation ... 66

LIST OF FIGURES

Figure Page

2-1 Basic Features of Roundabouts (Source: USDOT, FHWA Website) 6

2-2 HCM 2010 Lane-Based Capacity for Roundabouts (Source: HCM 2010) 14

3-1 Concepts of Gaps and Lags (Source: NCHRP Report 572) 32

4-1 Studied Roundabout in Lafayette, IN (Source: Google Maps) 40

4-2 Studied Roundabouts in Noblesville, IN (Source: Google Earth) 40

4-3 Studied Roundabout in Valparaiso, IN (Source: Google Earth) 40

4-4 Purdue Mobile Traffic Lab and its Features 41

4-5 A Screen Shot of the Data Extraction Tool 43

4-6 Vehicles Interaction and Conflict Area 44

4-7 Illustration of Rejected, Accepted, and Follow-up Headways 45

5-1 Cumulative Distribution Function of the Estimated Critical Headways
for the Base-Case Condition based on Probit Model 52

5-2 Cumulative Distribution Function of the Estimated Critical Headways for
the Base-Case Condition based on MLM 54

5-3 Effect of Heavy Vehicles on the Entry Capacity for Indiana Conditions 57

5-4 Effect of 10% Heavy Vehicles on the Entry Capacity Based on Service Time,
HCM, SIDRA, and Volume-Weighted Methods for Indiana Conditions 59

5-5 Effect of Nighttime/Twilight on the Entry Capacity for Indiana Conditions 60

5-6 Entry Capacity of Single-Lane Roundabouts for Indiana Conditions 63

5-7 Entry Capacity of Dual-Lane Roundabouts for Indiana Conditions 64

LIST OF ABBREVIATIONS

cdf	cumulative distribution function
CRS	Center for Road Safety
DOT	Department of Transportation
IN	Indiana
Lab	Laboratory
MLM	Maximum Likelihood Method
NRH	Number of Rejected Headways
pce	passenger car equivalent
pcu	passenger car unit
pdf	probability density function
RAB	Roundabout
sec	second
veh	vehicle
vs.	versus

ABSTRACT

Ahmad, Shaikh.M.S.C.E.,Purdue University, December 2014.Capacity-Related Driver Behavior on Modern Roundabouts Built on High-Speed Roads. Major Professor: Andrew Tarko.

The objective of this thesis was to investigate the factors that affect capacity-related driver behavior on modern roundabouts built on high-speed roads. The capacity of roundabouts is strongly affected by the behavior of drivers as represented by critical headway (critical gap) and follow-up headway (follow-up time). The effects of heavy vehicles (single-unit truck, bus, and semi-trailer) and area type (rural or urban) on roundabout capacity were investigated by comparing the critical headways for roundabouts located on high-speed and low-speed roads. The effects of nighttime conditions (in the presence of street lighting) were also considered. Data were collected using the Purdue Mobile Traffic Lab at four roundabouts built on state roads located in Indiana. The data were used to estimate a Probit model of the critical headways and their factors, as well as the follow-up headways. The findings revealed that drivers of heavy vehicles accepted critical headways that were 1.1 seconds longer than those of the passenger car drivers; on roundabouts built on high-speed roads in rural areas, drivers accepted critical headways that were 0.6 seconds longer than on roundabouts on low-speed roads in urban areas; and in nighttime conditions, drivers accepted critical headways that were 0.6 seconds longer than in daylight conditions.

In addition, it was determined that the gap-acceptance parameters for a single-lane roundabout on a low-speed state road were less than those of the National Cooperative Highway Research Program (NCHRP) Report 572 average estimated values – which are currently incorporated into Highway Capacity Manual (HCM) 2010, resulting on average in 30% higher capacity for Indiana conditions. In contrast, the estimated critical headway was larger for dual-lane roundabouts on high-speed state roads, resulting in 15% reduced capacity (for medium to high circulatory traffic volumes) for Indiana conditions.

The findings of this thesis are intended to improve capacity estimation for the roundabouts planned on Indiana state roads. The HCM 2010 capacity equations were updated with the new estimated gap-acceptance parameters for Indiana. The findings contribute to better understanding of the roundabout capacity factors.

CHAPTER 1. INTRODUCTION

1.1 Overview

As roundabouts have been recognized as a safe and efficient type of alternative intersections, their use is not only growing in urban and suburban areas but also on high-speed roads in rural areas throughout the U.S. The Indiana Department of Transportation (INDOT) has built several roundabouts on its state highways since 2008 and plans to build many more. INDOT is concerned about the effects of high-speed approaches (50 mph and higher) and the considerable presence of trucks on the operational performance and safety of these roundabouts. There is limited knowledge about the performance of rural roundabouts on state roads in the U.S. in general and in Indiana in particular.

From the highway capacity point of view, it is important to know whether a roundabout is a feasible solution for a specific location on a highway corridor or within a highway network. Such a decision is possible by knowing the performance of a roundabout under certain conditions, which can be accomplished through capacity analysis. Several empirical and analytical capacity models are available for roundabouts. The United Kingdom (UK) Linear Regression model, the Australian Gap-Acceptance model, and the U.S Highway Capacity Manual (HCM) 2010 model are the well-known models. The HCM model is one of the components of capacity analysis developed for U.S. conditions. (Rodegerdts, et al., 2007).

The gap-acceptance models include two main parameters: the critical headway (critical gap) and the follow-up headway (follow-up time). Critical headway is the shortest time headway between two consecutive vehicles on circulatory roadways that is acceptable to an average driver waiting to enter the roundabout safely. However, a distinction between "gap" and "headway" is important. A gap represents the time difference that the rear bumper of the leading vehicle clears the conflict line and the front bumper of the following vehicle occupies that line, whereas, headway represents time difference between the front-to-front bumpers. In this thesis, the term headway is used rather than that of gap. The follow-up headway is the average time headway between consecutive vehicles on the approach roadways entering the roundabout from a queue by accepting the same available headway in the circulatory traffic. Although default values for these parameters are reflected in the HCM 2010, the values are not applicable to all conditions. HCM recommends calibrating the gap-acceptance parameters for local conditions.

1.2 Problem Statement

Thirty roundabouts are being planned on state roads in Indiana; and there is a similar trend in other states. A limited number of research studies have been conducted on rural roundabouts in the U.S. The largest collection of roundabout data in the U.S., in existence since 2003, contains 90 percent of the data from urban and suburban areas (Rodegerdts, et al., 2007). This database was used for developing the HCM 2010 capacity model. In addition, only a few past studies on Indiana roundabouts have taken place, which were located in urban/suburban areas in Carmel, Indiana (Tarko et al., 2008; Wei and Grendard, 2012; Day et al., 2013). Carmel has been building roundabouts since the late 1990s, and Carmel drivers therefore are accustomed to them, unlike drivers elsewhere in Indiana. Therefore, the capacity-related findings obtained through these studies may not be transferable to larger roundabouts with high-speed approaches on Indiana state roads.

Moreover, the previous studies for Indiana roundabouts did not address dual-lane roundabouts or the effects of heavy vehicles (single-unit truck, bus, and semi-trailer) on roundabout capacity. Also, none of the studies addressed the effects of lighting conditions (nighttime/twilight in the presence of street lighting) as rush hour happens at twilight and relatively dark conditions during late fall and early winter. Therefore, this thesis is focused on roundabouts built on state roads in Indiana as well as on the factors that affect their operational performance.

1.3 Research Scope and Objectives

The scope of this thesis was to study the operational performance of modern roundabouts built on high-speed roads with a speed limit of 50 mph or higher located in rural/ suburban areas of Indiana. The capacity analysis was limited to the estimation of gap acceptance parameters (the critical and follow-up headways).

The research objective of this thesis was to evaluate the capacity of modern roundabouts built on high-speed roads. Specifically, the research aimed to identify the factors that affect the gap-acceptance behaviors of drivers on roundabouts built on high-speed Indiana state highways in rural areas. The effects of high-speed approaches and heavy vehicles on roundabout capacity were studied as well as the effects of nighttime/twilight conditions on drivers. The results are intended to improve the capacity analysis of roundabouts designed on Indiana state roads and to contribute to an increased understanding of capacity factors in general.

1.4 Thesis Organization

This thesis consists six chapters which are interrelated. Chapter 1 presents the objective of this thesis and discusses the gaps in previous roundabout studies. Chapter 2 provides background information on the current capacity models for roundabouts as well as the previous studies on the gap-acceptance parameters. A thorough literature review on critical headway estimation methods and the factors that affect estimation is also presented in this chapter. Chapter 3 presents the methodology used for data analysis, and Chapter 4 describes the data collection and data extraction processes. Chapter 5 presents the estimated statistical model and the results of the estimated critical headways and follow-up headways. The effects and significance of the studied conditions on roundabout capacity and a comparison of the calibrated model for local conditions based on the studied roundabouts vs. the HCM 2010 capacity model also are discussed in Chapter 5. Finally, Chapter 6 presents the conclusions, recommendations, and limitations of this thesis related to the capacity analysis of modern roundabouts built on high-speed roads.

CHAPTER 2. CAPACITY AND INLUENCING FACTORS

2.1 Overview

The concept of the modern roundabout was developed in the United Kingdom (U.K.) in 1966 and has been adopted in many other countries (Rodegerdts, et al., 2010). In the U.S., building roundabouts has been increasing since 1990 (Rodegerdts, et al., 2007). As of December 2013, approximately 3,700 roundabouts have been constructed throughout the country (History of Modern Roundabouts). The modern roundabouts should be distinguished from the old-style circular intersections (traffic circles or rotaries). Rotaries are usually large in diameter (greater than 300 ft., and because of this large diameter, the speed in circulatory roadways is high. The priority operation rule applicable to modern roundabouts is not valid for rotaries (Rodegerdts, et al., 2010).

A roundabout is defined in the NCHRP Report 672 – Roundabouts: An Informational Guide (2nd Edition), as follows:

> *A roundabout is a form of circular intersection in which traffic travels counterclockwise (in the United States and other right-hand traffic countries) around a central island and in which entering traffic must yield to circulating traffic* (p. 1-3).

The geometric features and traffic control devices for a single-lane roundabout are shown in Figure 2-1.

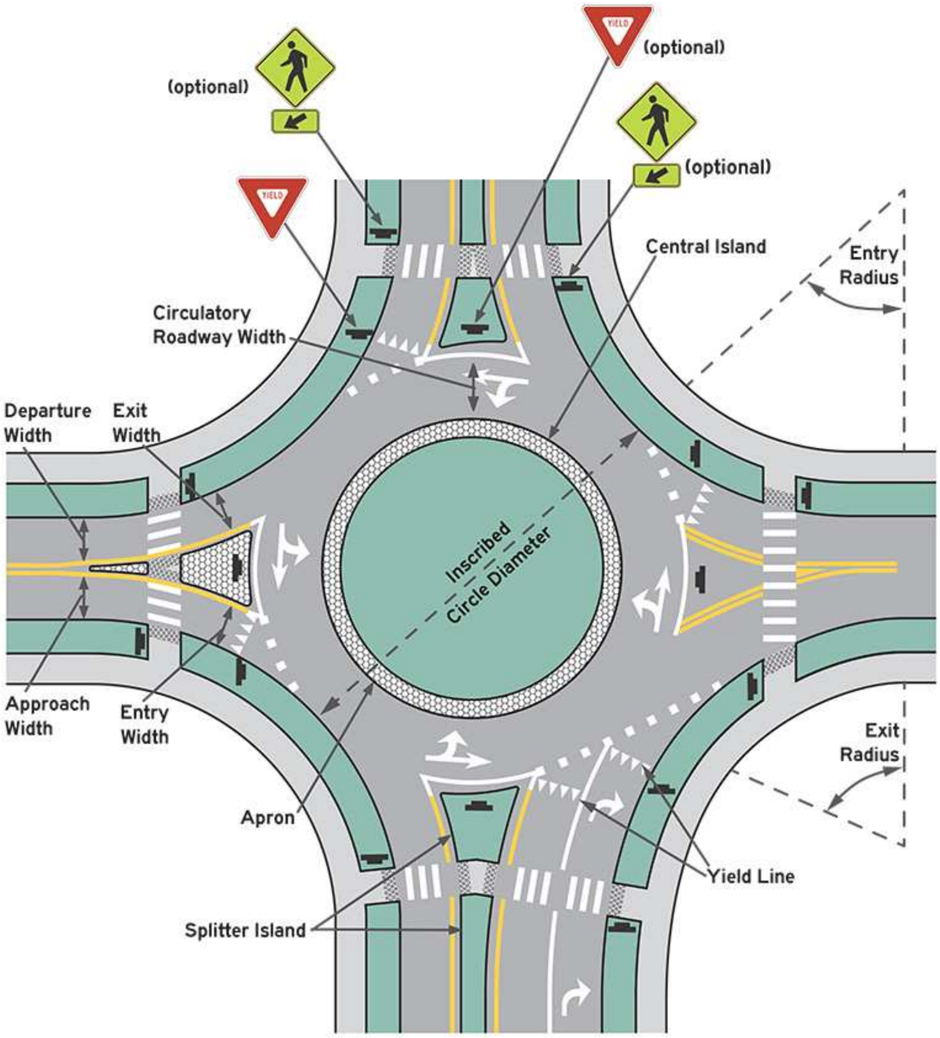

Figure 2-1 Basic Features of Roundabouts (Source: USDOT, FHWA Website)

2.2 Current Roundabout Capacity Models

Several models have been developed for roundabout capacity analysis. The most common approaches to modeling roundabouts include the empirical approach, gap-acceptance theory, and microscopic simulation. The empirical models are statistical and utilize regression to estimate the relationship between capacity and the geometric characteristics of roundabout (e.g., the UK Transport Research Laboratory (TRL) model).

The gap acceptance models are based on the mechanism of accepting or rejecting gaps in the major stream (circulating roadways on roundabouts) by drivers on the minor stream (approach roadways) (e.g., the Australian SIDRA INTERSECTION software model). The HCM 2010 capacity method includes a simple exponential regression model, in which the regression coefficients are based on gap acceptance behavior rather than the geometry of roundabouts. However, the method considers geometry in terms of the number of lanes. The simulation methods are computer-based programs that have the capability of simulating traffic and driver behavior at the microscopic level; Vissim is one such software program. The concepts, main parameters, and limitations of each type of model are briefly discussed in the following sections.

2.2.1 UK Empirical Capacity Model

In the empirical method, the effort is concentrated on developing a mathematical relationship between the entry capacity and the circulating flow rate based on significant factors that may affect the relationship. This relationship is assumed to be linear or exponential, as shown in Equations (2-1) and (2-2) (Yap et al., 2013). The coefficients are determined through statistical multivariate regression analysis.

$$q_e = A - B \cdot q_c \tag{2-1}$$

$$q_e = A \cdot \exp(B \cdot q_c) \tag{2-2}$$

Where,

q_e: Entry capacity (pc/h),

q_c: Circulating flow rate (pc/h),

A and B: Functions of roundabout geometry.

