5-2015

CAPACITY MODELS FOR MULTILANE ROUNDABOUTS AND THEIR EVALUATION USING MICROSCOPIC SIMULATION MODELS

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CAPACITY MODELS FOR MULTILANE ROUNDABOUTS AND THEIR EVALUATION USING MICROSCOPIC SIMULATION MODELS

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This thesis is submitted in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering

Under the Supervision of Dr. Kamran Ahmed

May 2015

Declaration of Original Work

I, Mohamad A. Shrayteh, the undersigned, a graduate student at the United Arab Emirates University (UAEU) and the author of the thesis titled "*Capacity Models for Multilane Roundabouts and Their Evaluation Using Microscopic Simulation Models*", hereby, solemnly declare that this thesis is an original research work done and prepared by me under the guidance of Dr. Kamran Ahmed, in the College of Engineering at UAEU. This work has not been previously produced as the basis for the award of any academic degree, diploma or similar title at this or any other university. The materials borrowed from other sources and included in the thesis have been properly cited and acknowledged.

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Abstract

Compared to previous versions of the manual, the Highway Capacity Manual 2010 has provided more comprehensive capacity models for single and multilane roundabouts. The Highway Capacity Manual 2010 multilane roundabout capacity models are limited to two-by-two lanes, that is, two entry lanes and two circulating lanes. These capacity models are not valid for the three-by-three–lane roundabouts (three entry lanes and three circulating lanes) due to different traffic flow characteristics and features. This limitation of the Highway Capacity Manual 2010 model is also clearly mentioned in the manual. In this research, capacity models and curves were developed for three-by-three–lane roundabouts. More than 168 hours of video recordings were done on 12 three-by-three–lane roundabouts. The extracted data from the video recordings was used to understand the traffic operations and to develop the capacity models. It was found that lane utilization of the outermost circulating lane was low, and drivers preferred to use the middle entry lane for through movements as compared to the other two lanes. Based on the performance and usefulness, exponential regression models were selected for capacity estimation. The capacity curves were developed for the entry approach and for each entry lane of the three-by-three–lane roundabout. These models were used to estimate the follow-up headway and critical gap. The output of the proposed models showed that the entry volume decreases with the increase of the circulating flow at the three-by-three–lane roundabouts. The proposed models were also validated using a microscopic traffic-simulation model. A close association was found between outputs from both models. Transportation engineers can use the capacity models and curves presented in this research to perform the three-by-three–lane roundabout capacity analysis.

Keywords: Three-by-three–lane roundabout, multilane roundabout, VisSim, capacity models, capacity curves, conflict areas.

Title and Abstract (in Arabic)

تطوير نمازج السعة \ القدرة الإستيعابية للدوارات ثلاثية المسارات

الملخص

وفر دليل قدرة الطرق السريعة 2010 (HCM 2010) نماذج قدرة للدوارات التي لها حارة واحدة (Single-Lane) و التي لها أكثر من حارة (Multi-Lane) كذلك وتعتبر هذه النماذج أكثر شمولية مقارنة مع الإصدارات السابقة لهذا الدليل. تقتصر هذه النماذج على الدوارات التي لها حارتان فقط داخل الدوار وعند دخول الدوار. هذه النماذج غير صالحة للدوارات الثلاثية المسارب (التي لها ثلاث حارات داخل الدوار وعند الوصول للدوار) نظرا لإختلاف خصائص تدفق حركة المرور والميزات لهذه الدوارات. وقد ذكر دليل قدرة الطرق السريعة 2010 (HCM 2010) بشكل واضح بأن هذه النماذج صالحة للدوارات التي لها حارتان فقط. في هذا البحث، تم تطوير نماذج القدرات (Capacity Models) ومنحنيات (Capacity Curves) للدوارات الثلاثية المسارب. لقد تم تسجيل أكثر من 168 ساعة فيديو لإثني عشر دوارا وكل هذه الدوارات هي ثلاثية المسارب. وقد استخدمت البيانات المستخرجة من تسجيلات الفيديو لفهم عمليات المرور وفي تطوير نماذج القدرات.وقد وجد أن استخدام الحارة الداخلية والتي هي على اقصى اليمين كان منخفضا حيث أن السائقين يفضلون استخدام الحارة الوسطى للذهاب قدما (Through) بالمقارنة مع المسربين الأخرين. وبناء على الأداء قد تم اختيار نماذج الانحدار الأسي لتقدير القدرات. وقد وضعت منحنيات القدرة على مسارب الدخول ككل وكل حارة دخول على حدة. أظهرت النتائج من النماذج المقترحة أن حجم دخول السيارات يتناقص مع زيادة تدفق السيارات المتداولة حول الجزيرة الوسطية، في الدوارات الثلاثية المسارب. لقد تم التحقق من صحة النماذج المقترحة أيضا باستخدام البرامج المختصة لمحاكاة نماذج حركة المرور. وقد كان هناك ارتباط وثيق بين المخرجات من كلا النموذجين. نماذج القدرات ومنحنيات المقدمة في هذا البحث يمكن أن تستخدم من قبل مهندسي النقل لتقدير القدرة الإستيعابية للدوارات الثلاثية المسارات قبل الشروع بتنفيذ الدوار.

كلمات دليلية: دوارات الثلاثية المسارب, الدوارات التي لها أكثر من حارة, برنامج المحاكاة للحركة المرورية (VisSim), نماذج القدرات, منحنيات القدرة, مناطق النزاع المرورية.

Acknowledgments

I would like to thank my advisor, Dr. Kamran Ahmed, for his tremendous support and encouragement throughout my research work. His efforts and support helped me carry out the research work and grow as a research scientist.

I would also like to thank Prof. William C. Taylor and Dr. Timur Mauga for serving as committee members. Their suggestions and advice helped me to carry out the research activities.

The efforts put out by my family, including my father, mother, and beloved wife Malak, have been tremendous. Without their support and prayers, it would have been impossible to complete the research work within the limited time frame. I would also like to thank my friends and relatives who supported me in every way they could to help me achieve my aspirations.

Finally, I express my deep thanks to Dr. Breiwish for his limitless support and encouragement at TrafQuest, the company I have been working for since 2007.

Dedication

I dedicate this thesis work to my parents, family, and coming-soon baby.

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List of Abbreviations

HCM:	Highway Capacity Manual
FHWA	Federal Highway Administration
LOS:	Level of Service
R.O.W:	Right of Way
CA:	Conflict Areas
PR:	Priority Rules
PCE:	Passenger Car Equivalent
PC	Passenger Car
DC	Data Collection
LV	Light Vehicle
HV	Heavy Vehicle
E- Lane 1:	Entry Volume at the first Lane – near the median for Field Data
E- Lane 2:	Entry Volume at the second Lane – middle lane
E- Lane 3:	Entry Volume at the third Lane – near the R.O.W boundary
E-Total:	Total Entry Volumes for the three entry lanes for Field Data
C-Lane 1:	Circulating Volume at the first Lane – near the internal island
C-Lane 2:	Circulating Volume at the second Lane – middle lane
C-Lane 3:	Circulating Volume at the third Lane – near the approach
C-Total:	Total Conflicting volume of the three circulating lanes for Field Data
V-E- Lane 1:	Same as “E-Lane 1” but for VisSim data/output
V-E- Lane 2:	Same as “E-Lane 2” but for VisSim data/output
V-E- Lane 3:	Same as “E-Lane 3” but for VisSim data/output

V-E-Total: Same as “E- Total” but for VisSim data/output

V-C-Lane 1: Same as “C-Lane 1” but for VisSim data/output

V-C-Lane 2: Same as “C-Lane 2” but for VisSim data/output

V-C-Lane 3: Same as “C-Lane 3” but for VisSim data/output

V-C-Total: Same as “C- Total” but for VisSim data/output

Chapter 1: Introduction

1.1. Overview

The Highway Capacity Manual (HCM 2010) [1] defines roundabouts as ". . . intersections with a generally circular shape, characterized by the yield on entry and circulation around a central island." Roundabouts are becoming popular all over the world. Concurrently, drivers' behavior toward and experience with roundabout rules and regulations are also maturing. Traffic operations and flow conditions at roundabouts are more dependent on the drivers' behavior, as compared to operations at signalized intersections. Drivers clearly understand stop and go regulations at signalized intersections (i.e., a green light means drivers can enter the intersection, whereas a red light means drivers need to stop and wait), whereas, it is difficult to convey to drivers when and when not to enter a roundabout. Whether to accept or reject the available gap in the circulating traffic to enter the roundabout depends wholly on the driver's discretion. The schematics of traffic operations at roundabouts complicate the modeling and estimation of the roundabout's capacity, particularly for multilane roundabouts that have more entering and circulating lanes. Hence, modeling traffic operations at multilane roundabouts is more complicated and difficult to develop. This issue is further complicated by the diverse mix of drivers in the UAE with differing social habits, backgrounds, and experiences.

Compared to previous version, HCM 2010 has provided more comprehensive capacity models for single- and multilane roundabouts. These empirical models were developed using data collected from thirty-one roundabouts located in the United States of America. The lane-by-lane capacity models were developed for single-lane as well as multilane roundabouts. According to HCM 2010, the application of capacity models for multilane roundabouts is limited to the roundabouts with two circulating lanes and a maximum of two entry lanes. HCM 2010 multilane capacity models cannot be applied on three-by-three-multilane roundabouts (with three circulating lanes and three entry lanes) because of the different lane movements and traffic flow parameters.