One well-known empirical model is the LR942 Linear Regression Model, which is most commonly used in the U.K. In this model, the entry capacity rate has a linear regression relationship to the circulating flow rate. The geometric characteristics of the entry roadways and the circulatory roadways are the main regression parameters. The model is shown in Equation (2-3) below.

$$Q_e = k \cdot (F - f_c \cdot Q_c) \text{ for } f_c Q_c \leq F, \text{ else } 0 \qquad (2\text{-}3)$$

$$k = 1 - 0.00347(\varphi - 30) - 0.978(1/r - 0.05)$$

$$F = 303x_2$$

$$f_c = 0.21T_D(1 + 0.2x_2)$$

$$T_D = 1 + \frac{0.5}{1 + \exp(\frac{D-60}{10})}$$

$$x_2 = v + (e - v)/(1 + 2S)$$

$$S = 1.6(e - v)/l'$$

Where,

Q_e: Maximum entry flow (veh/h)

Q_c: Circulating flow (veh/h)

e: Entry width (m)

v: Approach half-width (m)

l': Effective flare length (m)

r: Entry radius (m)

φ: Entry angle (°)

S: Measure of the degree of the flaring

D: Inscribed circle diameter (m)

The available software packages for the U.K. model are RODEL and ARCADY. Since the UK model is fully empirical and no theoretical basis exists to relate the capacity and the geometric characteristics, the model may not be applicable for U.S. roundabouts. According to the findings of NCHRP Report 572 (2007), which is considered the largest body of research on U.S. roundabouts, the detailed geometric features as reflected in the U.K. model have no significant effect on the capacity of a roundabout; rather, the aggregate level in terms of the number of lanes is able to capture the geometric effects.

2.2.2 Gap-Acceptance Capacity Models

Gap-acceptance models are developed based on the availability of the headways in the major stream traffic (circulating traffic on roundabouts) and driver gap-acceptance behavior in terms of critical headway and follow-up headway. The Australian SIDRA

INERSECTION model and the HCM 2010 capacity model fall into this category. Although the SIDRA and HCM models are developed based on the same approach, their assumptions for arrival headway distribution (in circulating traffic for roundabouts) are different. The SIDRA model is developed based on a bunched exponential assumption while the HCM model is developed based on a simple exponential assumption (Akcelik, 2011; Rodegerdts, et al., 2007). The SIDRA INTERSCTION model is shown in Equations (2-4) to (2-6).

$$Q_e = \max(Q_g, Q_m) \tag{2-4}$$

$$Q_g = \frac{3600}{t_f}\left[1 - \Delta_m q_m + 0.5\, t_f \varphi_m q_m\right] e^{-\lambda(t_c - \Delta_m)} \tag{2-5}$$

$$Q_m = \min(q_e, 60 n_m) \tag{2-6}$$

Where,

Q_e: Maximum entry capacity (veh/h),

Q_g: Gap-acceptance capacity (veh/h),

Q_m: Minimum capacity (veh/h),

q_e: Entry flow rate (veh/h),

q_m: Arrival flow rate (veh/h),

n_m: Minimum number of entry vehicles that can depart under heavy circulating flow conditions (veh/min),

λ: Arrival headway distribution factor (veh/h),

$$\lambda = \frac{\varphi_m q_m}{1 - \Delta_m q_m}$$

Δ_m: Intra-bunch Minimum headway in circulating traffic (sec),

φ_m: Proportion of free (un-bunched) circulating vehicles,

t_c: Critical headway (sec), and

t_f: Follow-up headway (sec).

As can be seen in Equation (2-5), critical headway and follow-up headway are among the main parameters. Default values for these parameters have been incorporated into the model and computer-based programs such as SIDRA INTERSECTION software, which is based on Australian research and practice. As shown in Table 2-2, the gap acceptance parameters for Australian drivers are considerably smaller than those of the U.S. If SIDRA standard software is used for capacity analysis of U.S. roundabouts without adjustment, an overestimation of the capacity can be expected. The NCHRP Report 572 findings also indicated that the aaSIDRA (2.0) model overestimates the capacity for U.S. roundabouts.

However, the assumptions of a congested condition (bunched) and a free condition (unbunched) for the arrival flow of a major stream (circulation) in SIDRA INTERSECTION appears to be reasonable for gap acceptance capacity models, and the traffic arrival pattern is not always expected to be random (Poisson). Therefore, evaluation of these assumptions for the HCM capacity model for U.S. roundabouts is recommended in the future.

2.2.3 HCM 2010 Capacity Model

Prior to 2000, limited research was performed on roundabouts in the U.S. because this type of intersection was not commonly used throughout the country. Deterministic software methods, such as RODEL, and simulation methods, such as Vissim, based on U.K. and German research practice, respectively, have been used since 1990 (Rodegerdts, et al., 2010). Chapter 17 of HCM 2000 provided a model for roundabout capacity analysis, but the model was restricted to single-lane roundabouts.

As roundabouts became increasingly popular, more studies were conducted on U.S. roundabouts. In 2007, NCHRP Report 572 presented the results of an in-depth investigation of the broad aspects of roundabouts, including safety, capacity, and design. In Chapter 4 of that report, a lane based exponential regression model was recommended for capacity analysis of single-lane and dual-lane roundabouts, as shown in Equations (2-7) to (2-9). It is worth mentioning that the capacity-related research findings of NCHRP Report 572 were incorporated in HCM 2010 in Chapter 21, a new chapter for roundabouts.

$$C_e = Ae^{(-Bv_c)} \tag{2-7}$$

$$A = \frac{3600}{t_f} \tag{2-8}$$

$$B = \frac{t_c - (t_f/2)}{3600} \tag{2-9}$$

Where,

C_e: Entry capacity (pc/h),

v_c: Circulating flow rate (pc/h),

t_c: Critical headway (sec), and

t_f: Follow-up headway (sec).

For single-lane roundabouts, the default values for *A* and *B* are 1,130 and 0.001, respectively. The same values are suggested for two entry lanes approaching one circulatory lane. For a single entry lane approaching two circulatory lanes, the value of *A* is the same as for the single-lane while *B* is 0.0007. In addition, for roundabouts with two entry lanes approaching two circulatory lanes, the value of *A* is the same while *B* varies for different lanes: 0.00075 for a left lane and 0.0007 for a right lane. These differences are shown graphically in Figure 2-2. As can be seen in Equations (2-8) and (2-9), functions *A* and *B* depend upon the two main parameters, critical headway and follow-up headway. Therefore, it can be concluded that the accuracy of the HCM model depends on how well these parameters are estimated.

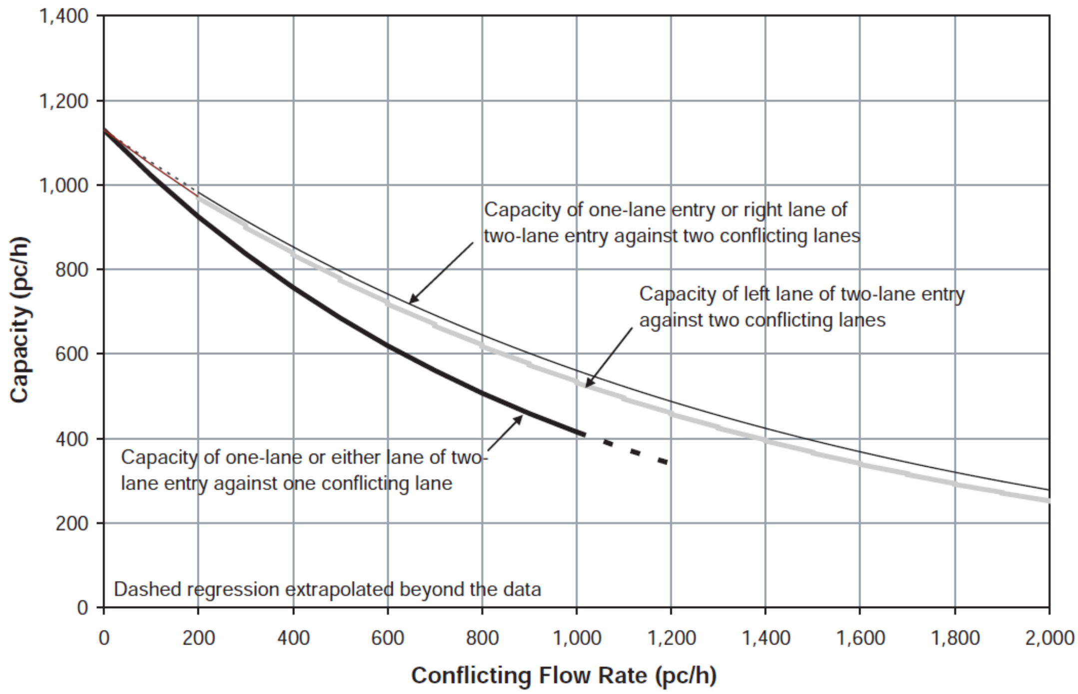

Figure 2-2 HCM 2010 Lane-Based Capacity for Roundabouts (Source: HCM 2010)

2.2.4 Simulation Methods

Simulation models are an alternative to empirical and analytical methods. These models are able to simulate traffic flow based on the car-following, lane-changing, and gap acceptance behaviors of drivers at intersections (Rodegerdts, et al., 2010). Simulation software such as Vissim is available for analyzing the capacity of individual intersections or intersections within a corridor/network. To analyze roundabout capacity in Vissim, the default values for the gap acceptance parameters should be adjusted to reflect the behavior of local drivers.

2.3 Previous Studies on Gap Acceptance Parameters

Many past studies estimated the two fundamental capacity parameters (critical headway and follow-up headway). A large research effort on roundabouts in the U.S. was conducted in NCHRP Project 3-65, the results of which were published in the NCHRP Report 572. The gap acceptance parameters were estimated based on data from 18 approaches (roundabouts located in urban/suburban areas) in five states. Table 2-1 shows the estimated parameters for single-lane and dual-lane roundabouts. These values were incorporated in the HCM 2010 capacity model for roundabouts. Moreover, many studies were conducted to estimate these values for individual states. Xu and Tian (2008) studied ten roundabouts in California and concluded that the estimated critical headways were consistent with the values reported in NCHRP 3-65 while the estimated follow-up headways were considerably smaller.

Table 2–1 Summary of Critical and Follow-up Headways for U.S. Roundabouts (Average Values in Parentheses) (Source: NCHRP Report 572)

Field Measurements	Single-Lane		Dual-Lane	
	Critical Headway (sec)	**Follow-up Headway (sec)**	**Critical Headway (sec)**	**Follow-up Headway (sec)**
Approach	4.2 – 5.9 (5.1)	2.6 – 4.3 (3.2)	na	na
Right Lane	na	na	3.4 – 4.9 (4.2)	2.7 – 4.4 (3.1)
Left Lane	na	na	4.2 – 5.5 (4.5)	3.1 – 4.7 (3.4)

na = not applicable

Previous research on roundabouts in Indiana also indicated that the critical headways and the follow-up headways were significantly lower compared to those presented in NCHRP Report 572. Tarko et al. (2008) studied a single-lane roundabout in Carmel, Indiana and estimated the mean critical gap as 3.1 sec and the average follow-up headway as 2.4 sec. Wei and Grendard (2012) also studied three single-lane roundabouts in Carmel to calibrate the HCM 2010 capacity model for single-lane roundabouts for local conditions. The study estimated the average critical headway as 3.5 sec and the average follow-up headway as 2.2 sec. Day et al. (2013) collected a large amount of data from another single-lane roundabout in Carmel and measured the median critical gap as 2.2 sec. The aforementioned studies examined driver behavior on roundabouts on low-speed roads in the daytime with a low presence of heavy vehicles. Therefore, these findings are not transferable to larger roundabouts on state highways with a considerable presence of heavy vehicles.

Gap-acceptance parameters vary across countries. The estimated parameters for selected countries are shown in Table 2-2. The differences in gap-acceptance values indicate that the behaviors of drivers vary, which could be due to their roundabout driving experience and risk acceptance level. However, the lack of a standard methodology may affect estimation due to the initial assumptions, which will be discussed in Chapter 3. A proper methodology and accounting for the influencing factors would yield more accurate capacity estimations.

Table 2–2 Gap-Acceptance Parameters for Selected Countries

Roundabout	Critical Headway (sec)	Follow-up Headway (sec)	Cited
Australia			(Vasconcelos et al., 2013)
1-Lane	1.4 – 4.9	1.8 – 2.7	
2-Lane (Left)	1.6 – 4.1	1.8 – 2. 2	
2-Lane (Right)	-	2.2 – 4.0	
Germany			(Vasconcelos et al., 2013)
[1/2] 40 ≤ D ≤ 60 m	5.6	2.5	
[2/2] compact 40 ≤ D ≤ 60 m	5.2	2.2	
[2/2] large D > 60 m	4.4	2.9	
Turkey			(Tanyel et al., 2007)
1-Lane	4.5 – 6.2	2.6 – 2.9	

[x/y]: Indicates number of entry lanes and circulatory lanes, respectively.

D: Inscribed Circle Diameter

2.4 Factors Influencing Driver Gap-Acceptance Behavior

2.4.1 Heavy Vehicles

The presence of heavy vehicles is expected to reduce the capacity of roundabouts. Rodegerdts, et al. (2007) reported that their parametric analysis for evaluating the correlation of heavy vehicles with the gap-acceptance parameters indicated a negative value, but the authors stated that this result was not confirmed and needs further exploration. On the other hand, a study by Wisconsin DOT (2011) on four roundabouts (two single-lane and two dual-lane) located in Wisconsin indicated longer gap-acceptance parameters for trucks compared to passenger cars. The study reported the differences as 0.1 to 3.1 sec for critical headways and 0.2 to 1.4 sec for follow-up headways. Likewise, Dahl and Lee (2012) concluded that the critical headways and follow-up times for trucks were higher than for cars based on the data from 11 roundabouts located in Vermont, Wisconsin, and Ontario, Canada. In their study, the average critical headway was estimated as 4.3 sec for cars and 5.2 sec for trucks, indicating a 0.9 sec longer critical headway for trucks. Fitzpatrick et al. (2013) also estimated a longer critical headway for heavy vehicles compared to cars based on a single-lane roundabout located in Amherst, Massachusetts; the critical headways for cars and heavy vehicles were 2.2 sec and 2.8 sec, respectively, which indicate that heavy vehicles accept a 0.6 sec longer critical headway, on average, than cars.

Although a larger critical headway is expected for heavy vehicles, studying more cases will increase the body of knowledge regarding heavy vehicle gap-acceptance behavior on roundabouts built on high-speed roads.

HCM considers the effect of heavy vehicles on capacity in terms of an adjustment factor (i.e., converting heavy vehicle flow to passenger car equivalent (pce) as shown in Equations (2-10) and (2-11). According to HCM, the adjustment factor for trucks is 2.0. However, Lee (2014) concluded that trucks on a roundabout affect the capacity more than this adjustment. The adjustment factor was estimated as 3.0 for a circulating flow rate between 540-840 pcu/h.

$$v_c = \frac{V}{f_{HV}} \tag{2-10}$$

$$f_{HV} = \frac{1}{1 + P_T(E_T - 1)} \tag{2-11}$$

Where,

v_c: Circulating flow rate (pce/h),

V: Demand flow rate (veh/h),

f_{HV}: Heavy-vehicle adjustment factor,

P_T: Proportion of demand volume (at circulatory lanes) that consists of heavy vehicles, and

E_T: Passenger car equivalent for heavy vehicles (the default HCM value for E_T is 2.0)

Akcelik and Associates (2012) suggested adjusting the gap-acceptance parameters rather than the flow rate with Equations (2-12) and (2-13). The heavy vehicle adjustment factor is to be calculated with Equation (2-11).

$$t'_c = \frac{t_c}{f_{HV}} \tag{2-12}$$

$$t'_f = \frac{t_f}{f_{HV}} \tag{2-13}$$

Where,

t'_c: Adjusted critical headway,

t'_f: Adjusted follow-up headway, and

f_{HV}: Heavy-vehicle adjustment factor.