This research is an effort to develop capacity models for three-by-three-multilane roundabouts. The data was collected from actual operating three-by-three multilane roundabouts located in the city of Al Ain (a major city in the Abu Dhabi Emirate). The collected data was used to develop lane-by-lane capacity models for three-by-three–lane roundabouts. The proposed capacity model was compared with the HCM 2010 capacity models for multilane roundabouts and validated using a microscopic traffic simulation model.

1.2. Thesis Scope and Objectives

1.2.1. Scope

The scope of this research work is limited to the following:

1) Derive capacity models and curves for three-by-three–lane roundabouts with three circulating lanes and three entry lanes at the entry approach.
2) Use real traffic data from three-by-three–lane roundabouts in the UAE.
3) Estimate the critical and follow-up time headways for the model built as part of this research using the HCM 2010 functions.

4) Use the microscopic simulation software VisSim to validate the capacity models for the three-by-three–lane roundabouts developed within this research.

1.2.2. Objectives

This intensive research has the following objectives:

1) Review capacity analysis methodology for multilane roundabouts.
2) Collect and record real-time field data related to traffic flow and operations at multilane roundabouts in the United Arab Emirates.
3) Develop local models and design curves that can be used by local transportation authorities and municipalities to evaluate the performance of existing multilane roundabouts and facilitate the design of new roundabouts in the UAE.
4) Validate the proposed lane-by-lane capacity model using microscopic simulation software.

1.3. Thesis Organization

This thesis is organized into the following eight chapters:

Chapter 1. **Introduction:** This chapter defines what a roundabout is and provides a brief description of drivers' behaviors at these traffic systems. The scope and objectives of the thesis are also presented in this chapter.

Chapter 2. **Literature Review:** This chapter provides a comprehensive literature review of previous studies related to existing roundabout capacity models, as well as their limitations and methods.

Chapter 3. **Roundabouts:** This chapter presents an introduction to the roundabout types, geometric terms, and parameters. Multilane roundabouts, their rules and regulations, and their importance to the UAE and the city of Al Ain are also covered.

Chapter 4. **Research Methodology and Data Collection:** This chapter illustrates the research methodology that was built and followed for the research work. The data collection procedures, site selection criteria, the data needed, and the data collection methodology are also presented in this chapter.

Chapter 5. **Data Extraction and Analysis:** This chapter explains the procedure used for data extraction, the criteria for data selection, and the data analysis.

Chapter 6. **Development of Capacity Models for Three-by-Three Lane Roundabouts:** This chapter illustrates an overview of the capacity models and methodology for capacity model development.

Chapter 7. **Validation of Proposed Capacity Curves Using Microscopic Simulation Models:** This chapter discusses the selected microscopic simulation software VisSim and the criteria used for selection. The chapter also describes the VisSim features and capabilities, coding methodology, and simulation output.

Chapter 8. **Conclusions and Recommendations:** Conclusions for the completed research and recommendations for further studies are highlighted in this chapter.

Chapter 2: Literature Review

2.1. Introduction

The capacity analysis method for single- and multilane roundabouts is a common research topic for transportation engineers over the past two decades. The increasing popularity of roundabouts prompted researchers to develop comprehensive methodologies for roundabout capacity analysis and traffic operation evaluation. The concept of the modern roundabout came about in the United Kingdom in 1966 [2]. Numerous capacity equations had been developed by different agencies. HCM 2010 [1] defines a roundabout as "... intersections with a generally circular shape, characterized by yield on entry and circulation around a central island."

Many studies [3; 4; 5; 6] were carried out all over the world to develop and calibrate roundabout capacity models. Capacity models were presented for single- and multilane roundabouts. However, multilane roundabout capacity models have been limited to two-by-two–lane roundabouts, that is, two entry and two circulating lanes. These models may not be valid for roundabouts with three entry lanes and three circulating lanes.

Four modeling methods are discussed in this thesis, including the weaving theory model, empirical regression model, gap acceptance model, and simulation-based method. Each of these methods/models has its own identifiable parameters and considerations, which are explained in the following sections.

2.2. Weaving Theory Model

During the earlier stages of roundabout design, Wardrop [7] considered the roundabout capacity as the maximum throughput involved in the weaving sections. With the “give way” rule used in modern roundabouts, the entering vehicles are more susceptible to emerge bottlenecks [8]. Consequently the weaving section model is not applicable anymore.

The weaving section is defined as the region where a traffic bottleneck might happen at the old-style roundabouts. The maximum possible throughput in this area could be the capacity of the entire roundabout. Wardrop [7] proposed the weaving section theory model (Equation 2-1). A few conditions should be satisfied to apply this model: the diameter of the central island designated as (D) should be greater than 40 m, and the weaving section width designated as (w) should be between 6.1 and 18 m. Because these conditions cannot be satisfied for many roundabouts, it is not applicable everywhere. Furthermore, the vehicles circulating within the roundabout have priority among the vehicles entering the roundabout with the proposed “give way” rule. The UK Department of the Environment proposed an improved model as shown in [9] (Equation 2-2).

$$Q = 280\,(1 + \frac{e}{w})\,(1 - \frac{p}{3})/(1 + \frac{w}{l}) \qquad \text{Equation 2-1}$$

$$Q = \frac{160/(w+e)}{w+l} \qquad \text{Equation 2-2}$$

In these equations, Q is roundabout capacity, e is average width of approach ($e = (e_1 + e_2)/2$, m), w is width of weaving section (m), p is the proportion of weaving traffic in the weaving section (%), l is the length of the weaving section (m), e_1 is the width of the access approach (m), and e_2 (m) is the circulatory width in front of the splitter island. Based on the weaving section, the weaving theory model only applies to medium-to-large-scale multilane roundabouts. This earlier model primarily considers the static characteristics and ignores traffic flow time-variant features.

The modern roundabout has fewer weaving observations because its central island diameter is less than 40 meters. Therefore, the weaving theory model may not be appropriate for current functioning and operational modes [10].

2.3. Empirical Regression Model

The conflicting volume or empirical regression model forms a regression equation between the roundabout's entry volume and its circulating volume. Hence, it estimates the roundabout capacity at each entry lane or approach.

The Federal Highway Administration (FHWA) publication, *Roundabout: An Information Guide* [11], presented capacity equation for a single-lane roundabout as shown in Equation 2-3. According to the FHWA guide, the entry flow at the roundabout is linearly related to the conflicting flow. Equation 2-3 represents the capacity model formulated by FHWA.

$$Entry\ Capacity = 1212 - 0.544(Conflicting\ flow) \qquad \text{Equation 2-3}$$

The prediction is significant under saturated flow conditions. This model also states that "pseudo conflict" produced by vehicles leaving the roundabout could be considered a factor in determining the capacity of the roundabout [12]. Several countries, such as Jordan, Switzerland, and the United Kingdom, use empirical regression models [8; 13; 14]. The model is also recommended by the

FHWA [15; 16]. Table 2-1 shows some of the regression models used in different countries around the world.

Table 2-1: Empirical Regression Models for Different Countries

Country	Regression Model
Jordan	$C_e = e^{\frac{A-BQ_c}{10,000}}$
USA (FHWA)	$C_e = 1218 - 0.74\, Q_c$
Switzerland (Bovy)	$C_e = \frac{1}{y}\left[1{,}500 - \left(\frac{8}{9}\right)(BQ_c + aQ_{exit})\right]$; $a = a_0\left(1\frac{1}{3} - \frac{2}{3}\sqrt{\frac{Q_{exit}}{C_{exit}}\frac{Q_{exit}}{Q_t}}\right)$ and $Q_t = Q_c + Q_{exit}$
Germany (Stuve)	$C_e = Ae^{\frac{-BQ_c}{10,000}}$
UK (Kimber)	$C_e = F - f_cQ_c$; $f_c = 0.29 + 0.116e$; $F = 329e + 35u + 2.4D - 135$

NOTE: C_e is entry capacity, Q_C is conflicting volume, and Q_{exit} is exiting volume.In Switzerland's model: γ is the effect of the number of entry lanes: one lane = 1, double lanes = [0.6,0.7]. β is the effect of the number of circulatory lanes: one lane = [0.9,1.0], double lane = [0.6,0.8]. α is the effect of the exiting vehicles; α_0 is the mid-value of α. A, B represents the intercept and slope constants, respectively.

Many researchers have improved the regression models by taking into account the roundabout geometric effects. Polus et al. [17] considered the roundabout diameter as a factor to determine the roundabout capacity as shown in Equation 2-4. However, the data he used were collected at small- to medium-sized and single-lane roundabouts, without considering the number of lanes and its effects.

Al-masaeid et al. [14] established another capacity model as presented in Equation 2-5. He considered many parameters such as circulating flow, lane width, island diameter, and the entrance to exit distance. According to his improved model, the predicted values were close to other models but valid only for low traffic volumes.

$$C_e = 394D^{0.31}e^{-0.00095Q_c} \qquad \text{Equation 2-4}$$

$$C_e = 168.2D^{0.312}S^{0.219}e^{0.071EW+0.019RW}e^{\frac{-5.602Q_c}{10,000}} \qquad \text{Equation 2-5}$$

In these equations, *D* is the diameter of central island, *S* is the distance between the entrance and exit, *EW* is the entry width, and *RW* is the circulatory width.

Wei et al. [18] established a new concept known as “streamline” to estimate the roundabout capacity based on the traffic video data. This method is applicable mainly to single-lane roundabouts because analyzing videos for multilane roundabouts can be difficult.

Al-Madani [12] proposed a model that considers high-demand situations, and he performed its comparison with other models. On the other hand, Martijn et al. [19] used Bovy’s model and improved it to take into account effects of slow traffic on the roundabout capacity, as shown in Equation 2-6 to Equation 2-8.

$$C_e = C_{e,h}F_{exit}P_e \qquad \text{Equation 2-6}$$

$$F_{exit} = 1 - P_{blocking} = 1 - (x^{N+1} - 0.14x) \qquad \text{Equation 2-7}$$

$$P_e = e^{-q_{c,b}t_0} \quad where\ t_0 = t_{cr,b} - 0.5t_{f,b} \qquad \text{Equation 2-8}$$

In these equations, x is the virtual V/C ratio, N is the space between the roundabout and cycle facility expressed in number of cars, $P_{blocking}$ is the probability of exiting vehicles blocking the roundabout, $q_{c,b}$ is the volume of circulating cyclists (bic/s), $t_{cr,b}$ is the critical gap to cyclists (s), $t_{f,b}$ is the follow-up headway, C_e is the entry capacity (pcu/h), $C_{e,h}$ is the entry capacity due to the main conflicts (pcu/h), F_{exit} is the reduction factor caused by the downstream exit, and P_e is the probability that the exit is not blocked by cyclists.

The regression models presented above are easy to establish and can be adapted to local roundabouts. Because generalizing several models for all types of roundabouts is not easy, there are some limitations in practice as stated here [10]:

- There is a huge demand for the needed data.
- The model must be adapted for different areas, and transferability is not well defined or well studied.
- Traffic stream considerations are lacking within these models [16].

2.4. Gap Acceptance Capacity Models

Modern roundabouts give priority to the circulating vehicles, therefore, the entry traffic flows are considered minor streams. This concept is also applied at two-way stop-controlled (TWSC) junctions.

Gap acceptance theory can be used to develop the roundabout capacity model [20]. This developed model is well defined, systematic, and based on a theoretical background. The special properties of gap acceptance models are accepted worldwide in estimating the capacity of roundabouts.

Gap acceptance models have a few vital parameters, such as critical gap and follow-up time, that can provide traffic data at the microscopic level. Therefore, this model could demonstrate the time-variant features of traffic flows at roundabouts.

HCM 2010 presented nonlinear regression capacity equations based on data collected from thirty-one sites in the United States. The models are based on the comprehensive study presented in NCHRP Report-572 [21].

2.4.1. Highway Capacity Manual (HCM 2010)

The capacity models provided by HCM 2010 were for single- and multilane roundabouts. The multilane roundabouts were limited to a maximum of two-by-two–lane roundabouts (i.e., two entry lanes and two conflicting or circulating lanes). Table 2-2 shows the capacity models presented in HCM 2010.

Table 2-2: HCM 2010 Roundabout Capacity Equations

Roundabout Type	Lane Configuration	Model Equation
Single Lane	1 by 1	$C_{e,pce} = 1130e^{(-1.0\times10^{-3})v_{c,pce}}$
		Equation 2-9
Multilane Roundabout	2 by 1	$C_{e,pce} = 1130e^{(-1.0\times10^{-3})v_{c,pce}}$
		Equation 2-10
	1 by 2	$C_{e,pce} = 1130e^{(-0.7\times10^{-3})v_{c,pce}}$
		Equation 2-11
	2 by 2	$C_{e,R,pce} = 1130e^{(-0.7\times10^{-3})v_{c,pce}}$
		Equation 2-12
		$C_{e,L,pce} = 1130e^{(-0.75\times10^{-3})v_{c,pce}}$
		Equation 2-13

In the equations above, the following representations are present:

$C_{e,pce} = Lane\ Capacity, passenger\ cars\ per\ hr\ (pc/hr)$

$v_{c,pce} = Conflicting\ Flow\ Rate, pc/hr$

$C_{e,R,pce} = Right\ Lane\ Capacity, pc/hr$

$C_{e,L,pce} = Left\ Lane\ Capacity, pc/hr$

2.4.1.1. General Methodology

Chapter 21 of HCM 2010 [1] presented a procedure for analyzing roundabouts. It introduced the unique characteristics of roundabout capacity and presented specific terminology related to roundabouts. For ease of reference, the following terms are defined, and they are illustrated in Figure 2-1:

v_e = *entry flow rate*

v_C = conflicting flow rate

v_{ex} = exit flow rate

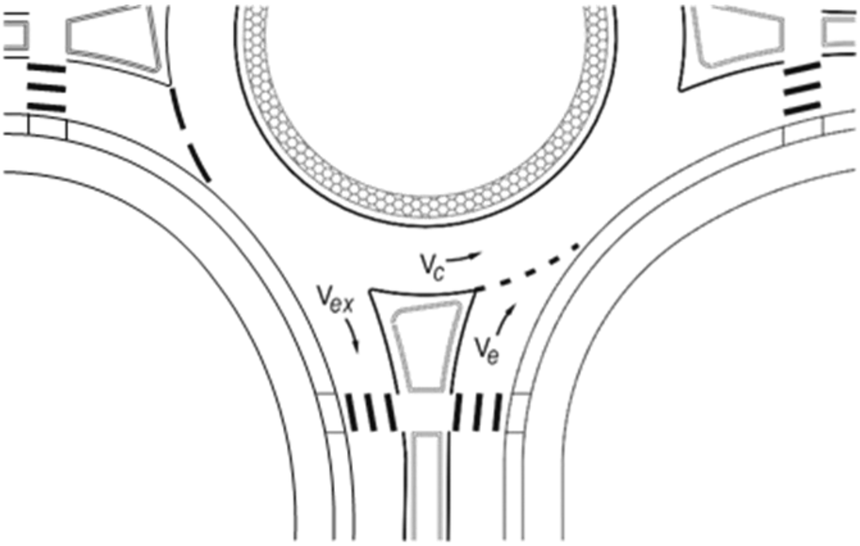


Figure 2-1: Roundabout Main Terms [1]

Intersection analysis models generally fall into two categories: regression and analytical. Regression models use field data to develop statistically derived relationships between geometric features and performance measures such as capacity and delay. Analytical models are based on traffic flow theory combined with the use of field measures of driver behavior, resulting in an analytic formulation of the relationship between the field measures and performance measures such as capacity and delay [1].

As the conflicting flow rate v_C increases, the entry flow rate will decrease

waiting to find a gap to enter the roundabout.

2.4.1.2. Single-Lane Roundabouts

The capacity of a single-lane roundabout with one entry lane and one circulating lane can be calculated using

$$C_{e,pce} = 1{,}130\ e^{(-1.0*10^{-3})v_{c,pce}} \qquad \text{Equation 2-14}$$

where

$c_{e,pce}$ = lane capacity, adjusted for heavy vehicles (pc/h), and

$v_{c,pce}$ = conflicting flow rate (pc/h).

2.4.1.3. Multilane Roundabouts

Multilane roundabouts have more than one lane on at least one entry and at least part of the circulatory roadway. The number of entry, circulating, and exiting lanes may vary throughout the roundabout. Because of the many possible variations, the computational complexity is higher for multilane roundabouts [1].

Several capacity equations addressed in HCM 2010 are based on the number of conflicting lanes and number of entry lanes. Note that the methodologies and models presented in HCM 2010 are limited to two-by-two–lane roundabouts.

Capacity for Two Entry Lanes Conflicted by Two Circulating Lanes

The capacities of the right and left lanes on the two-by-two–lane roundabout as described in HCM 2010 are presented as:

$$C_{e,R,pce} = 1{,}130\ e^{(-0.7*10^{-3})v_{c,pce}} \qquad \text{Equation 2-15}$$

$$C_{e,L,pce} = 1{,}130\ e^{(-0.75*10^{-3})v_{c,pce}} \qquad \text{Equation 2-16}$$

where

$c_{e,R,pce}$ = capacity of the right entry lane, adjusted for heavy vehicles (pc/h),

$c_{e,L,pce}$ = capacity of the left entry lane, adjusted for heavy vehicles (pc/h), and

$v_{c,pce}$ = conflicting flow rate (total of both lanes) (pc/h).