On the other hand, a volume-weighted method for adjusting gap-acceptance parameters was introduced by Dahl and Lee (2012). According to this approach, the representative gap-acceptance parameters can be calculated from Equations (2-14) and (2-15). A separate analysis for estimating the gap-acceptance parameters for cars and trucks was recommended; and the adjusted gap-acceptance parameters using the above equations can be used as inputs to any gap-acceptance capacity models (Dahl & Lee, 2012). This approach appears to be a reasonable way to adjust gap-acceptance parameters to capture the effect of truck traffic on the entry capacity.

$$t'_c = t_{c,C} \cdot (1 - P_{TE}) + t_{c,T} \cdot P_{TE} \tag{2-14}$$

$$t'_f = t_{f,CC}(1 - P_{TE})^2 + \left(t_{f,CT} + t_{f,TC}\right)(1 - P_{TE})P_{TE} + t_{f,TT} \cdot P_{TE}^2 \tag{2-15}$$

Where,

t'_c: Adjusted critical headway,

t'_f: Adjusted follow-up headway,

P_{TE}: Percentage of trucks at entry lanes,

Sub C stands for car and sub T stands for truck (e.g. sub CT means car following truck), and all other terms are as defined previously.

Lee and Khan (2013) improved the volume-weighted approach by accounting for the truck traffic at both the entry and at the circulation roadways, as shown in Equations (2-16) and (2-17).

$$t'_{c,C,i} = t_{c,C,CC,i}\left(1 - P_{TC,i}\right)^2 + \left(t_{c,C,CT,i} + t_{c,C,TC,i}\right)\left(1 - P_{TC,i}\right)P_{TC} + t_{c,C,TT,i} \cdot P_{TC}^2, i \quad (2\text{-}16)$$

$$t'_{c,T,i} = t_{c,T,CC,i}\left(1 - P_{TC,i}\right)^2 + \left(t_{c,T,CT,i} + t_{c,T,TC,i}\right)\left(1 - P_{TC,i}\right)P_{TC} + t_{c,T,TT,i} \cdot P_{TC}^2, i \quad (2\text{-}17)$$

Where,

$t'_{c,C,i}$: Denotes adjusted critical headway for cars approaching entry lane i,

$t'_{c,T,i}$: Denotes adjusted critical headway for trucks approaching entry lane i,

P_{TC}: Percentage of trucks at circulatory lanes,

Sub *C* stands for car and sub *T* stands for truck (e.g. sub *CT* means car accepting gap between a car and a truck), and all other terms are as defined previously.

The adjusted critical headways of cars and trucks based on the above equations to be substituted with $t_{c,C}$ and $t_{c,T}$ of Equation (2-14), respectively. Although the suggested adjustments account for the possible effects of truck traffic on roundabout capacity, the estimation of several critical headways for different conditions which are less likely to happen (e.g. truck accepting a headway between two trucks on the circulation) may not be that desirable because such details would require a relatively larger sample size to cover all the conditions.

2.4.2 Lighting Conditions

Limited research has been done on the effect of lighting conditions on the roundabout capacity. Tenekeci et al. (2009) studied several roundabouts in the UK in order to quantify the effects of adverse weather and lighting conditions on the entry capacity. In their study, data were collected utilizing video recording tools during different road surface and lighting conditions. The data were analyzed using the UK linear regression empirical model for roundabout capacity analysis; the results indicated that dry-dark conditions reduced the entry capacity by 6.3% on average for the entry saturation condition and 14.2% for the average circulation flow condition, which is comparable to the base condition of dry-light. The authors defined “dark” as a condition in which no natural light is present but rather is artificial. Burrow (1986) estimated a 5% reduction in roundabout capacity in the dark condition compared to the light condition (as cited in Tenekeci et al., 2009). Although their research quantified the impact of the dark condition on the entry capacity, the findings are not necessarily transferable to U.S. roundabouts. In addition, including the effects of the light condition on driver behavior is desirable for gap-acceptance capacity models.

2.4.3 Congestion

Driver behavior may be affected by the level of congestion on a roundabout as longer delays may lead to more aggressive actions. Congestion can be represented by control delay or the length of a queue on the approach. Delay also may be represented by the number of rejected gaps or waiting time at the first position of the queue. Mahmassani and Sheffi (1981) used a Probit procedure and data from actual observations to find the effects of delay on gap-acceptance behavior, represented by the number of rejected gaps, at an unsignalized intersection. They concluded that the critical headway is a decreasing function of the number of rejected gaps. Hamed et al. (1997) concluded that the waiting time at the first position of a queue at T-leg intersections affected driver behavior; the longer the waiting time was, the more likely the drivers were to accept shorter gaps. On the other hand, a study by Wisconsin DOT (2011) indicated that the effects of the queue length on the critical headways and follow-up headways were not significant.

The decision of the driver in the first position of a queue, who inspects the available headway, may be more critical than the other measures. In addition, a number of rejected gaps psychologically may determine the driver's decision more than the waiting time (i.e., by rejecting many gaps, the driver may think in terms of missed opportunities rather than the time delay). Also, the queue length may not represent congestion well as a long queue can dissipate rather quickly if there is no or less circulating traffic, while a short queue will take longer time to dissipate if there is considerable circulating traffic. Therefore, the number of rejected headways, as a proxy, was considered to evaluate the effect of congestion on driver behavior.

On the other hand, generally, roundabouts on high-speed roads are less congested than those in urban areas, and only a few past studies therefore have addressed capacity-related driver behavior on such roundabouts. In order to have a better understanding of the operational performance of roundabouts on high-speed roads, it is important to know whether congestion affects driver behavior on the roundabouts located on those roads.

2.4.4 Other Factors

Road-surface condition (dry or wet) may affect driver behavior on roundabouts. A study by Tenekeci et al. (2009) on UK roundabouts indicated that the wet-light condition reduced the entry capacity by 7.1%, comparable to the dry-light condition. The weather effect on capacity-related driver behavior is not investigated in this thesis; however, it is important information for locations with extended rainfall seasons during the year. Therefore, it should be considered in future studies on roundabouts in the U.S.

2.5 Critical Headway Estimation Methods

Since the critical and follow-up headways strongly affect the capacity of a roundabout, valid estimation of these parameters is important. Various methods of gap-acceptance analysis are used for unsignalized intersections in general and for roundabouts in particular.

Raff's method, perhaps the oldest method for estimating critical gap, continues to be used in research. Fitzpatrick et al. (2013) used this method to estimate the critical headways for cars and trucks on a roundabout located in Amherst Massachusetts. Dahl and Lee (2012) also used this method for the same purpose on nine roundabouts in Wisconsin and Ontario, Canada, although they presented the estimated critical headways as the average of the Raff and Probability Equilibrium methods. Although Raff's concept is empirical and simple, Miller (1972) indicated that traffic volume variability affects critical headway estimation using this method (as cited in Brilon, 1999).

The Probit method is another technique used for critical headway estimation. Daganzo (1981), Mahmassani and Sheffi (1981), and Hamed et al. (1997) used this method to estimate critical headways for unsignlized intersections, as well as the effects of other factors (e.g. waiting time and number of rejected gaps).

The Maximum Likelihood Method (MLM) has been widely used for estimating mean critical headways for roundabout capacity analysis. Rodegerdts et al. (2007), Xu and Tian (2008), and Tarko et al. (2008) used this method to estimate the mean and standard deviation of critical headway on roundabouts.

The reliability of critical headway estimation methods have been evaluated in several studies. Brilon et al. (1999) described eight methods for critical gap estimation: the Siegloch method for the saturated traffic condition and the lag, Raff, Harders, Logit, Probit, Hewitt, and MLM methods for unsaturated traffic conditions. The authors evaluated these methods with simulation for various generated traffic conditions for major and minor streams based on certain assumptions, and they concluded that the MLM and Hewitt methods produced the best results. The assumptions were shifted-Erlang distribution for critical and follow-up headways, hyper-Erlang distribution for traffic on major and minor streams, and consistent driver behavior (the driver maintains the generated critical headway until departure). However, generating major and minor traffic based on assumed distributions and consistent driver behavior degraded the robustness of the evaluation method. Therefore, the evaluation method could be improved with more realistic assumptions to reflect the actual traffic arrivals and to correspond to the assumptions of the estimation method in question (e.g., Probit assumes normal distribution for the critical headways, rather than shifted-Erlang distribution).

Tarko et al. (2008) performed a study to estimate driver gap acceptance parameters on roundabouts. Two methods of critical headway estimation were used in their study: the MLM and a new method that assumed inconsistent driver behavior (i.e., drivers may accept headways smaller than the earlier rejected ones). To evaluate the accuracy of the used methods, simulation was performed using Vissim. The criterion for comparison was the service time in the first position of the queue. Based on a comparison of the service times of the simulated scenario and the actual one, it was concluded that MLM was preferred over the new method for the studied case. However, the comparison was based on the mean values only because the version of Vissim they used did not allow entering the estimated standard deviations for the critical headway. It was suggested that the evaluation method could be improved by including both the mean and standard deviation of the critical headway in order to evaluate the assumption of driver consistency.

Vasconcelos et al. (2013) studied six roundabouts in Portugal and estimated their gap-acceptance parameters using the Raff, Wu (Probability Equilibrium Method), Troutbeck (MLM), Siegloch, and Logit methods. The authors evaluated the accuracy of the methods by comparing the estimated (based on the estimated parameters) and the observed capacities (based on the field observations). Their general conclusion was that the estimated results were within the range of the observed capacities. Furthermore, it was implied that none of the methods were superior to the others.

Troutbeck (2014) used simulation to determine that the MLM can provide consistent and unbiased estimation of the mean critical gap while the Probability Equilibrium method could not.

Most of the past studies estimated the critical headways with the assumption that drivers are consistent (i.e., drivers always reject gaps shorter than the accepted ones); therefore, only the largest rejected gap and the accepted gap for each driver were considered in their analysis. This assumption can be questioned in light of research which indicated that some drivers reject gaps longer than the one they eventually accept, as was the case for the observations in this thesis.

Critical headway is a random variable that varies across drivers or even across the decisions of the same driver because of his/her different perception ability, risk acceptance, etc. Therefore, a certain distribution must be assumed and its parameters (mean and standard deviation) are the objective of estimation. Log-normal distribution has been assumed in many studies – particularly those used MLM, and is suggested by Troutbeck (2014). Wu (2012) concluded that the Weibull distribution better fitted critical headway, compared to the log-normal distribution. The conclusion was based on the Probability Equilibrium approach, which was introduced by the author (more details in Wu, 2012). In contrast, Troutbeck performed simulation and concluded that log-normal is preferred over Weibull distribution. Normal distribution was assumed in the past studies as it is the underlying distribution of the Probit method. However, it is implied that there is no strong empirical or theoretical basis to determine the distribution type of critical headways.

Although most of the above-mentioned methods have been used for estimation of critical headway, a tradeoff between the methods could be helpful. Therefore, the concepts, assumptions, and limitations of the widely used MLM and the Probit method are briefly discussed in the next section in order to select one of them as the preferred method for this thesis. In addition, simulation with more realistic assumptions (discussed in Chapter 5) will be helpful to verify the preferred method.

2.5.1 Tradeoff between the MLM and the Binary Probit Method

MLM is widely used for estimating the mean and standard deviation of critical headway. This method assumes that the driver's critical headway is between the largest rejected headway and the accepted headway and that the driver is consistent (i.e., always accepts a headway larger than the associated rejected headway). However, this method has the following limitations:

- For inconsistent driver behavior (i.e., the driver accepts a shorter gap than the largest associated rejected gap), the method recommends reassigning a value for the largest rejected gap just below the associated accepted gap (as cited in Troutbeck, 2014). The data extraction in this thesis revealed that 5 to 10 percent of the observed drivers accepted shorter gaps than the largest associated rejected gap. Therefore, seeking alternative methods to account for this assumption may be desirable.
- The method assigns zero or a very small value for the absence of a rejected gap for drivers who accept the first gap (Troutbeck, 2014) because of its pairwise analysis approach. This assumption can also be questioned as this causes a biased sample due to the assumption of zeros for no rejected gaps.
- The method estimates the mean and variance of the critical headways only, as was used in NCHRP Report 572 and in Troutbeck (2014). The significance of explanatory variables other than the measured rejected or accepted headways

were determined through a parametric analysis (Rodegerdts, et al., 2007). A more convenient method would be to estimate the critical headway and determine the significance of the influencing factors.

On the other hand, the Probit method considers the driver's decision as a binary choice (i.e., the driver has the choice to reject or accept a gap). This method primarily could be preferred to the MLM for the following reasons.

- The assumption of driver inconsistency can be relaxed by including all the rejected headways and only the accepted headway for an individual driver, regardless which one is larger.
- There is no need to pair the headways (to assume values for the observations with no rejected headways) as this method considers rejection and acceptance decisions independent from one another.
- Typically, as many explanatory variables as available can be included in the model in order to determine their significance on the critical headway.

Another difference between these methods is the assumption of the critical headway distribution. MLM basically assumes a log-normal distribution where binary Probit assumes normal distribution. Troutbeck (2014) mentioned that log-normal is a reasonable distribution because of its non-negative property; however, the choice of other distributions was not rejected, because of the lack of strong empirical and theoretical bases. A problem with normal distribution can happen with a smaller mean and a larger standard deviation; in such a case, the probability of having negative critical headway values tends to increase. However, negative values could infer the condition of reversal priority (i.e., circulating traffic yields for entering traffic) in the case of heavy traffic on the approach.

As a result of the above discussions, the Probit method is primarily selected for estimating the critical headway parameters and determining the significance of the influencing factors on driver gap-acceptance behavior in this thesis. Besides, estimation results from MLM are also reported for comparison purposes. Furthermore, simulation is performed to validate the selected method.

CHAPTER 3. RESEARCH METHODOLOGY

3.1 General Approach

Following the widely accepted approach to capacity analysis, gap-acceptance data were analyzed and the critical and follow-up headways were estimated. Traffic operations on four roundabouts built on Indiana state highways were video-recorded with high-resolution cameras during the morning and afternoon peak hours during fall 2013 and spring 2014. Utilizing a special image analysis tool, developed at the CRS, headways were measured and other explanatory variables (shown in Table 4-4) were noted. The binary Probit concept was used for the estimation of the mean and standard deviation of the critical headways, as well as for the evaluation of the influencing factors. The measured follow-up headways for each condition were averaged and the standard deviations were calculated.

In addition to a reasonable estimation technique, the gap-acceptance analysis in this thesis required proper preparation of data. NCHRP Report 572 considered three approaches for determining the inclusion of observations: (1) all accepted and rejected gaps and accepted lags, (2) observations that contained at least a rejected gap, and (3) observations where queuing was observed during the entire minute and contained a rejected gap. Method (2) was preferred in the NCHRP study. The concept of gaps and lags are shown in Figure 3-1.

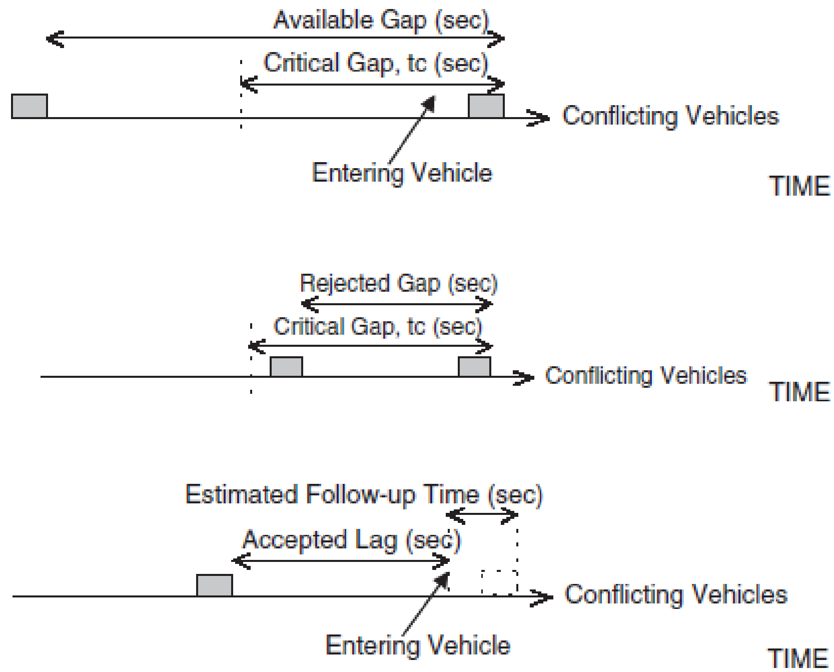

Figure 3-1 Concepts of Gaps and Lags (Source: NCHRP Report 572)

Since a lag is a portion of a gap, inclusion of lags in the data set leads to underestimation of the critical headway (Rodegerdts, et al., 2007; Tarko, et al., 2008). Likewise, due to low to medium traffic volumes on the studied roundabouts, especially in rural areas, obtaining enough observations from a queue during the entire minute was not feasible. Therefore, the data set in this thesis followed method (2), which is consistent with the NCHRP Report 572 methodology.

Furthermore, it was assumed that driver behavior is inconsistent. Considering this assumption, each rejected headway contributes information about driver consistency. Information from the extracted observations in this thesis confirmed inconsistent driver behavior as 5 to 10 percent of the drivers accepted shorter headways over the associated rejected headway(s). Therefore, all rejected headways and accepted headways were included in the analysis.

Unlike the MLM pairwise analysis, the Probit method considers each event (rejected or accepted) as an independent decision, even for the same driver. Therefore, all rejected and accepted headways were included for the model estimation, without any adjustment, as discussed earlier.

To evaluate the effects of the influencing factors on driver behavior and, in turn, on the capacity, a driver of a passenger car approaching a single-lane roundabout on a low-speed road during daylight conditions was set as the base case.

Finally, the assumptions and the techniques used for estimating critical headways were evaluated with simulation. The difference in the average delays (sec/veh) at the first position of the queue between the simulated scenarios and the actual observations was considered as the performance measure.

3.2 Binary Probit Method

The binary Probit concept was selected to estimate the critical headway and the effects of the studied variables. Let us assume that $t_i$is the shortest headway acceptable to a driver at the moment the driver inspects headway h_i. This shortest acceptable headway (critical headway) depends on some variables taking values $\boldsymbol{X_i}$ and other unknown conditions represented by error term ε_i at the time when headway h_i is inspected. The error term is assumed normally distributed with zero mean and standard deviation σ. Hence, the critical headway can be represented as Equation (3-1).

$$t_i = \boldsymbol{\beta X}_i + \varepsilon_i \tag{3-1}$$

The probability of headway acceptance can be related to the duration of the available headway. The probability P that headway h_i is accepted is shown in Equation (3-2). Substituting t_i with its function results in a standard binary Probit model, as shown in Equations (3-3) to (3-5).

$$P(Y_i = 1|\boldsymbol{X}_i) = P(t_i \leq h_i) \tag{3-2}$$

$$P(Y_i = 1|\boldsymbol{X}_i) = P\left(\frac{\varepsilon_i}{\sigma} \leq \frac{h_i - \beta X_i}{\sigma}\right) \tag{3-3}$$

$$P(Y_i = 1|\boldsymbol{X}_i) = \Phi\left(\beta_h^* h_i - \beta^* X_i\right) \tag{3-4}$$

$$P(Y_i = 1|\boldsymbol{X}_i) = \Phi\left(\frac{1}{\sigma} h_i - \frac{\beta}{\sigma} X_i\right) \tag{3-5}$$

Where,

Y: Binary variable taking value 1 when headway is acceptable and value 0 otherwise

P: Probability that headway accepted by a driver

h_i: Measured headway

Φ: The standardized cumulative normal distribution

t_i: Critical headway

σ: Standard deviation of a critical headway (the scaling parameter)

β_h: Estimated parameter for the headway variable

$\beta = (\beta_0, \beta_1, \beta_2 \ldots)$: Estimable parameter for an intercept and other variables

$X = (1, X_1, X_2 \ldots)$: Explanatory variable

Statistical Analysis Software (SAS) using the maximum-likelihood estimator was utilized to estimate the model parameters $\boldsymbol{\beta}^*$ in Equation (3-4). Then, the critical headway parameters – mean (μ) and standard deviation (σ) – were calculated from Equations (3-6) and (3-7), as reported by SAS (SAS/STAT® 9.3 User's Guide, 2011).

$$\mu = \frac{\beta^*}{\beta_h^*} \quad (3\text{-}6)$$

$$\sigma = \frac{1}{\beta_h^*} \quad (3\text{-}7)$$

The *t* – statistic was used to determine the significance of the model coefficients. The significance level of 0.05 (95% confidence level) was used. The effects of the significant variables on roundabout capacity were evaluated by calibrating the HCM 2010 capacity model to reflect the local conditions.

3.3 Maximum Likelihood Method (MLM)

MLM was also used in the current research to estimate the mean and variance of the critical headways in order to ensure that the differences between the values estimated in this thesis and those of the NCHRP Report 572 were not due to different applied methodologies. The recommended procedure by Troutbeck (2014) was followed for the MLM, as described below.

If $F(a_i)$ and $F(r_i)$ are the cumulative distribution functions (CDF) of the accepted gaps and rejected gaps, respectively, then the likelihood (L) of the critical headway for an individual driver is:

$$L = F(a_i) - F(r_i) \tag{3-8}$$

The likelihood for the entire population of drivers is the product of the individual likelihoods as:

$$L = \prod_{i=1}^{n} [F(a_i) - F(r_i)] \tag{3-9}$$

The log-likelihood (LL) function is used for simplification as:

$$LL = \sum_{i=1}^{n} ln[F(a_i) - F(r_i)] \tag{3-10}$$

To estimate the mean and variance of the critical headways, the log-likelihood function was maximized. An iterative process was required to maximize this function; a spreadsheet was utilized for this purpose. In this procedure, the initial values for the mean (m) and variance (s^2) were required as inputs. Log-normal distribution was assumed for the distribution of critical headways. Eventually, the desirable parameters, the mean (μ), and the variance (σ^2) of the critical headways ware calculated from Equations (3-11) and (3-12).

$$\sigma^2 = \ln\left(\frac{s^2}{m^2} + 1\right) \tag{3-11}$$

$$\mu = \ln(m) - 0.5\ \sigma^2 \tag{3-12}$$

3.4 Simulation

The assumptions and methods used in this thesis for estimating critical headways were evaluated with simulation. The assumptions for the Probit method were as follows: inconsistent driver behavior (may accept headways smaller than the earlier rejected ones) and normal distribution of critical headways across drivers; and the assumptions for the MLM were as follows: consistent driver behavior (always accept headways larger than the earlier rejected one) and log-normal distribution of critical headways across drivers. Based on the estimated models for critical headways, two possible scenarios were evaluated.

1. Inconsistent driver behavior and normal distribution of the critical headways. This scenario was evaluated based on the results from the Probit model, in which all rejected headways and accepted headways were included.
2. Consistent driver behavior and log-normal distribution of critical headways. As the Probit method is restricted to the normal distribution assumption, this scenario was evaluated based on the results from the MLM, in which the accepted headway and the largest rejected headway for the driver in question were included (with adjustment of the largest rejected headway just below the accepted headway in the case of a higher value).

The performance measure considered in the evaluation was the difference in the actual average delay (sec/veh) at the first position of the queue and that of the simulated scenarios since delay is one of the most important elements of the capacity analysis. To measure the actual time that the drivers spent in the first position of the queue, the Traffic Tracker tool, developed by CRS, was used to mark the real time for each driver maneuvering on the single-lane roundabout for three hours. The information from the recorded time stamped was used to measure the individual observed delays.

In addition, the gap-acceptance parameters were estimated from the same observations. Then the gap-acceptance behaviors of the same drivers were simulated based on the estimated mean and standard deviation of the critical and follow-up headways. Finally, the actual delays from observations and those of the simulations were compared.

CHAPTER 4. DATA

4.1 Data Collection

To investigate the effects of high speed, heavy vehicles and lighting conditions on the capacity of modern roundabouts on high-speed roads, the capacity-related behaviors of drivers in four roundabouts on Indiana state highways were studied. One of the high-speed roundabouts is located on SR25 near Lafayette, Indiana. The T-intersection was replaced with a three-leg two-lane roundabout in 2012 as shown in Figure 4-1. The speed limit on the north approach was 55 mph. As for all state roads, considerable traffic demand for trucks is expected on this roundabout. Videos were recorded to study driver behavior, including truck drivers, on the high-speed approach. Two other roundabouts on SR32/38, located near Noblesville, Indiana, also were studied. These roundabouts were constructed in a rural/suburban area of the new diverted alignment of SR32/38 in 2011. The speed limit on the main approaches was 55 mph, while on the other approaches, it was 35 mph. As for other state highways, truck traffic was expected on this route. Videos were recorded from the traffic on both roundabouts during the day and nighttime/twilight conditions. The geometric configuration of these roundabouts is shown in Figure 4-2. For comparison purposes, driver behavior was studied on a low-speed approach roundabout on Indiana 130, located in an urban area of Valparaiso, Indiana. The speed limit for all the approaches of this roundabout was 35 mph.

Figure 4-1 Studied Roundabout in Lafayette, IN (Source: Google Maps)

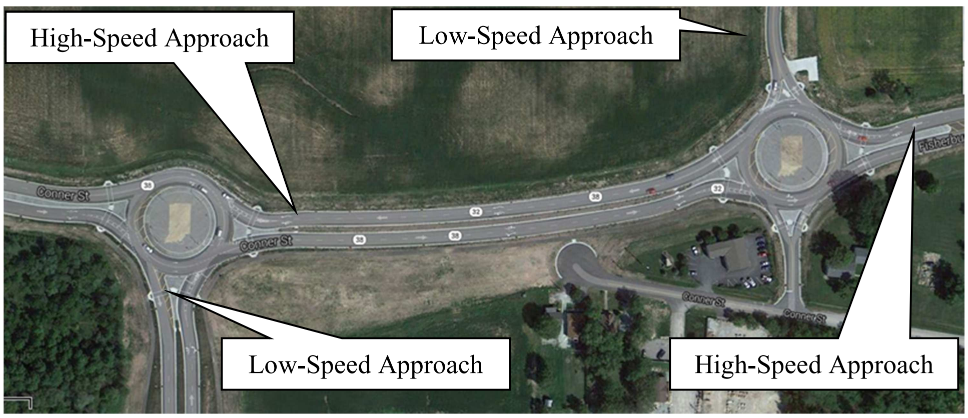

Figure 4-2 Studied Roundabouts in Noblesville, IN (Source: Google Earth)

Figure 4-3 Studied Roundabout in Valparaiso, IN (Source: Google Earth)

Technically, this roundabout is classified as a single lane, and its geometric configuration is shown in Figure 4-3. The geometric characteristics, highest approach speed and year-opened to traffic of the studied roundabouts are summarized in Table 4-1.

Data were collected on the studied roundabouts during the morning and afternoon peak hours in fall 2013 and spring 2014. The Purdue mobile traffic lab which has two high-resolution dome cameras mounted on a pneumatic mast, was used to record the traffic flow on the roundabouts. All the necessary tools, including a computer with double monitors and 4TB storage for video recording, were set up in the van. The van was parked at the locations close enough to the roundabouts to record the entering and circulating traffic flows. Figure 4-4 shows the mobile traffic van and its features. Over 100 hours of video were recorded.

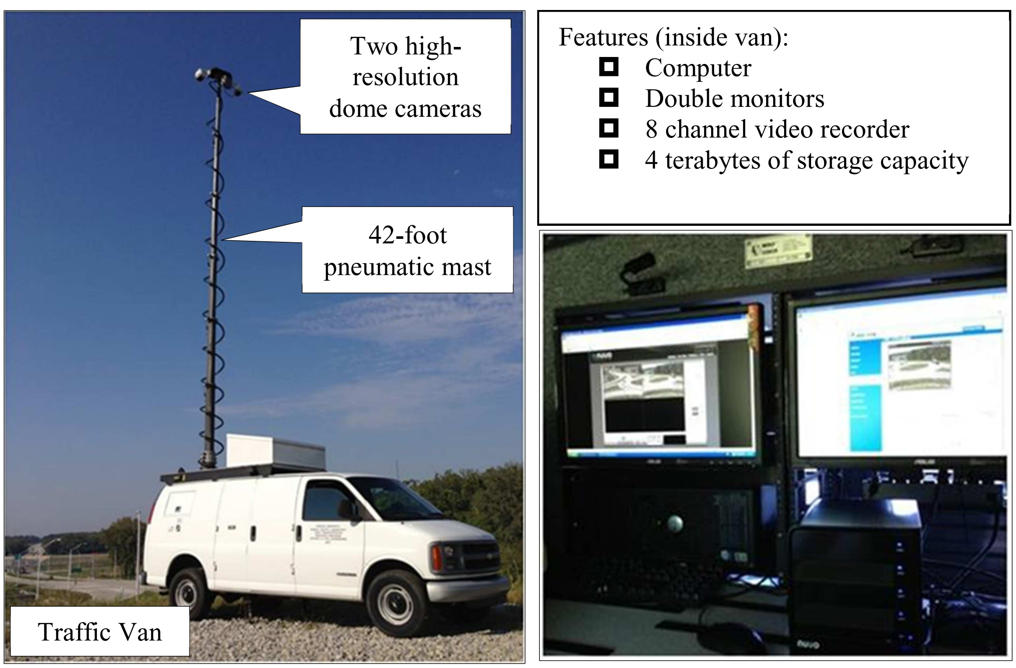

Figure 4-4 Purdue Mobile Traffic Lab and its Features

Table 4–1 Studied Roundabouts

Roundabout	Number of Approaches	# Entry Lanes	# Circulatory Lanes	Highest Approach Speed (mph)	Installation Year
SR 25 – Old SR 25, Lafayette	3	2	2	55	2012
SR 32/38 –Union Chapel Road, Noblesville	3	2	2	55	2011
SR 32/38 – Promise Road, Noblesville	4	varies	2	55	2011
Indiana 130 – LaPorte Ave – N. Sturdy Road, Valparaiso	4	varies	1	35	2008

4.2 Data Extraction

The rejected/accepted and follow-up time headways were extracted with a special image analysis tool developed by CRS. This tool has the ability to record time stamps in one-tenth of a second as well as the local coordinates. Other information about the roundabouts (e.g., lane use, turning movement, vehicle type, weather conditions, visibility conditions, and aggregate geometric characteristics (number of lanes) also was noted. A screen shot from the tool is shown in Figure 4-5. During the data extraction from two-lane roundabouts (dual circulatory lanes), it was observed that entering vehicles yielded, to all the circulating vehicles, regardless of the lanes.