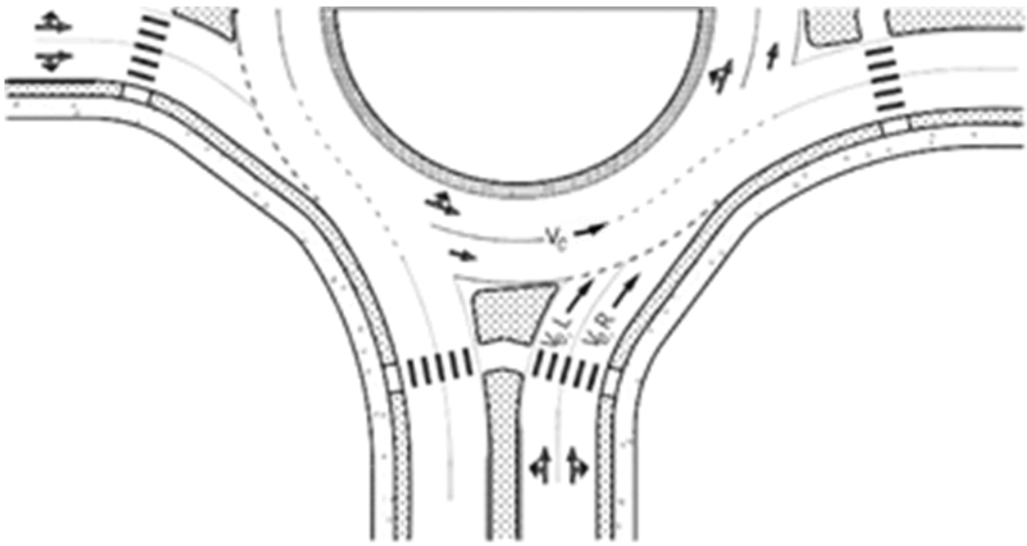


Figure 2-2: Two-Lane Entry Conflicted by Two Circulating Lanes [1]

2.4.1.4. Capacity Model Calibration

As stated in HCM 2010, the capacity models presented previously can be generalized by using the following expressions:

$$C_{pce} = A\ e^{(-Bv_c)_c} \qquad \text{Equation 2-17}$$

$$A = \frac{3{,}600}{t_f} \qquad \text{Equation 2-18}$$

$$B = \frac{t_c - (\frac{t_f}{2})}{3{,}600} \qquad \text{Equation 2-19}$$

v_c = conflicting flow (pc/h),

t_c = critical headway (s), and

t_f = follow-up headway (s).

Therefore, the capacity model can be calibrated by using two parameters: the critical headway t_c and the follow-up headway t_f.

2.4.2. Other Gap Acceptance Studies

Akcelik [22] presented an assessment of the HCM 2010 roundabout capacity model by comparing the HCM 2010 models with SIDRA INTERSECTION software [23]. The author is also the developer of SIDRA software, one of the most popular software tools for analyzing traffic operations at roundabouts. According to the author, HCM 2010 roundabout models are theoretically based on the gap-acceptance methodology, similar to the SIDRA software. The study concluded that roundabout geometry alone is not enough to analyze the capacity of roundabouts as validated later by HCM 2010. Stanek.D [24] presented a comparative study of different capacity model/charts, namely, HCM 2010, FHWA Roundabout: Informational Guide, HCM 2000, SIDRA INTERSECTION, SimTraffic, VisSim, and Paramics. All of the models were applied on single-lane roundabouts. After comparing the models, the study recommended that calibration is needed according to the local traffic conditions and to use more than one analysis method for reliable outputs.

Some countries, such as Australia, Denmark, and the United States (HCM), use the gap acceptance model. Based on the fact that the major stream obeyed the shifted negative exponential distribution, Tanner [25] derived the capacity of minor stream at unsignalized intersections (Equation 2-20). Later, Troutbeck [20] and

Akcelik [26] considered Cowan's M3 distribution for the major stream, and they improved the entry capacity model [20; 26] as shown in Equation 2-21 and Equation 2-22. Associated with the number of lanes in the major approach of the road, Hagring [27] initiated a generic formula to estimate the roundabout capacity that was based on Tanner's equation (Equation 2-23). HCM 2000 and 2010 provide the calibration technique [28]. The capacity models for the single-lane roundabouts are presented as Equation 2-24 and Equation 2-25, respectively. Note that Akçelik [29] reviewed the aaSIDRA model frequently in line with his recent studies.

$$C_e = \frac{3{,}600\ q_c(1-\Delta\ q_c)\ e^{-q_c(T-\Delta)}}{1-e^{-q_c T_0}} \qquad \text{Equation 2-20}$$

$$C_e = \frac{3{,}600\ q_c\ a\ e^{-\lambda(T-\Delta)}}{1-e^{-\lambda T_0}} \qquad \text{Equation 2-21}$$

$$C_e = \frac{3{,}600(1-\Delta\ q_c + 0.5\ a\ q_c\ t_f)e^{-\lambda(T-\Delta)}}{t_f} \qquad \text{Equation 2-22}$$

$$C_e = \Lambda \prod_i \frac{a_i q_i}{\lambda_i} \frac{e^{-\sum_k \lambda_k T_k}}{e^{-\Lambda\Delta(1-\sum_m \lambda_m T_{0m})}} \qquad \text{Equation 2-23}$$

$$C_e = \frac{3{,}600\ q_c e^{-q_c T}}{1-e^{-q_c T_0}} \qquad \text{Equation 2-24}$$

$$C_e = \frac{3{,}600}{T_0}\ e^{(\frac{T-0.5T_0}{3{,}600})q_c} \qquad \text{Equation 2-25}$$

In these equations, q_c is the traffic flow rate in a major road (veh/h), Δ is the minimum headway (s), T is the critical gap (s), T_0 is the follow-up time (s), α is the proportion of free vehicles, $\Lambda = \sum i\ \lambda_i$, λ is the decay constant, λ_k (λ_m) is the decay constant of lane k(m), T_k is the critical gap of lane k (s), and T_{0m} is the follow-up time of lane m (s).

Critical gap is the most important parameter in the gap acceptance model. Many researchers [30; 31; 32; 33; 34; 35; 36; 37] formulated equations to estimate the critical gap. Al-Masaeid [38] performed a comparison study of the capacity models developed by Australia and Germany. This comparison was based on approximating the critical gap with a logit model and simulating the follow-up time.

Based on Cowan's M3 distribution, Tanyel et al. [39] considered the free vehicles proportion effect along with Troutbeck's revised model. He concluded that the HCM 2000 technique could be used to set the initial approximation of the capacity. This is effective for single-lane roundabouts after the upper- and lower boundaries are estimated [40; 41].

Roundabout capacity models presented in HCM 2010 are based on the NCHRP Report 572 [21] as shown in Equation 2-26. Wei et al. [42] verified the HCM 2010 calibration technique by using the real field data. The obtained outcomes proved that the model is reliable with the collected data if and only if the flow rate is less than 800 vph, and the capacity is overestimated when the flow rates exceed 800 vph.

$$C_{pce} = A\, e^{(-Bq_c)} \ ; A = \frac{3{,}600}{T_0} \ ; \ B = \frac{T-(\frac{T_0}{2})}{3{,}600} \qquad \text{Equation 2-26}$$

On the other hand, some local studies were conducted based on the gap acceptance model. Wang et al. [43] concluded with a capacity model that considers right turn flow rate; he did apply the queuing theory to re-study the slow traffic consequences and came up with a realistic capacity model.

Xiang et al. [10] took into consideration the lane's interaction and impact. He also proposed a capacity model for two-lane roundabouts, which is expressed in Equation 2-27, but it is valid only for low-channelized traffic volumes. Bo et al. [44] proposed a step-by-step and iterative solution to estimate the roundabout capacity. He considered that an equilibrium occurs as the entry volume approaches the total capacity, but he ignored the interaction between the lanes. Guo [45] did examine the roundabout capacity for altered circumstances based on the theory of gap acceptance.

$$C_e = 3{,}600\ \frac{qe^{-\lambda(T-\Delta)}}{1-e^{-\lambda T_0}}\left[1-\frac{2q_1q_2}{q_1+q_2}\Delta\right] + 3{,}600\frac{a_2q_2e^{-\lambda_2(T-\Delta)}}{1-e^{-\lambda_2 T_0}} \qquad \text{Equation 2-27}$$

2.5. Microscopic Traffic Simulation Models

Two types of tools are used when analyzing roundabout capacity. The first one is based on the calculations model used in RODEL and aaSIDRA for instance, while the other type is micro-simulation based as VisSim and SimTraffic.

Bared et al. [46] recognized that the roundabout capacity obtained from VisSim is less than the capacity of the aaSIDRA software. He determined that this is applicable for both the single-lane and the double-lane roundabouts.

Several scenarios were built in VisSim, and many comparisons made with the NCHRP 572 data. The lane-based capacity models for double-lane as well as triple-lane roundabouts were derived as shown in Equation 2-28 and Equation 2-29, respectively.

Li et al. [47] conducted a simulation experiment to examine the sensitivity analysis. They set forward a revised model in relation with the influencing factors and capacity coefficients.

$E_L = e^{\left(7.2079 - \frac{1.3008 * C_1}{1,000} - \frac{1.2940 * C_2}{1,000}\right)}; R^2 = 0.960$ $E_R = e^{\left(7.2079 - \frac{0.9259 * C_1}{1,000} - \frac{1.0120 * C_2}{1,000}\right)}; R^2 = 0.987$	Equation 2-28
$E_L = e^{\left(7.0754 - \frac{1.1864 * C_1}{1,000} - \frac{1.0813 * C_2}{1,000} - \frac{0.9479 * C_3}{1,000}\right)}; R^2 = 0.955$ $E_M = e^{\left(7.0754 - \frac{0.6758 * C_1}{1,000} - \frac{1.1556 * C_2}{1,000} - \frac{0.9049 * C_3}{1,000}\right)}; R^2 = 0.980$ $E_R = e^{\left(7.0754 - \frac{0.5569 * C_1}{1,000} - \frac{0.9044 * C_2}{1,000} - \frac{1.0258 * C_3}{1,000} + 0.2795 * R_t\right)}; R^2 = 0.955$	Equation 2-29

In these equations, E_L *is the capacity of the left-turning lane (vph),* E_M *is the capacity of the middle lane (vph),* E_R *is the capacity of the right-turning lane (vph),* C_1 *is the circulating volume of the inner lane (vph),* C_2 *is the circulating volume of the middle lane,* C_3 *is the circulating volume of the outer lane, and* R_t *is the proportion of right-turning vehicles in the total entry volume.*

In conclusion, the simulation-based models can provide more realistic scenarios of the traffic operation at roundabouts because the operation characteristic can be modeled and reflected accurately. On the other hand, the precision of the calculations can be affected by the complicated calibration process.

As discussed previously, a number of studies were done all over the world to develop and calibrate roundabout capacity models. Capacity models were presented for both single-lane and multilane roundabouts. However, multilane roundabout capacity models are limited to two-by-two–lane roundabouts, that is, two entry lanes and two conflicting lanes. These models may not be valid for the roundabouts with three entry lanes and three circulating lanes. This research is an effort to study the traffic operations and develop the capacity model for the three-by-three–lane roundabout.

Chapter 3: Roundabouts

3.1. Introduction

Modern roundabouts were initially introduced in England during the 1960s to resolve some existing problems with the traffic circles and rotaries. The “give way” rule gives the priority to the circulating traffic against the entering traffic, which must yield. Roundabouts proved to be a much more efficient intersection than rotaries and even signalized junctions in some cases.

In addition, roundabouts are considered safer than signalized intersections because there is no chance to have direct impact at a right angle due to the geometric nature of roundabouts.

3.2. Types of Roundabouts

There are three basic types of roundabouts:

- Conventional roundabout: An anticlockwise, one-way circular roadway around a raised-curb central island for circulating traffic, with more than two approaches that have multiple vehicle entries.
- Mini-roundabout: A one-way circular roadway around a flush central island of up to 4 meters in diameter, usually without flared entries.
- Turbo roundabout [48]: A new type of roundabout that minimizes the conflicts at roundabouts by forcing the motorists to know their direction at the entry approach before entering the roundabout. Figure 3-1 shows the basic shape of the Dutch turbo roundabout.

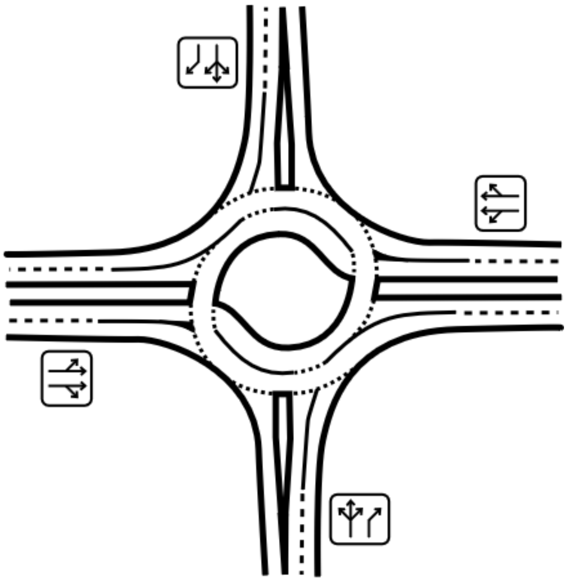


Figure 3-1: The Basic Shape of the Dutch Turbo Roundabout [49]

3.3. Geometric Terms and Parameters

3.3.1. Geometric Terms

The main geometric terms at roundabouts are related to entry and exit radii, circulating roadway and lane widths, approach and lane widths, central island, and inscribed circle diameters. Figure 3-2 illustrates the main geometric terms of the roundabout.

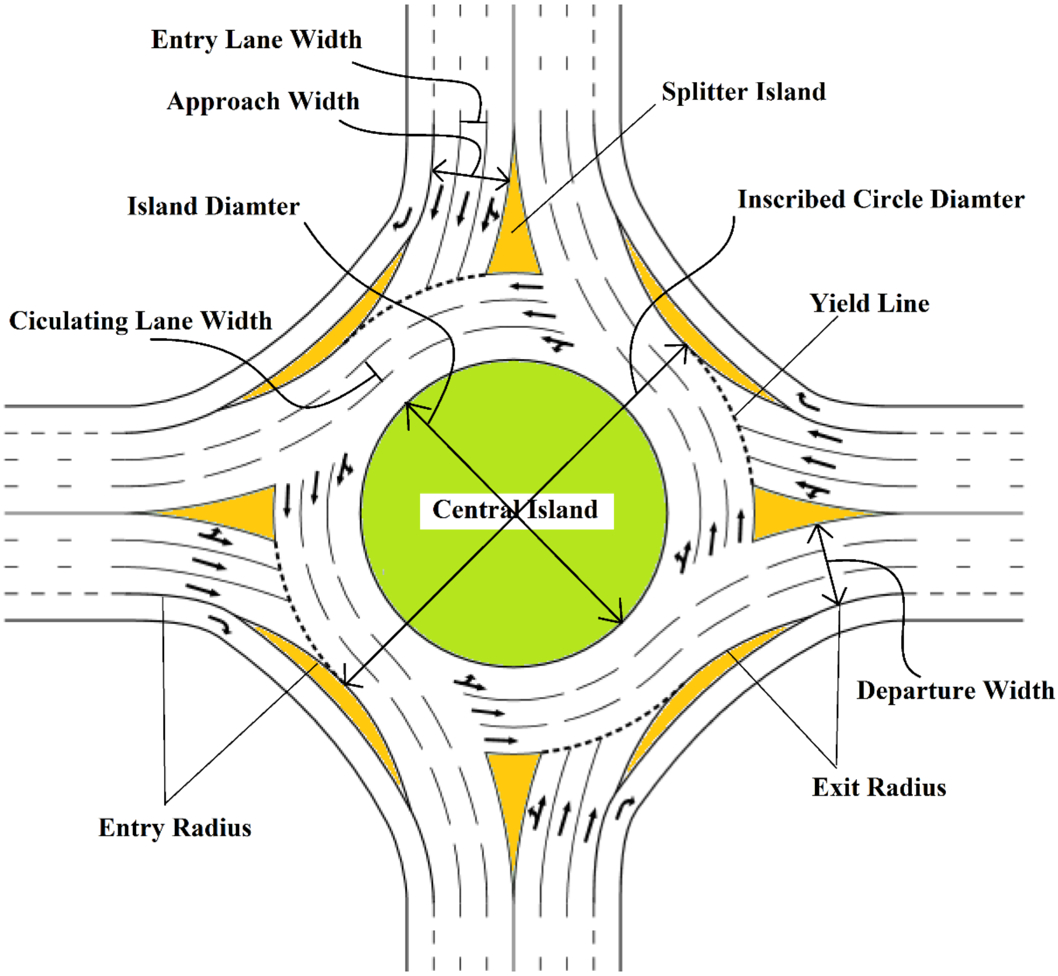


Figure 3-2: Main Geometric Terms of Roundabouts

3.3.1.1. Critical Gap

Critical gap is the gap that motorists wait at the entry lane or approach to enter the roundabout. Critical gap size (in seconds) depends on the drivers' behavior as some drivers accept smaller gaps than others. Figure 3-3 illustrates the gap concept.

3.3.1.2. Follow-Up Headway

The follow-up is the headway between two successive vehicles entering from the entry approach as shown in Figure 3-3. The follow-up time is usually measured when there is a queue at the entry lane or approach.

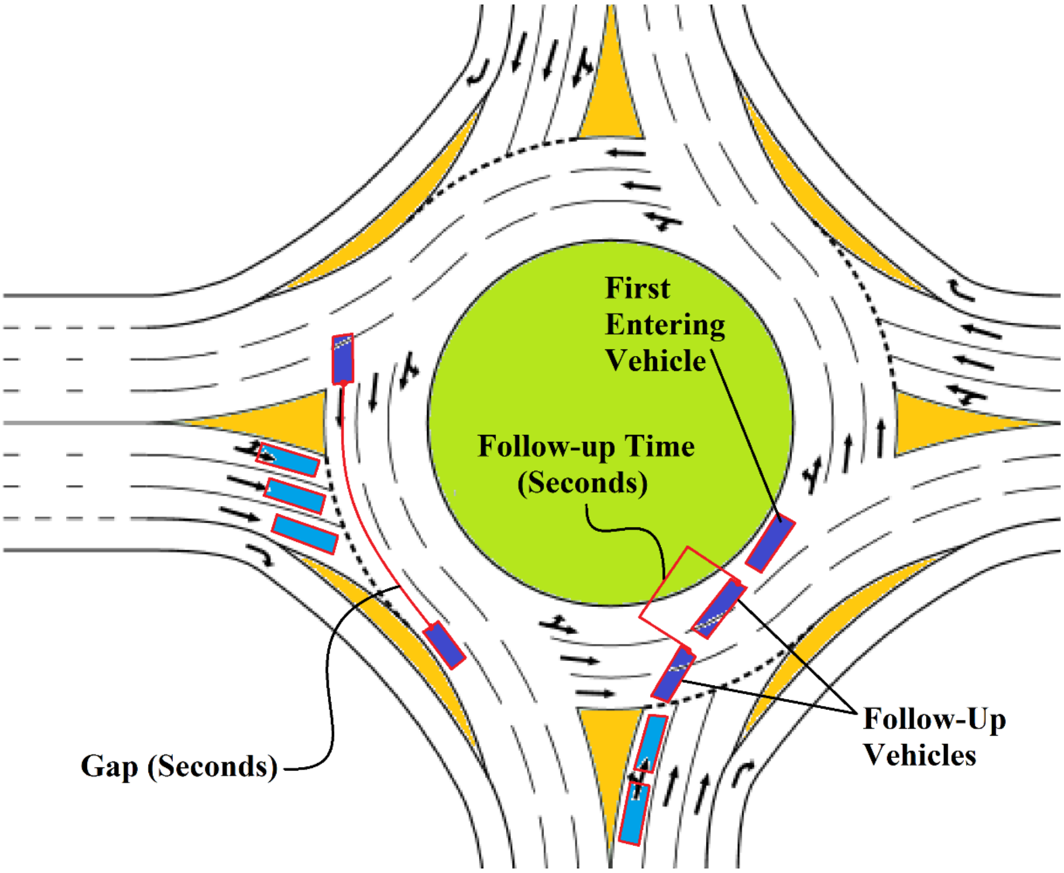


Figure 3-3: Critical Gap and Follow-Up Time Definitions

3.4. Multilane Roundabout

The multilane roundabout has two or more entry lanes and two or more circulating lanes. Typically, the two types of multilane roundabouts are the two-by-two–lane roundabouts, which have two entry lanes and two circulating lanes, and the three-by-three–lane roundabouts, which have three entry lanes and three circulating lanes. In this research, we are developing capacity models for three-by-three–lane roundabouts.