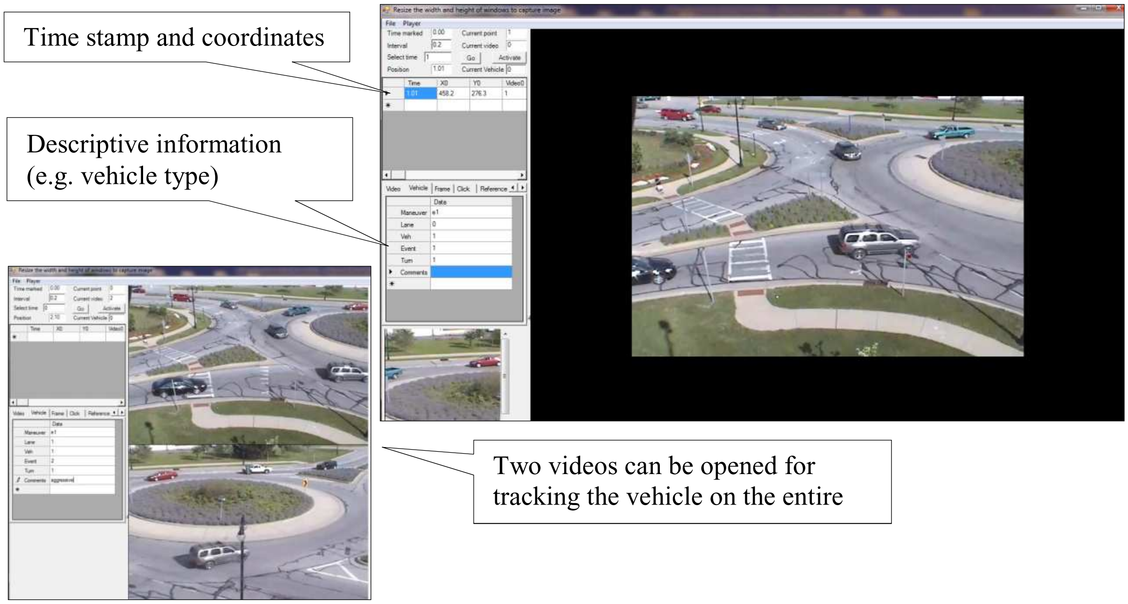

Figure 4-5 A Screen Shot of the Data Extraction Tool

For measuring the observed headways, the following definitions were helpful and are graphically illustrated in Figures 4-6 and 4-7; however, engineering judgment was also valuable.

Yield line: the outer edge of the circulatory lane (outer lane in multiple-lane roundabouts) within an approach. This line is not always the marked yield line.

Conflict line: the left edge of a corridor used by a vehicle entering the circulatory lane from an approach.

Entering vehicle: a vehicle passing with its front bumper at the yield line and continuing into the roundabout.

Circulating vehicle: a circulating vehicle that crosses the conflict line. A circulating vehicle in any of the two circulatory lanes is circulating for a vehicle entering the

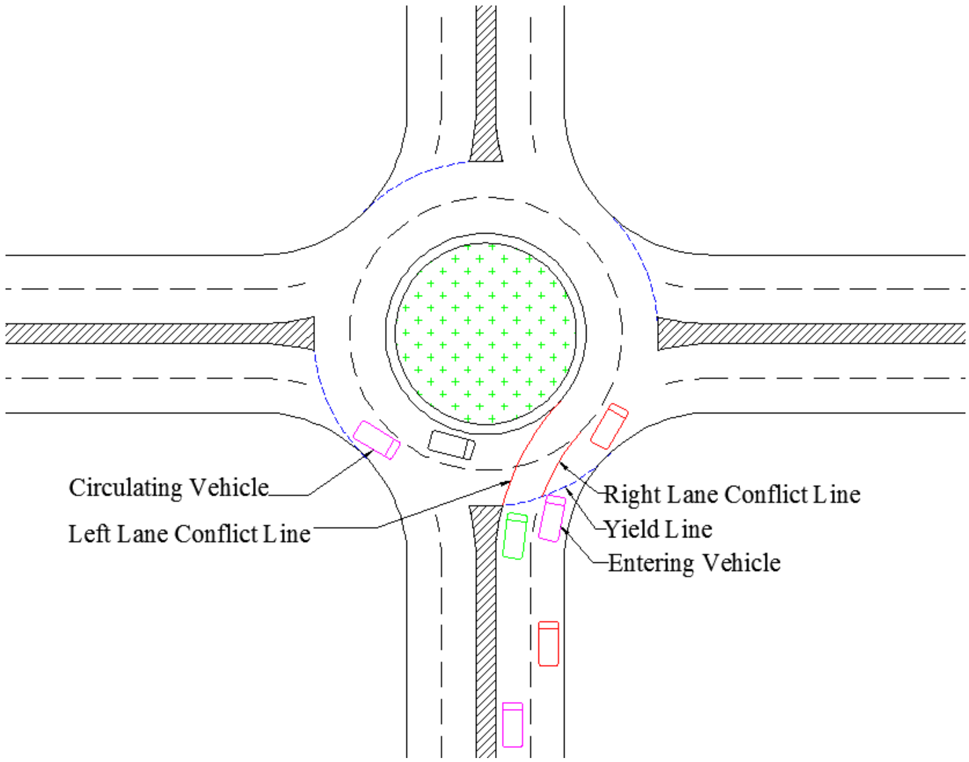

Figure 4-6 Vehicles Interaction and Conflict Area

roundabout from the left approach lane. A circulating vehicle in the outer circulatory lane is circulating for a vehicle entering the roundabout from the right approach lane.

Time headway: the time between two consecutive circulating vehicles crossing the conflict line. The time headway is *accepted* if a vehicle stopped on the approach enters the roundabout between the two vehicles. The time headway is *rejected* if a vehicle stopped on the approach does not enter the roundabout between the two vehicles.

Follow-up time: the time between two consecutive entering vehicles crossing the yield line (either from a stationary or moving queue) and accepting the same time headway between circulating vehicles.

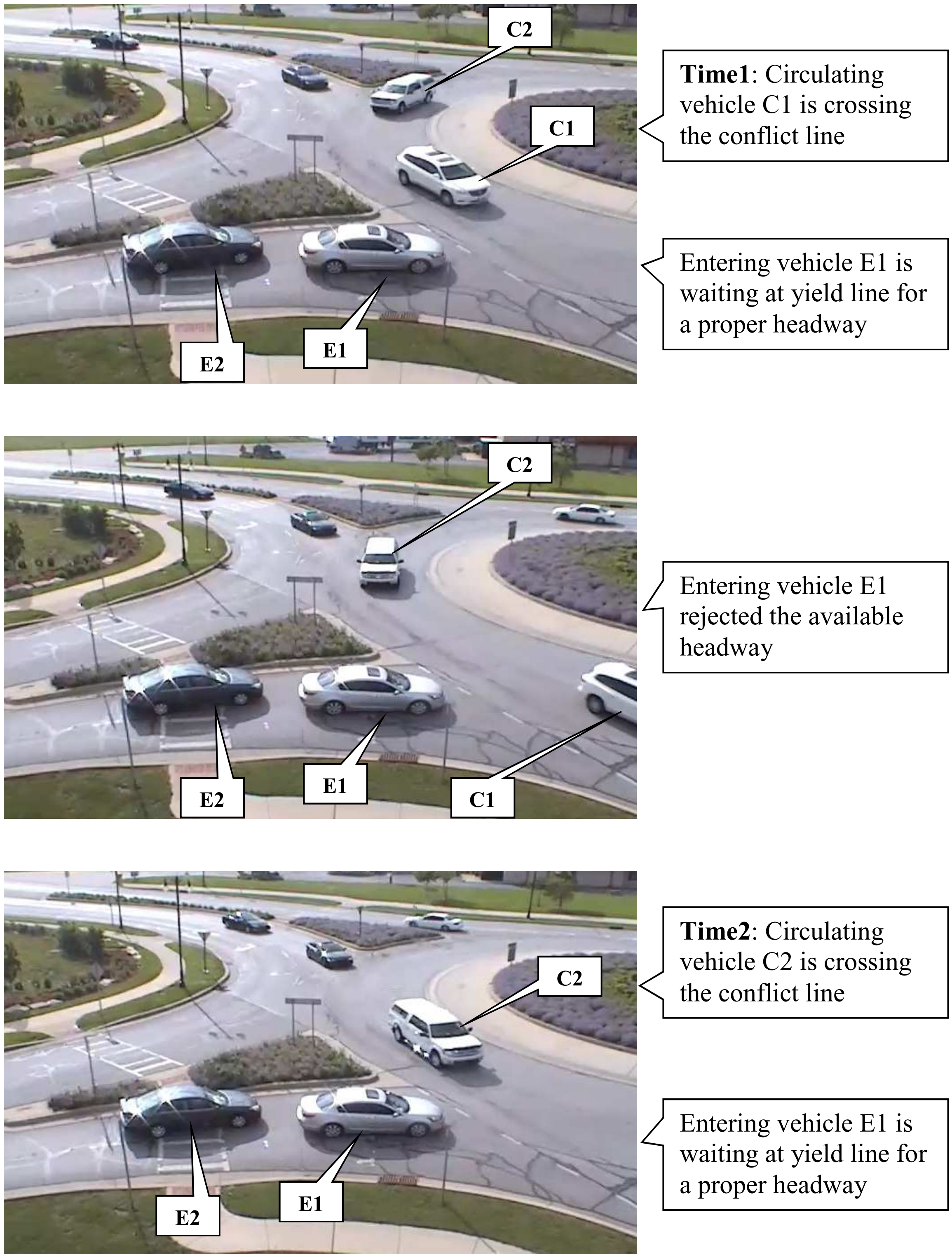

Figure 4-7 Illustration of Rejected, Accepted, and Follow-up Headways
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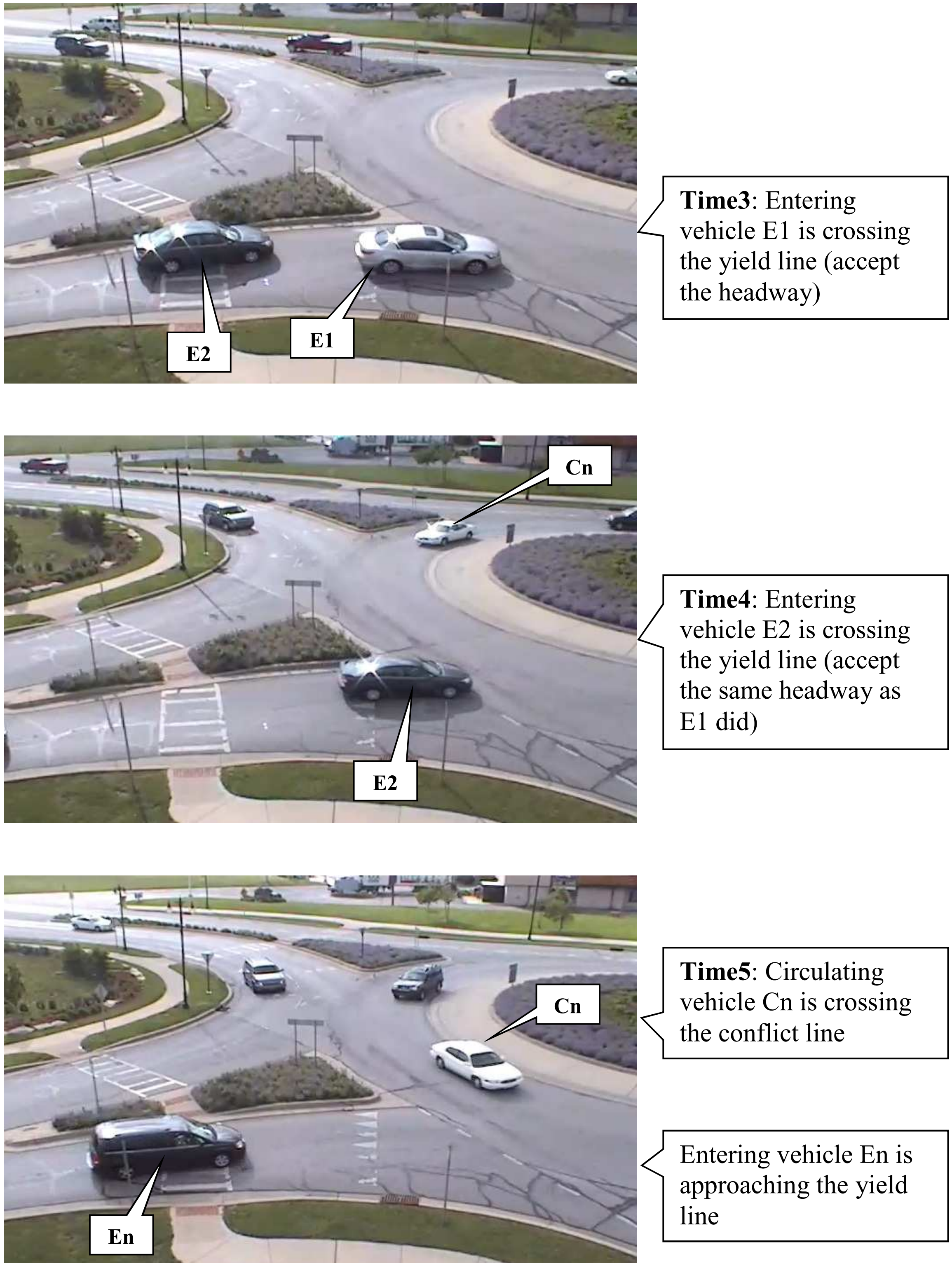

Figure 4-7 Illustration of Rejected, Accepted, and Follow-up Headways
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Based on the recorded time stamps at the specific conditions described above, the headways were calculated as follows:

Rejected headway = Time2 – Time1

Accepted headway = Time5 – Time2

Follow-up headway = Time4 – Time3

The data set extracted from the video footage contains 2,899 observations for critical headway and 813 observations for follow-up headway estimations. The observations are broken down by roundabout in Table 4-2 and by studied factors in Table 4-3. The available variables for model estimation are shown in Table 4-4.

Table 4–2 Sample Size and Date of Data Collection

Roundabout	**Approach**	**Sample Size**		**Date of Data Collection**
		Rejected/Accepted Headway	**Follow-up Headway**	
SR 25 – Old SR 25, Lafayette	E	160	47	October 2013
SR 32/38 –Union Chapel Road, Noblesville	N	365	130	May 2014
SR 32/38 – Promise Road, Noblesville	S	181	30	December 2013
Indiana 130– LaPorte Ave–N. Sturdy Road, Valparaiso	All	2,193	606	June 2014

Table 4–3 Sample Size by Studied Factors

Condition	Rejected/Accepted Headway	Follow-up Headway
Rural Area	544	165
Heavy Vehicle	108	12
Nighttime/twilight	121*	10
Right-Lane	254	15
Right-Turn	50	-

*Observations are from one rural roundabout.