3.5. Three-by-Three-Lane Roundabouts

A multilane roundabout that has three entry lanes and three circulatory lanes is known as a three-by-three–lane roundabout. These multilane roundabouts are not common with only a few found all over the world. Therefore, few studies are available about the operations, type of violations, and capacity models for these three-by-three–lanes roundabouts. HCM 2010 [1] provides models and flow parameters for multilane roundabouts but only for two-by-two–lane roundabouts. The city of Al Ain in the UAE has had a number of three-by-three–lane roundabouts operating for the past ten to fifteen years. The drivers are very familiar with the rules and regulations at three-by-three–lane roundabouts. However, it should be noted that almost 85% of the UAE population are expatriates and mostly come from countries that either do not have or have very few multilane roundabouts.

3.5.1. Rules and Regulations for Three-by-Three-Lane Roundabouts

The rules and regulations to drive in a three-lane roundabout are almost similar to the conventional two-lane roundabouts. Figure 3-4 shows the typical three-by-three–lane roundabout with channelized right turn movements and also lane configuration and movements allowed on each lane.

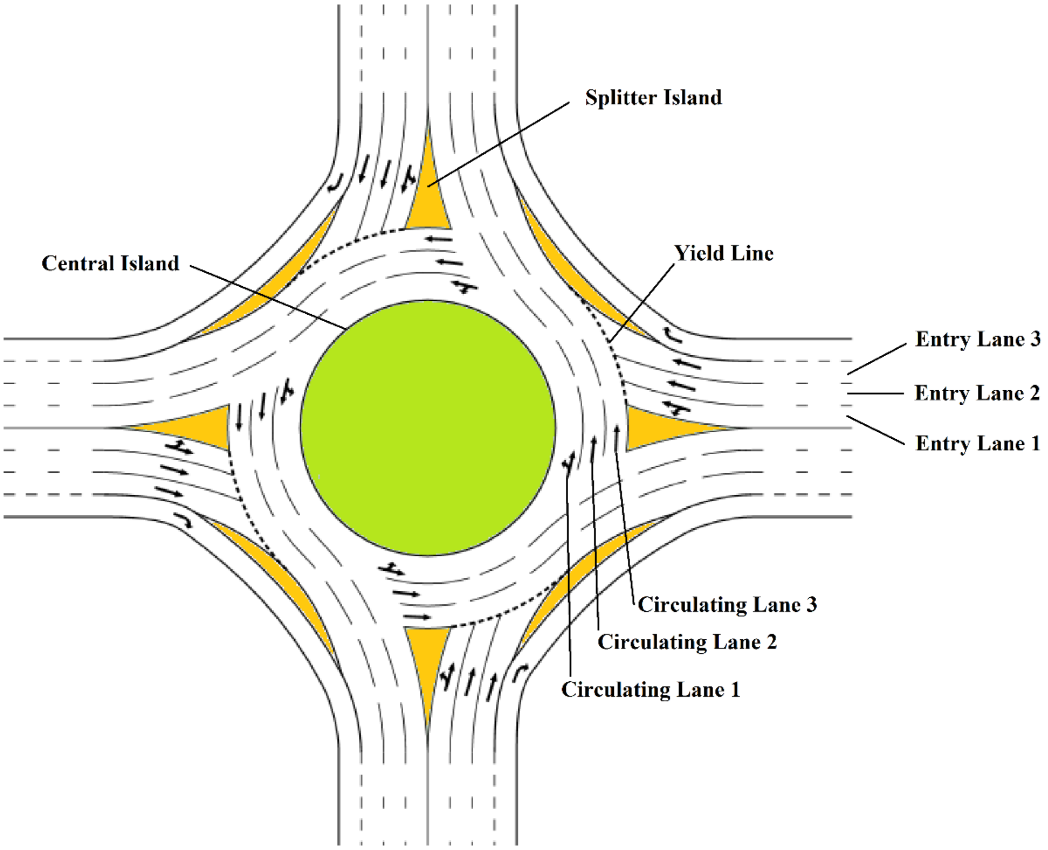


Figure 3-4: Typical Three-by-Three-Lane Roundabout – Basic Elements

According to the official road user code for Abu Dhabi [50], the rules and regulations for lane movements on three-by-three–lane roundabouts are as follows:

- Vehicles in entry lanes 2 and 3 can drive through if the right turn is channelized; if not, then entry lane 3 can be used for both through and right maneuvering.
- Vehicles in entry lane 3 can maneuver both through and left.
- Vehicles in circulating lanes 2 and 3 should only turn right.
- Vehicles in circulatory lane 1 can maneuver both through and right.

3.5.2. Types of Violations on Three-by-Three–Lane Roundabouts

Although there are a number of violation types in three-by-three–lane roundabouts, the following are considered the major ones:

A. Yield Line Violation

The vehicles should stop before the yield line on the entry lane to give the right of way to the vehicles circulating in the roundabout. The entry lane vehicles should be cautious that they don't block the view of other drivers in the entry lane and also not to disturb the flow of the vehicles at the outermost circulatory lane. For this purpose yield lines are marked at each entry lane. If the vehicles don't stop before the yield line while waiting for an appropriate gap between circulating vehicles, a yield line violation occurs. Figure 3-5 shows a graphical illustration of a yield line violation at the entry approach.

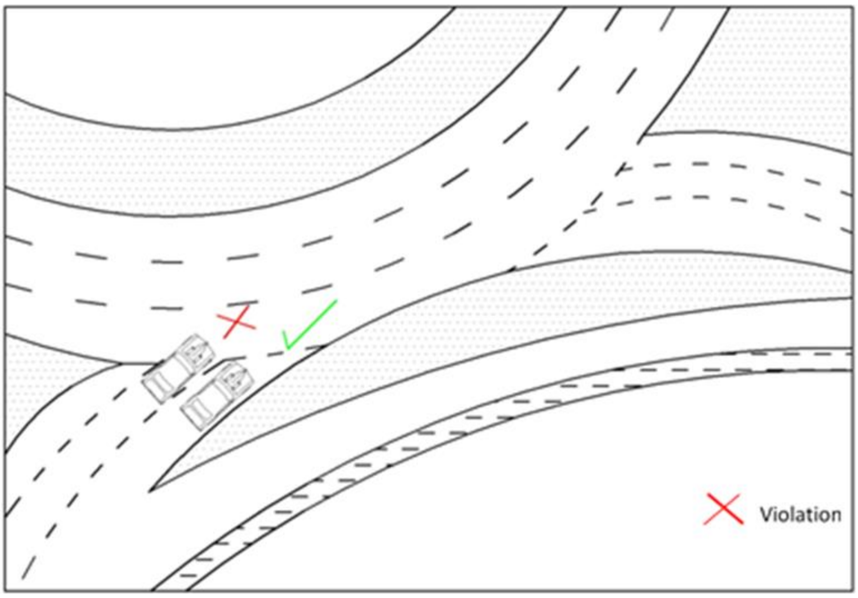


Figure 3-5: Yield Line Violation

B. Circulatory Lane Change Violation

The circulating vehicles should maintain a particular lane according to their exit leg, if they do not, it is considered a circulatory lane change violations as shown in Figure 3-6. The vehicles circulating in the innermost lane have the privilege to go through or turn right on the next exit leg, whereas the vehicles moving on the middle and outermost lane in the roundabout should turn right at the next coming exit.

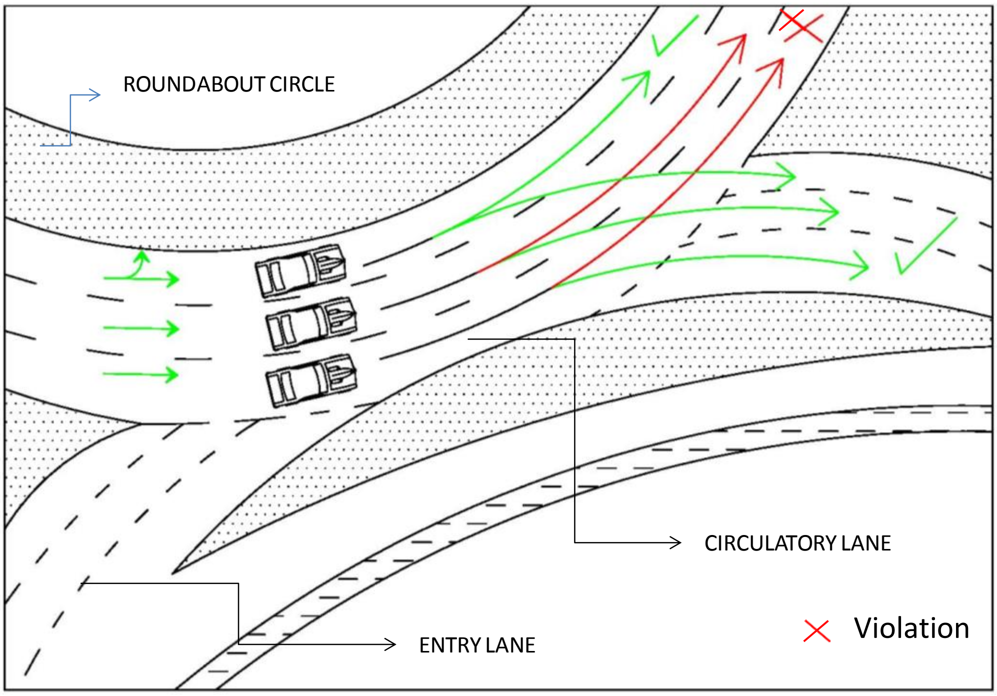
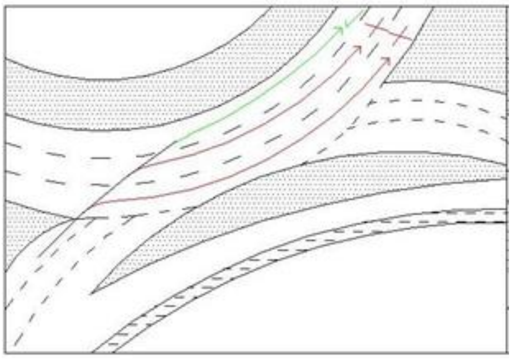


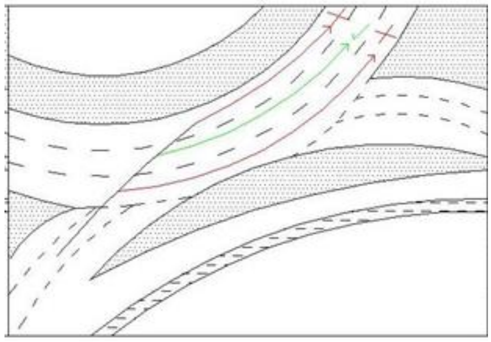
Figure 3-6: Circulatory Lane Change Violation

C. Entry Lane Change Violation

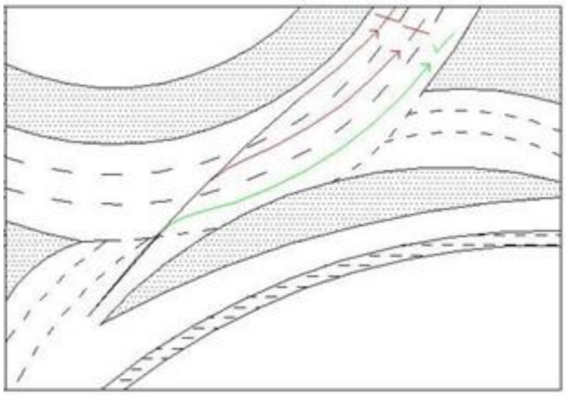
The drivers entering the roundabout should select the appropriate lane in advance based on the desired movement in the intersection: right, through, or left. Vehicles shouldn't change their lane when entering the circulatory lanes or during the circulation in the roundabout. The vehicles entering from the innermost lane should circulate in the roundabout in the innermost circulating lane. Similarly, the vehicles entering from the middle and outermost lanes should travel in the middle and outermost circulating lanes, respectively. When drivers change lanes after entering the circulatory lanes, it results in an entry lane change violation as illustrated in Figure 3-7.



Entry Lane 1



Entry Lane 2



Entry Lane 3

Figure 3-7: Entry Lane Change Violation

3.5.3. Research Significance Related to the UAE

As compared to other parts of the world, a number of three-by-three–lane roundabouts have been operating for the past ten to fifteen years in the UAE. The city of Al Ain, where this research study was conducted, is known as the "City of Roundabouts" because of the high number of roundabouts. Moreover, most of the roundabouts are three-by-three multilane roundabouts.

As discussed in the previous chapter, a number of research projects were done all over the world to understand the roundabout traffic operations and develop design standards for roundabouts. This research is different from previous research studies, and the output of this research will be significant for the UAE due to the following.

3.5.3.1. Local Drivers' Experience and Background

Drivers' population in the emirate of Abu Dhabi is distinctive due to the higher percentage of expatriates. It is estimated that more than 85% of the population of the Abu Dhabi emirate are from other countries. Drivers coming from different backgrounds have diverse driving experiences. Some of them had never driven on roundabouts prior to coming to the UAE. Therefore, models developed based upon the data collected in other countries are not valid for the local traffic conditions and driver behavior in Abu Dhabi.

3.5.3.2. Two-Lane Roundabouts versus Three-Lane Roundabouts

Abu Dhabi has a large number of three-lane roundabouts (i.e., three entry lanes and three circulating lanes). However, the existing roundabout capacity models and design standards were developed for two-lane roundabouts (i.e., two entry lanes and a maximum of two circulating lanes). Traffic operations and drivers' behavior at two-lane and three-lane roundabouts are different from each other. Therefore, models developed for two-lane roundabouts are not valid for three-lane roundabouts.

Capacity models were developed for three-lane roundabouts in this research. The detailed research methodology and model development was presented in the proceeding chapters.

Chapter 4: Research Methodology and Data Collection

4.1. Introduction

The aim of this study was to develop capacity models for three-by-three–lane roundabouts based on the local traffic conditions and drivers' behavior. Figure 4-1 illustrates the detailed methodological steps adopted for the study. The specific methods involved in the site selections process and data collection with the selected roundabouts are discussed in detail in the following sections of this chapter.

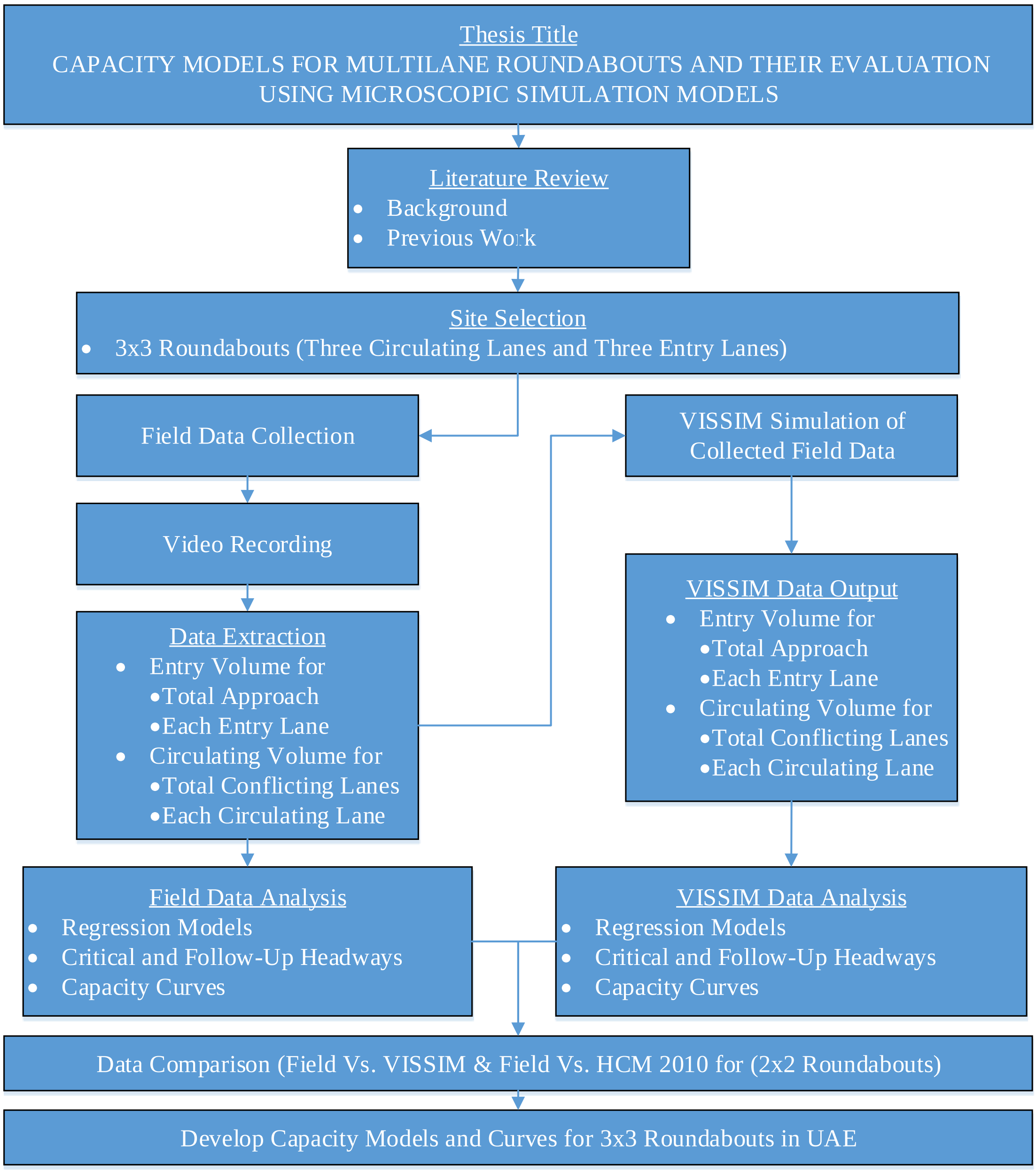


Figure 4-1: Flowchart for Research Methodology

4.2. Site Selection

4.2.1. Criteria

The following criteria were considered while selecting the roundabouts for data collection:

- Roundabouts should have three circulating lanes and three entry lanes for at least two approaches.
- All selected roundabouts should have proper lane markings for lane movements and configuration.
- Roundabouts should have the appropriate traffic signs to inform drivers that they are approaching the roundabout (e.g., “Roundabout Ahead” sign) at least 200 meters before the roundabout.
- The peak period should be marked by high traffic demand. (This criteria is explained more in Chapter 5, “Data Extraction and Analysis.”)