Table 4–4 Variables Available to Estimate Critical Headways

Variable No.	Variable Description
1	Measured Headway (sec)
2	Event (decision): 1 if accepted, 2 if rejected, 3 if follow-up
3	Number of Rejected Headways (as proxy to congestion level)
4	Vehicle Type: 1 if car or pickup, 2 if Single Unit Truck, 3 if Bus, 4 if Trailer, 5 if other types (e.g. motorbike)
5	Approach Speed: 1 if high-speed, 2 if low-speed
6	Lane Use: 1 if left, 2 if right
7	Turning Maneuver: 1 if through/left/U-turn, 2 if right
8	Lighting Condition: 1 if daytime, 2 if twilight, 3 if nighttime
9	Weather Condition: 1 if no rain, 2 if rainy
10	Area Type: 1 if urban, 2 if rural

Finally, the extracted data were organized in a usable format for future research work. Table 4-5 shows a sample of the data inventory format. The codes used for the explanatory variables are as described in Table 4-4.

Table 4–5 Data Inventory Format

RAB	Approach	Weather	Light	Driver	Headway	Event	NRH	Veh Type	Lane	Turn	Area Type
4	2	1	1	1	2.52	2	0	4	1	1	1
4	2	1	1	1	2.97	2	1	4	1	1	1
4	2	1	1	1	7.68	1	2	4	1	1	1
4	2	1	1	2	1.2	2	0	4	2	2	1
4	2	1	1	2	6.66	1	1	4	2	2	1
4	2	1	1	3	2.2	2	0	4	1	1	1
4	2	1	1	3	1.87	2	1	4	1	1	1
4	2	1	1	3	1.66	2	2	4	1	1	1
4	2	1	1	3	1.48	2	3	4	1	1	1
4	2	1	1	3	8.34	1	4	4	1	1	1
4	2	1	1	4	2.14	2	0	2	1	1	1
4	2	1	1	4	2.28	2	1	2	1	1	1
4	2	1	1	4	1.97	2	2	2	1	1	1

CHAPTER 5. RESULTS AND DISCUSSION

5.1 Results

5.1.1 Binary Probit Model for Critical Headways

SAS statistical software was used to estimate the model for critical headways. The estimated binary Probit model is shown in Table 5-1. The base conditions were defined as a passenger car, low-speed approach in an urban area, daylight, and single-lane roundabout. The independent variables that were found to be statistically significant at a 5% significance level were measured headway, dual-lane in rural area, heavy vehicles, nighttime/twilight conditions, and number of rejected headways (as a proxy variable for congestion level). The constant (intercept) was also significant.

Table 5–1 Binary Probit Model for Critical Headway Estimation

Variable	**Parameter Estimate**	***t* - value**
Constant (Intercept)	-4.775	-27.44
Measured Headway	1.016	26.00
Dual-Lane in Rural Area	-0.545	-3.77
Heavy Vehicles (Trucks and Buses)	-1.015	-3.61
Nighttime/twilight (in the Presence of Street Lighting)	-1.202	-2.84
Number of Rejected Headways (As Proxy to Congestion Level)	0.511	5.77
Number of Observations	2,894	
Maximum Likelihood at Convergence	– 512.360	
McFadden Adjusted ρ^2	0.696	

The effects of the significant variables on critical headway are quantified using Equations (3-6) and (3-7) and summarized in Table 5-2:

Table 5–2 Effects of the Influencing Factors on Critical Headways

Variable	**Sample Size**	**Effect**	**Magnitude (sec)**
The Base-Case Condition (Single-lane, urban area, passenger car, daylight)	1153	Base	4.7
Dual-Lane in Rural Area	544	Increasing	0.5
Heavy Vehicles (Trucks and Buses)	108	Increasing	1.0
Nighttime/twilight (in the Presence of Street Lighting)	121	Increasing	0.7*
Number of Rejected Headways (As Proxy to Congestion Level)	968	Decreasing	0.5

*The clear difference between nighttime and daylight is 1.2 (rural daytime) – 0.5(rural nighttime) = 0.7.sec, because the data were collected from a rural roundabout only.

Although the estimated model revealed the fact that the driver behavior is affected by the number of rejected headways, it is more convenient to have one model to normalize this effect, for practice purposes. Therefore, the NRH indicator variable is excluded from the model. For the estimated model without this variable refer to Appendix B (Table B-1). Consequently, the base-case critical headway was estimated 4.4 sec (as opposed to 4.7 sec). The cumulative distribution function of the estimated critical headways (normal distribution with mean, μ, 4.4, and standard deviation, σ, 1.0) for the base-case condition is shown in Figure 5-1. The estimated critical headways for other conditions along with the MLM results and NCHRP Report 572 findings are summarized in Table 5-3.

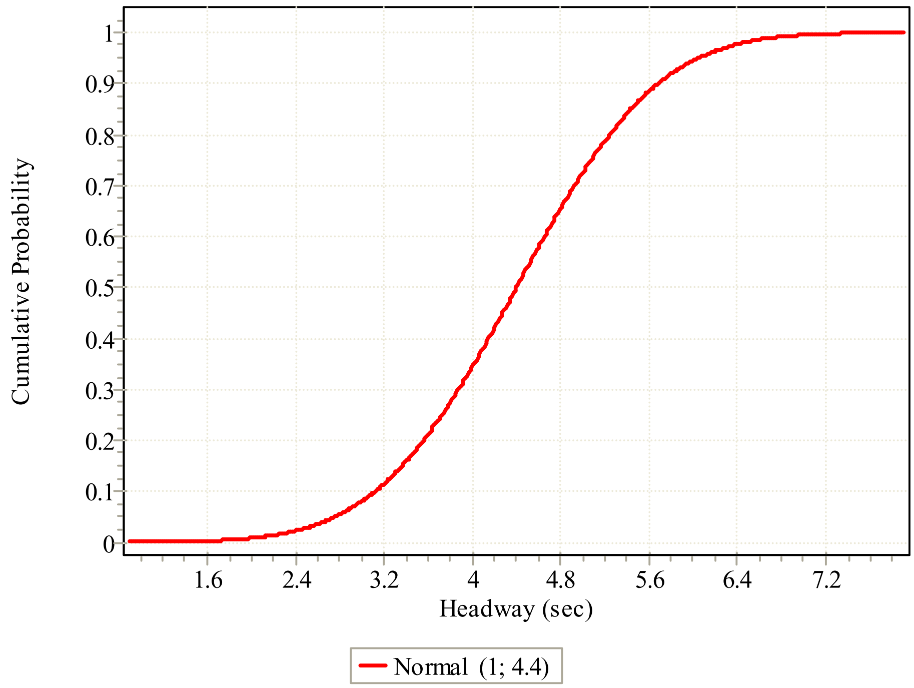

Figure 5-1 Cumulative Distribution Function of the Estimated Critical Headways for the Base-Case Condition based on Probit Model

Table 5–3 Estimated Critical Headways: MLM, Probit Method and NCHRP 572 Findings

Condition	Critical Headway (sec)		
	MLM	**Probit**	**NCHRP 572 (HCM 2010)**
Single-lane	4.2 (0.8)*	4.4 (1.0)*	5.1
Dual-lane (right and left)	4.9 (1.2)	5.0 (1.0)	4.2 R and 4.5 L
Heavy vehicles (trucks and buses)	5.3 (0.8)	5.5 (1.0)	-
Nighttime/twilight (in the presence of street lighting)	5.6 (0.8)	5.6 (1.0)	-

*Standard Deviations in Parentheses

5.1.2 MLM Results for Critical Headways

The estimation for critical headways was repeated using the MLM procedure recommended by Troutbeck (2014), for comparison purposes. The original sample was divided into separate scenarios to estimate the means and standard deviations of the critical headways for the base case, dual-lane in rural area, heavy vehicles, and nighttime/twilight conditions. As the MLM requires pairwise observations, only the largest rejected headway and the accepted headway were considered. Therefore, the congestion effect based on the number of rejected headways could not be estimated. The estimated critical headways based on the MLM are shown in Table 5-4.

Table 5–4 Summary of Estimated Critical Headways Based on MLM

Condition	Sample Size	Critical Headway (sec)
Single-Lane in Urban Area	1152	4.2 (0.8)*
Dual-Lane in Rural Area	316	4.9 (1.2)
Heavy Vehicles (Trucks and Buses)	66	5.3 (0.8)
Nighttime/twilight (in the Presence of Street Lighting)	60	5.6 (0.8)

*Standard Deviations in Parentheses

The cumulative distribution function of the estimated critical headways (log-normal distribution with mean, μ, 4.2, and standard deviation, σ, 0.8) for the base-case condition is shown in Figure 5-2.

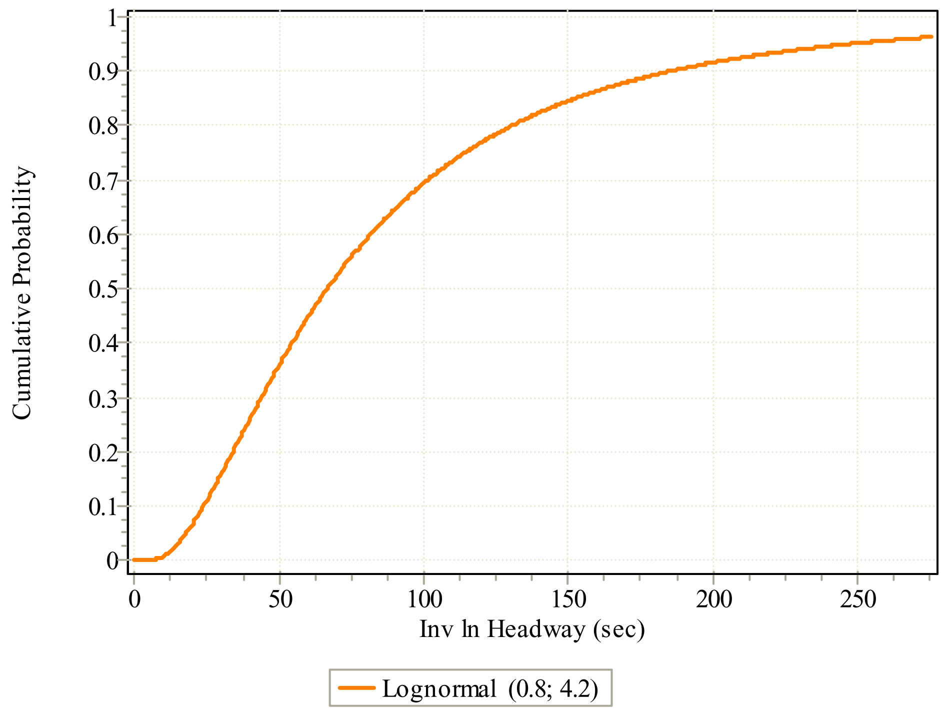

Figure 5-2 Cumulative Distribution Function of the Estimated Critical Headways for the Base-Case Condition based on MLM

5.1.3 Follow-up Headways

The follow-up headways were averaged and are presented in Table 5-5. The average follow-up headways for heavy vehicles and nighttime conditions are based on relatively small sample sizes and require further data in order to make a stronger conclusion. Based on the estimated values, 2.7 sec can be used as a representative follow-up headway for all the studied conditions, but for heavy vehicles.

Table 5–5 Summary of Estimated Follow-up Headways (sec) for the Studied Conditions (Standard Deviations in Parentheses)

Condition		Single Lane	Dual Lane	
	Sample Size	**Approach**	**Left Lane**	**Right Lane**
Single-Lane in Urban Area	[174, 334, 15]*	2.7 (0.6)	2.7 (0.6)	2.5 (0.4)
Dual-Lane in Rural Area	20, 41, 135	2.6 (0.4)	2.8 (0.7)	2.5 (0.8)
Heavy vehicles (trucks and buses)	-,12,-	-	3.3 (0.9)	-
Nighttime/twilight (in the Presence of Street Lighting)	10, -, -	2.5 (0.4)	-	-

*Values correspond to three samples: approach, left-lane, and right-lane; respectively.
"-" indicates no data

5.2 Discussion

The results are discussed from three different viewpoints: (1) significance of the influencing factors on driver gap-acceptance behavior, (2) the calibrated HCM 2010 capacity equations for Indiana conditions, and (3) the methodological approach for critical headway estimation.

5.2.1 Capacity Factors

The results indicated that drivers of heavy vehicles (trucks and buses) were likely to accept 1.1 sec longer headways than drivers of passenger cars. Such a result was expected because of truck's lower acceleration rates and longer lengths require more time to clear the conflict area. Likewise, the difference in the follow-up headways was 0.6 sec. A proper method of accounting for the capacity effects of heavy vehicles is adjusting the service time – the time spent at the first position in queue before entering the roundabout. This method is used in the HCM to calculate the capacity of a traffic lane shared by different turning movements at unsignalized intersections (Highway Capacity Manual, 2010). The average service time is calculated from Equation (5-1) separately for passenger cars and heavy vehicles (say trucks) for various circulatory flows, and then the average mixed service time was calculated from Equation (5-2). Finally, the mixed entry capacity is calculated using Equation (5-3).

$$S_{car} = \frac{1}{C_{car}}, \quad S_{truck} = \frac{1}{C_{truck}} \tag{5-1}$$

$$S_{mix} = P_{car} \cdot S_{car} + P_{truck} \cdot S_{truck} \tag{5-2}$$

$$C_{mix} = \frac{1}{S_{mix}} \tag{5-3}$$

Where,

S_{car}, S_{truck}: Average service times for cars and for trucks in hours, respectively,

C_{car}, C_{truck}: Entry capacities for cars and for trucks in veh/h, respectively,

P_{car}, P_{truck}: Proportions of cars and trucks in the entry lanes, respectively,

S_{mix}: Average service time for the mixed flow in hours, and

C_{mix}: Entry capacity of the mixed flow in veh/h,

The entry capacity values for the mix of 90% passenger cars and 10% heavy vehicles and for various circulatory flows were estimated using the HCM capacity equations with the new estimated gap-acceptance parameters. The obtained capacities for mixed flow are compared to the corresponding capacities of a flow with no trucks in Figure 5-3. The reduced entry capacity for 10% heavy vehicles for various circulatory flows was estimated 7%, on average. This reduction was estimated 12% and 25% for 20% and 50% heavy vehicles, respectively.

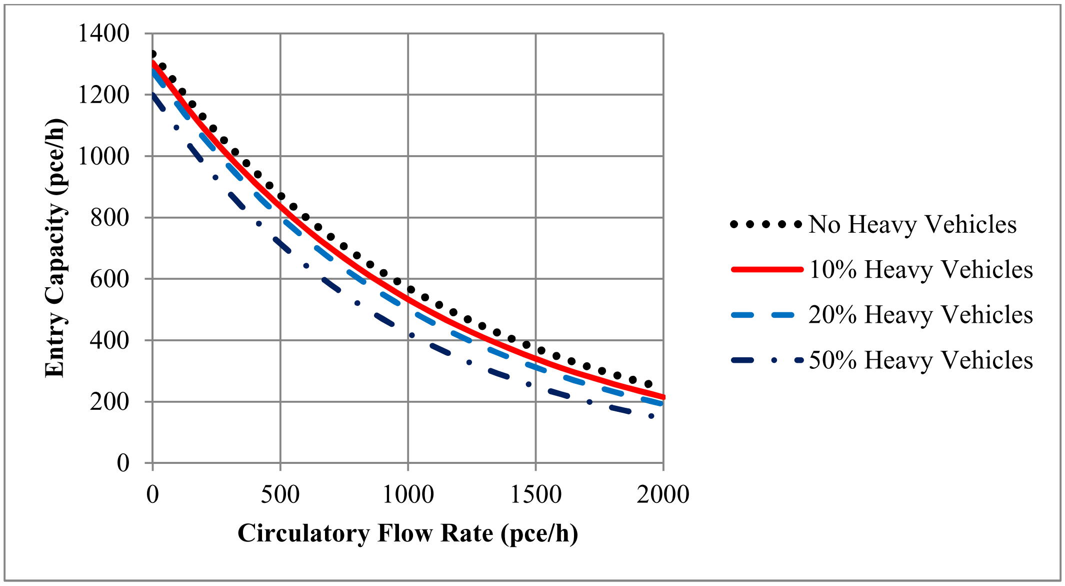

Figure 5-3 Effect of Heavy Vehicles on the Entry Capacity for Indiana Conditions

As discussed in Chapter 3, the HCM method considers the effects of heavy vehicles by converting the circulating heavy vehicle to a passenger car unit flow rate using an adjustment factor. SIDRA accounts for heavy vehicles by adjusting the critical and follow-up headways. The volume-weighted is another method introduced by Dahl and Lee (2012). The HCM method provides the vehicle adjustment factor of 0.91 calculated for 10% heavy vehicles on a roundabout approach (the same percentage for the circulating traffic) with Equations (2-10) and (2-11). The adjusted conflicting flow rates calculated with HCM method are shown in Column 2 of Table 5-6.

On the other hand, the SIDRA method provided the adjusted critical and follow-up headways of 4.4 sec and 2.7 sec, respectively, calculated with Equations (2-12) and (2-13).

$$t'_c = \frac{t_c}{f_{HV}} = \frac{4.4}{0.91} = 4.8 \text{ sec}, \quad t'_f = \frac{t_f}{f_{HV}} = \frac{2.7}{0.91} = 3.0 \text{ sec}$$

According to the volume-weighted method, the adjusted critical headways are calculated using Equations (2-14) and (2-15), as below. It was assumed that the follow-up headway for car following car is equal to that of car following truck and similar case for trucks.

$$t'_c = t_{c,C} \cdot (1 - P_{TE}) + t_{c,T} \cdot P_{TE}$$

$$t'_c = 4.4 \cdot (1 - 0.1) + 5.5 \cdot (0.1) = 4.5 \text{ sec}$$

$$t'_f = t_{f,CC}(1 - P_{TE})^2 + \left(t_{f,CT} + t_{f,TC}\right)(1 - P_{TE})P_{TE} + t_{f,TT} \cdot P_{TE}^2$$

$$t'_f = 2.7(1 - 0.1)^2 + (2.7 + 3.3)(1 - 0.1)0.1 + 3.3 \cdot (0.1)^2 = 2.8 \text{ sec}$$

Table 5-6 and Figure 5-3 present the entry capacity values, calculated with the three aforementioned methods, for a range of circulating traffic volumes.

Table 5–6 Effect of 10% Heavy Vehicles on the Entry Capacity Based on Service Time, HCM, SIDRA, and Volume-Weighted Methods for Indiana Conditions

Circulatory Flow		Entry Capacity (pce/h)				
(veh/h)	(pce/h)	No Heavy Vehicles	Service Time	HCM	Volume-Weighted	SIDRA
0	0	1330	1304	1330	1280	1210
200	220	1122	1092	1103	1077	1004
400	440	947	914	916	907	833
600	660	799	764	760	763	691
800	880	675	638	631	642	574
1000	1100	570	534	523	541	476
1200	1320	481	446	434	455	395
1400	1540	406	372	360	383	328
1600	1760	342	310	299	322	272
1800	1980	289	259	248	271	226
2000	2200	244	215	206	228	187

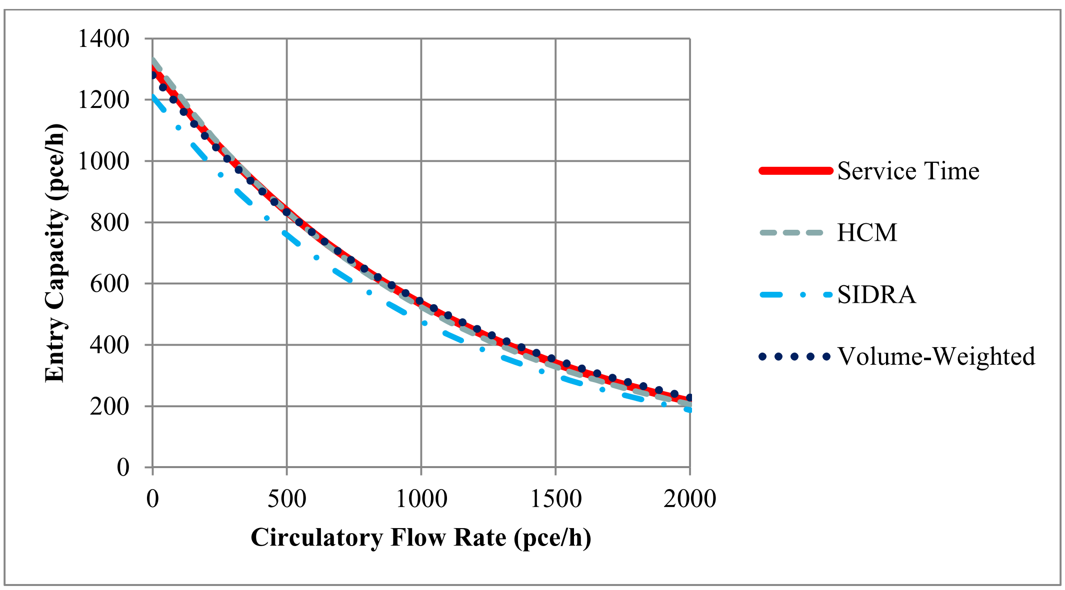

Figure 5-4 Effect of 10% Heavy Vehicles on the Entry Capacity Based on Service Time, HCM, SIDRA, and Volume-Weighted Methods for Indiana Conditions

As seen in Table 5-6 and Figure 5-4, the HCM method does not consider the fact that heavy vehicles on the approach have larger follow-up headways, thus over estimating the entry capacity at low circulating traffic. The SIDRA method produces the capacity estimates lower than the other methods. Evaluation of the reliability of these methods is recommended.

The effect of nighttime/twilight condition (in the presence of street lighting) indicated additional capacity reduction caused by a 0.6 sec longer critical headway than in daylight conditions, which was possibly due to poor visibility and the glare effect, which can adversely affect driver perception, resulting in longer critical headways. The reduction in capacity due to nighttime/twilight conditions is shown in Figure 5-5.

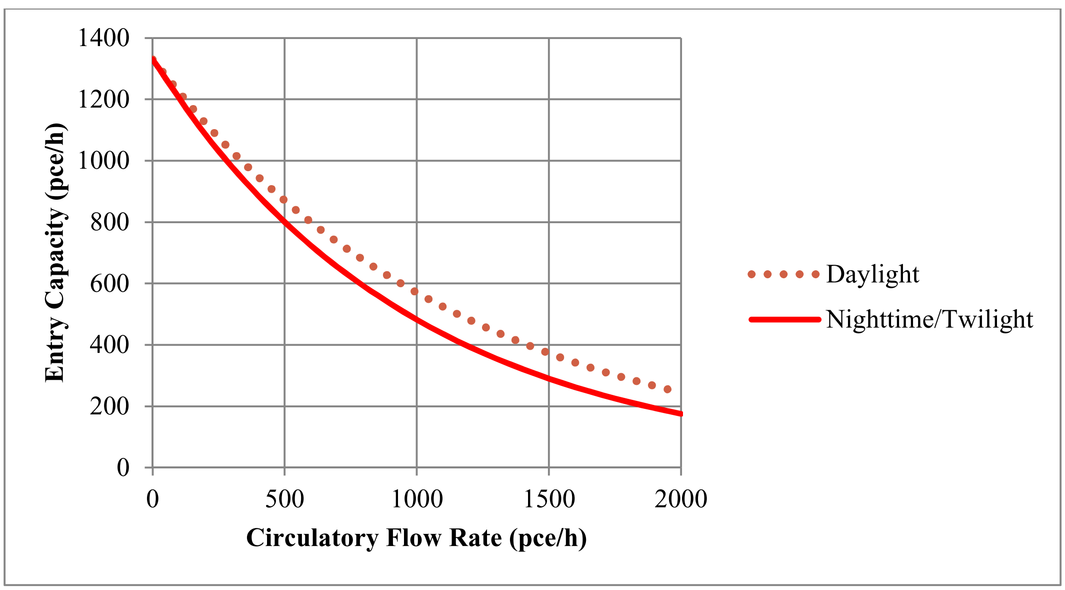

Figure 5-5 Effect of Nighttime/Twilight on the Entry Capacity for Indiana Conditions

Moreover, the number of rejected headways more than one, as an indicator variable, was statistically significant. The parameter sign was positive as expected, which implied that drivers who inspect the available shorter headways adapt to the existing condition and finally accept a shorter headway. Drivers in this situation accepted 0.5 sec shorter critical headways, on average, as indicated by the results.

On the other hand, the effect of the right turning maneuvers on the critical headway was not statistically different from other turns, and the effect of the right lane was not statistically different from the left lane. However, drivers accepted shorter headways when turning right or when entering the roundabout from the right lane than other drivers. This result may be attributed to the shorter paths across the conflict areas on roundabouts followed by these drivers than by other drivers. This may lead to higher confidence and to accepting shorter headways.

5.2.2 Indiana Conditions vs. HCM 2010

The mean critical headway for the studied single-lane roundabout was estimated 4.4 sec, which is 0.7 sec shorter than the NCHRP Report 572 average findings of 5.1 sec for single-lane roundabouts. In a separate calculation, the follow-up headway was estimated 2.7 sec, which is 0.5 sec smaller. Since functions A and B of the HCM capacity model depend upon the gap-acceptance parameters, the new values that reflect the local condition were 1,330 (as opposed to 1,130) and 0.00085 (as opposed to 0.001), respectively. The calibrated model for single-lane roundabouts on state roads in urban areas, based on the case study, is shown in Equation (5-4).

$$C_e = 1{,}330e^{(-0.85\times10^{-3})v_c} \tag{5-4}$$

The effects of the estimated gap-acceptance parameters on the entry capacity for different circulating traffic conditions are shown in Figure 5-6. For comparison purposes, the HCM entry capacity for single-lane roundabouts is also illustrated in the same figure. In the ideal situation when there is no conflicting traffic, the saturation flow rate (the maximum traffic flow a lane can serve in one hour) depends upon the follow-up headway only and is 1,330 pce/h for the local condition, which is 200pce/h higher (18% increase) than that of the HCM for roundabouts. At heavy traffic (e.g. 1,400 veh/h) this difference is approximately 130 pce/h (46% increases). The difference in capacities can be averaged as 30% increase for local conditions. Generally, this implies that drivers are more accustomed to roundabouts in urban areas and accept smaller headways, which improves the capacity.

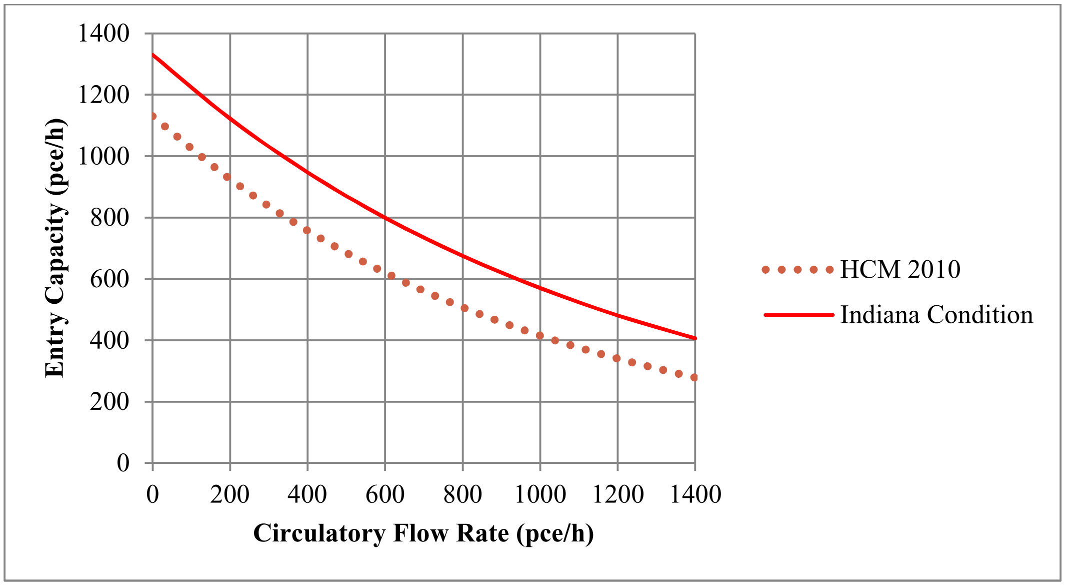

Figure 5-6 Entry Capacity of Single-Lane Roundabouts for Indiana Conditions vs. that of the HCM 2010

On the other hand, the critical headway on dual-lane roundabouts in rural areas was estimated 5.0 sec, on average. The estimated critical headway is larger than the average critical headways for the left and right lanes reported in NCHRP Report 572. In contrast to the NCHRP 572 findings, the critical headway in the right lane compared to the left lane was not statistically significant. On rural high-speed roads, drivers experience lower delays than on low-speed urban roads due to fewer traffic control features (e.g. intersections), which implies that drivers reject longer headways. This behavior may become more aggressive when rural roads start experiencing longer delays. On the other hand, the follow-up headway was estimated 2.7 sec, on average, which is 0.5 sec shorter than the NCHRP Report 572 findings for dual-lane roundabouts. The calibrated equation, based on the new estimated gap-acceptance parameters, for dual-lane roundabout in rural areas is shown in Equation (5-5).

$$C_e = 1{,}330e^{(-1.0\times10^{-3})v_c} \quad (5\text{-}5)$$

The difference in the entry capacity is shown in Figure 5-7 for a range of circulating traffic. As can be seen, the entry capacity is higher (10% increase, on average) for light circulating traffic (up to 500 pce/h) and lower (15% decrease, on average) for medium to heavy circulating traffic (500-2,000 pce/h), compared to the left lane calculated capacity from the HCM equation. The implication is that drivers behave differently on roundabouts on high-speed approaches; this was expected as roundabout is relatively a new traffic control feature on high-speed roads.

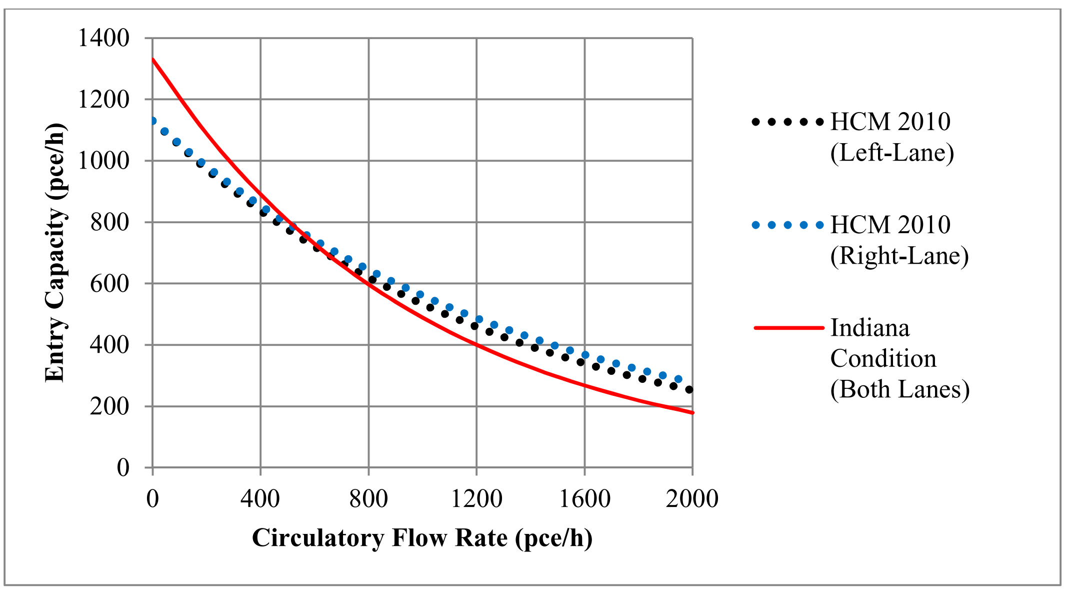

Figure 5-7 Entry Capacity of Dual-Lane Roundabouts for Indiana Conditions vs. that of the HCM 2010

The calibrated capacity equations for both single-lane and dual-lane roundabouts are helpful for capacity estimation of Indiana roundabouts on state roads.

5.2.3 Model Evaluation

The estimated gap-acceptance parameters from three hours of traffic operations on a single-lane roundabout were used for the simulation purpose. The results of the estimated critical headways, based on different methods, are shown in Table 5-7. The average follow-up time was 2.7 sec with a standard deviation of 1.0 sec.

Table 5–7 Estimated Critical Headways

Model	Assumptions	Distribution	Sample Size	Critical Headway (sec)	Standard Deviation
Probit	Inconsistent driver behavior	Normal	1149*	4.478	0.958
MLM	Consistent driver behavior	Log-normal	580	4.175	0.796

*The sample includes all rejected headways as opposed to the largest ones.

The gap-acceptance behaviors of the same drivers were simulated based on the estimated parameters in such a way that random critical headways were generated based on random probabilities (between 0 and 1) and the estimated mean and standard deviation, which was consistent with the assumptions of the used methods. For consistent behavior one critical headway was generated for one approaching driver while for inconsistent behavior as many critical headways as the number of decisions of the same approaching driver were generated. It is worth mentioning that unlike previous studies reviewed in literature, traffic was not generated on the entering or circulation roadways, rather the behavior of the actual drivers were simulated.

The delay at the first position of the queue was set as a criterion. The estimated delay based on simulation was compared to the measured delay from the actual observations. The results are shown in Table 5-8. The simulation results indicated very close average delays between the scenarios. The *t*-statistic test showed that the differences were not statistically significant among the simulated scenarios as well as with the actual one. Nevertheless, the average delays resulted from the Probit estimated critical headways are slightly on the conservative side and the assumption of inconsistent driver behavior seems to be more realistic than the assumption of fully consistent behavior.

Table 5–8 Simulation Results to Evaluate Different Methodological Assumptions for Critical Headway Estimation

Scenario	Delay at the First Position of the Queue (sec/veh)	
	Average	Standard Deviation
Actual	3.364	7.471
Inconsistent driver behavior and normal distribution of critical headways (Probit)	3.419	6.295
Consistent driver behavior and log-normal distribution of critical headways (MLM)	3.296	7.530

Furthermore, the difference in the results when all the rejected headways were used, were rather limited, comparable to the case with only the largest rejected headway (4.424 sec as opposed to 4.251 sec), the estimated models are shown in Appendix B (Tables B-3 and B-4). Using all the rejected headways corresponds to the assumption of the lack of driver consistency in rejecting headways while selecting the largest value is equivalent to the assumption of full consistency. Thus, the assumption of inconsistent driver behavior allows using all the data collected which contributes to a more confident estimation of the critical headways and to a more adequate model that is not contradicted by the observable data.

To summarize the above discussions, a number of factors, including vehicle type and lighting condition, influence driver gap-acceptance behavior on roundabouts, which in turn affect the capacity. Ignoring such factors may lead to inaccurate capacity estimation and less of an understanding of roundabout operational performance. Furthermore, using the default HCM 2010 capacity equations for roundabouts without calibrating to local conditions may over- or under-estimate the capacity for these conditions. Furthermore, a realistic and efficient estimation method of the gap acceptance parameters is important; the assumption of inconsistent driver behavior may be expected to result in more accurate estimations.

CHAPTER 6. CONCLUSIONS

6.1 Conclusions

Previous studies on roundabouts mainly focused on mean critical headway and follow-up headway estimation. Limited research was found in the literature review that investigated the effects of heavy vehicles and other factors influencing these parameters. Furthermore, most of the studies were on roundabouts in urban/suburban areas. The motivation for the present research was to investigate the effects of heavy vehicles, along with the area type and nighttime/twilight conditions, on the critical headway and follow-up headway of drivers maneuvering roundabouts on high-speed roads.

This thesis revealed that heavy vehicles increased the critical headway, and in turn reduced the entry capacity of roundabouts. Drivers of heavy vehicles, on average, accepted a 1.1 sec longer critical headway than drivers of passenger cars. The effects of nighttime/twilight conditions indicated additional capacity reduction caused by a 0.6 sec longer critical headway compared to daylight conditions. Likewise, drivers on dual-lane roundabouts in rural areas accepted a 0.6 sec longer critical headway than drivers on single-lane roundabouts in urban areas. Furthermore, the number of rejected headways more than one, as an indicator variable, was found statistically significant with a positive sign. Contrary to some previous research results, including NCHRP Report 572, the difference between the critical headways for the left and right lanes on dual-lane roundabouts was not statistically significant. Also, the difference in critical headways for the right turning movement compared to other turns (through, left and U-turn) was not statistically significant.

Moreover, it was determined that the gap-acceptance parameters for a single-lane roundabout on a low-speed state road were less than those of the National Cooperative Highway Research Program (NCHRP) Report 572 average estimated values – which are currently incorporated into Highway Capacity Manual (HCM) 2010, resulting on average in 30% higher capacity for Indiana conditions. In contrast, the estimated critical headway was larger for dual-lane roundabouts on high-speed state roads, resulting in 15% reduced capacity (for medium to high circulatory traffic volumes) for Indiana conditions.

The MLM (Troutbeck) method is widely used for estimating the mean and variance of the critical headway. However, this method does not account for the fact that driver behavior may be inconsistent (i.e., drivers may accept shorter gaps than the largest associated rejected gaps). Furthermore, the MLM method was not designed to determine the influence of other factors in the critical headway estimation. Therefore, the concept of standard binary Probit method was used in this thesis in order to relax some of the MLM assumptions. In addition, the observed driver behaviors (from video records) and the findings from simulations revealed that the assumption of inconsistent driver behavior in gap-acceptance analysis is valid and leads to more reasonable estimations.

Consequently, the critical headway estimates were obtained with all the rejected headways using the Probit model. The obtained estimates of the critical headway were only slightly different from the estimate obtained with the MLM method when only the largest rejected headway for each driver were used. Nonetheless, inclusion of full information (all rejected headways) is recommended to account for inconsistent driver behavior and to obtain more reliable estimates.

The findings of this thesis are intended to improve capacity estimation for the roundabouts planned on Indiana state roads. The HCM 2010 capacity equations were updated with the new estimated gap-acceptance parameters for Indiana. The findings contribute to better understanding of the roundabout capacity factors.

6.2 Recommendations

The research findings may be helpful in improving capacity estimation for Indiana roundabouts located on high-speed state roads. Studying more roundabouts on high-speed roads, particularly, in nighttime conditions is recommended. Furthermore, roundabouts still may be new to many drivers so repeating similar studies in the future is needed to update the knowledge after more drivers have adjusted to this relatively new design and to more frequent delays on state roads.

6.3 Research Limitations

Since this thesis covered a limited number of sites in the state of Indiana, the results need to be improved by studying more sites around the country in order to generalize the effects of the studied conditions on the capacity of roundabouts built on high-speed roads.

The findings of this thesis are based on low and medium traffic volumes presently observed on high-speed rural and suburban roads. Heavy traffic flow may affect driver behavior; therefore, studying such roundabouts in heavier traffic conditions might improve the results.

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Appendix A Descriptive Statistics

This appendix presents some descriptive statistics of the observed headways.

Basic Statistics

Table A-1 Observed Maximum Rejected and Minimum Accepted headways

Roundabout	**Max Rejected Headway (sec)**	**Min Accepted Headway (sec)**
SR 25 – Old SR 25, Lafayette	6.33	4.87
SR 32/38 –Union Chapel Road, Noblesville	6.14	2.29
SR 32/38 – Promise Road, Noblesville	6.27	4.26
Indiana 130– LaPorte Ave–N. Sturdy Road, Valparaiso	7.31	2.57

The observed follow-up headways varied from 1.0 sec to 5.0 sec, for all the studied roundabouts.

Rejected/Accepted Headway Distributions

Utilizing EasyFit tool, the probability density functions (pdf) of the measured rejected and accepted headways, for the single-lane roundabout, are shown in Figure A-1. The best fit, among over sixty distribution types programmed in the EasyFit tool, was the Pearson 5 for rejected headways and Burr for accepted headways. This was not the case for all the studied roundabouts. Therefore, it is implied that the observed rejected/accepted headways distribution is not reasonable to use as a base for the latent critical headway distribution.

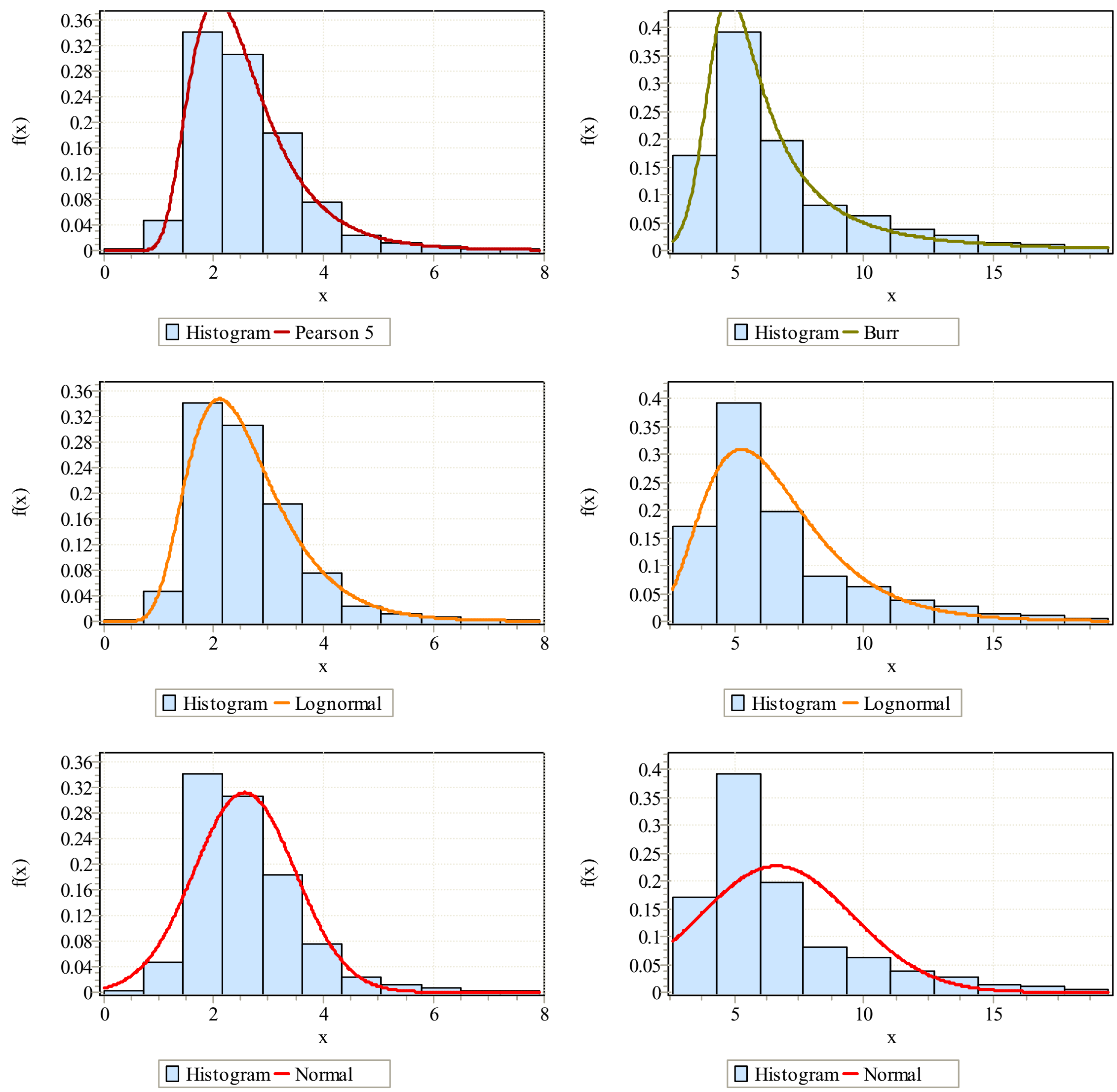

Figure A-1 pdf of the Measured Rejected and Accepted Headways for the Studied Single-Lane Roundabout (Left: Rejected Headways; Right: Accepted Headways)

Appendix B Intermediate Results from SAS Binary Probit Models

This appendix presents the results of several statistical models that have been pointed to in Chapter 5.

Table B-1 Binary Porbit Model for Critical Headways (NRH is not considered)

Variable	**Parameter Estimate**	***t* - value**
Constant (Intercept)	-4.480	-28.59
Measured Headway	1.006	26.59
Dual-Lane in Rural Area	-0.568	-4.03
Heavy Vehicles (Trucks and Buses)	-1.091	-3.92
Nighttime/twilight (in the Presence of Street Lighting)	-1.198	-2.94
Number of Observations	2,894	
Maximum Likelihood at Convergence	– 529.425	

Table B-2 Estimated Critical Headways for the Studied Conditions (based on Table B-1)

Condition	**Sample Size**	**Critical Headway (sec)**
The Base-Case Condition (Single-lane, urban area, passenger car, daylight)	2121	4.4 (1.0)*
Dual-Lane in Rural Area	544	5.0 (1.0)
Heavy Vehicles (Trucks and Buses)	108	5.5 (1.0)
Nighttime/twilight (in the Presence of Street Lighting)	121	5.6 (1.0)

*Standard deviations in parentheses

Table B-3 Binary Porbit Model for Critical Headways (including all rejected headways)

Variable	Parameter Estimate	*t* - value
Constant (Intercept)	-4.690	-25.97
Measured Headway	1.060	24.19
Number of Observations	2,121	
Maximum Likelihood at Convergence	–434.260	

The estimated mean and standard deviation of the critical headway, based on the model shown in Table B-3, are 4.424 sec and 0.943 sec, respectively.

Table B-4 Binary Porbit Model for Critical Headways (only the largest rejected headways)

Variable	Parameter Estimate	*t* - value
Constant (Intercept)	-3.860	-19.18
Measured Headway	0.908	19.25
Number of Observations	1,152	
Maximum Likelihood at Convergence	–381.160	

The estimated mean and standard deviation of the critical headway, based on the model shown in Table B-4, are 4.251 sec and 1.101 sec, respectively.