Figure 4-2 shows one of the selected roundabouts meeting the above criteria.

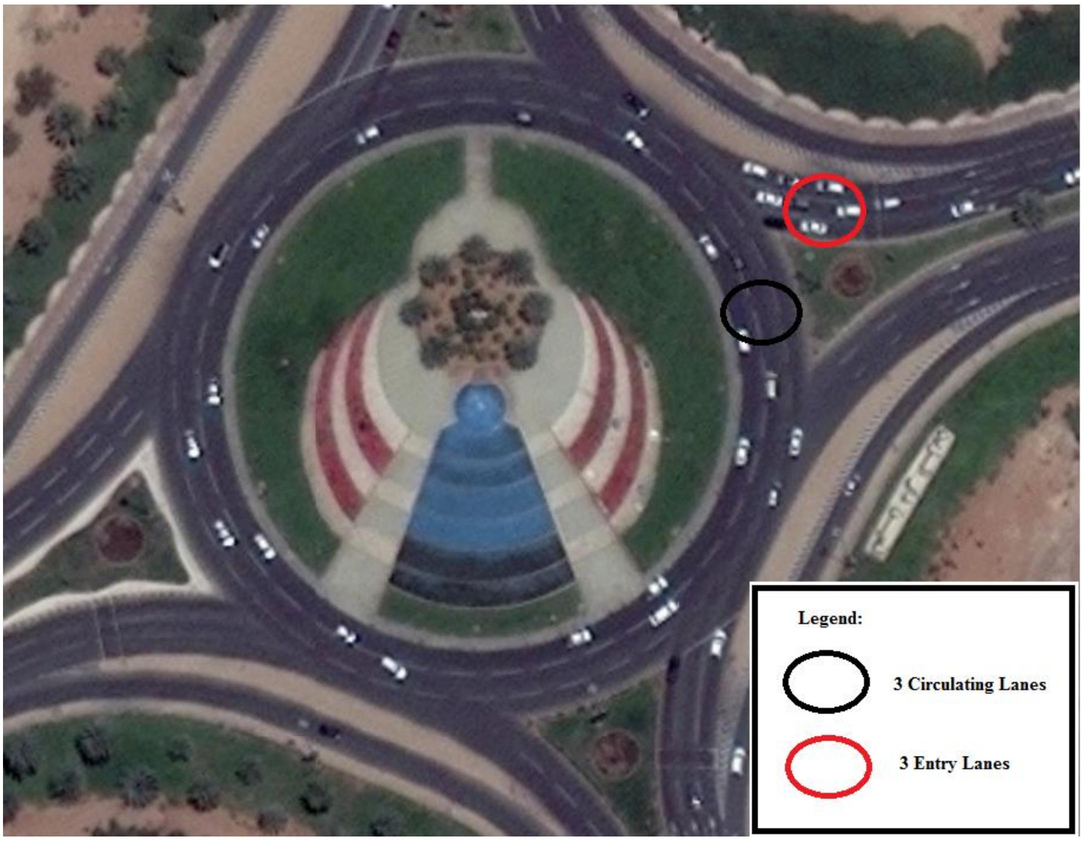


Figure 4-2: Three-by-Three-Lane Roundabout

4.2.2. Selected Sites

As discussed earlier, a number of multilane roundabouts are located in Al Ain. Based on the criteria mentioned above, twelve roundabouts were selected for data collection. Figure 4-3 provides a view of the selected sites.

Figure 4-3: Selected Roundabouts for Data Collection

Table 4-1 shows the outer circle and inner circle diameters and crossing streets of the twelve selected roundabouts. The inner circle diameter is between 60 and 100 meters; while the outer circle diameter ranges from 84 to 124 meters for the selected roundabouts. Most roundabouts were located near schools, which explains the high traffic demands during peak periods.

Table 4-1: Selected Sites Information

Roundabout #	Diameters (m)		First Street Name	Second Street Name
	Outer Circle	Island/Inner Circle		
1	84/108*	60/84*	Hazzaa Bin Sultan	135/Khalifa Bin Zayed
2	124	100	Hazzaa Bin Sultan	141st
3	84	60	Hazzaa Bin Sultan	Khalid Bin Sultan
4	84	60	124th/Al Baladiyya	Hamdan Bin Mohammad
5	124	100	122nd/Khalifa Bin Zayed Al Awwal	Khalid Bin Sultan/147th
6	104	80	124th	Khalid Bin Sultan/147th
7	124	100	130th/Zayed Al Awwal	Khalid Bin Sultan/147th
8	84	60	134th Street	Khalid Bin Sultan/147th
9	84	60	130th/Zayed Al Awwal	Sultan Bin Zayed Al Awwal
10	84	60	130th/Zayed Al Awwal	141/Al Jamai’
11	124	100	134th Street	141/Al Jamai’
12	124	100	Zayed Al Awal	135/Khalifa Bin Zayed

**This roundabout has an elliptical shape. The smaller value indicates the minor diameter, and the higher value indicates the major diameter.*

Figure 4-4 to Figure 4-15 show aerial views of the twelve selected locations. Roundabouts 1, 2, 3, 7, and 11 have three circulating and three entry lanes with exclusive right-turn lanes on each approach. Roundabout 4 is a three-by-three–lane roundabout with exclusive right-turning lanes on the north and west approaches, as shown in Figure 4-7. Figure 4-8 shows the aerial view of three-by-three–lane roundabout 5 with only right-turning channelization on the west and south approaches. The aerial view of roundabout 6 is shown in Figure 4-9. Roundabout 7 has three circulating lanes and three entry lanes except for the south approach, which only has two entry lanes. Similarly, roundabout 8 has two lanes on the south entry approach and three circulating and three entry lanes on other approaches. Roundabout 9 has three approaches without right-turn channelization, as shown in Figure 4-12. Aerial views of roundabouts 10 and 12 are shown in Figure 4-13 and Figure 4-15, respectively. Both roundabouts do not have any right-turning exclusive lanes on any approach. Moreover, roundabout 12 has two lanes on the east entry approach. All of the selected roundabouts have three circulating lanes, and most of the approaches have three entry lanes. Note that the data from approaches with two entry lanes were not used for the analysis and model development.

Figure 4-4: Roundabout 1 Location and Features

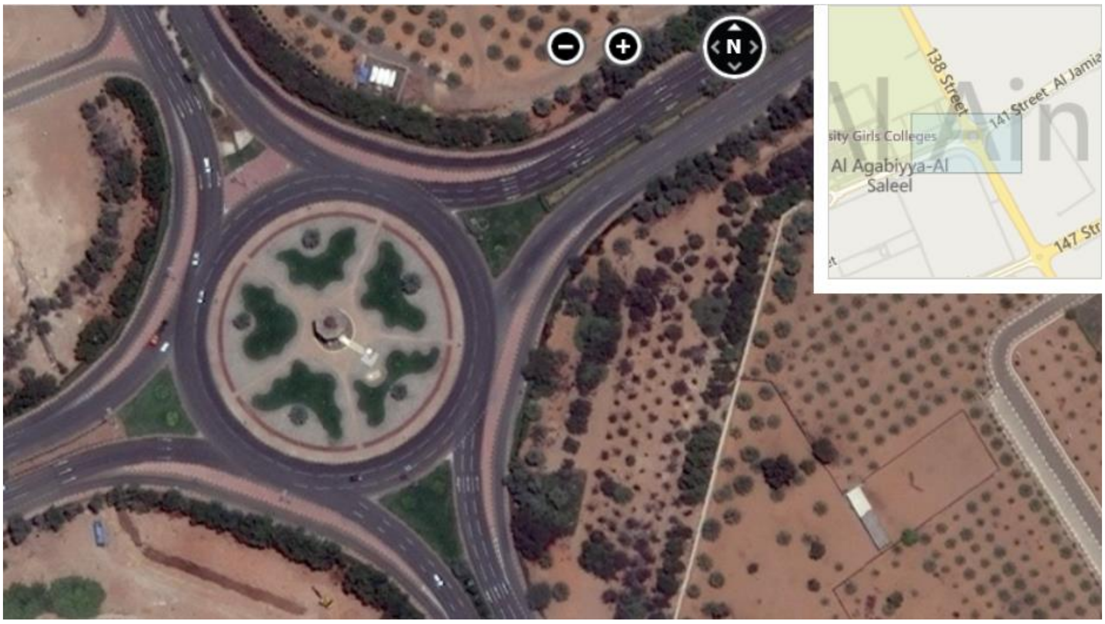


Figure 4-5: Roundabout 2 Location and Features

Figure 4-6: Roundabout 3 Location and Features

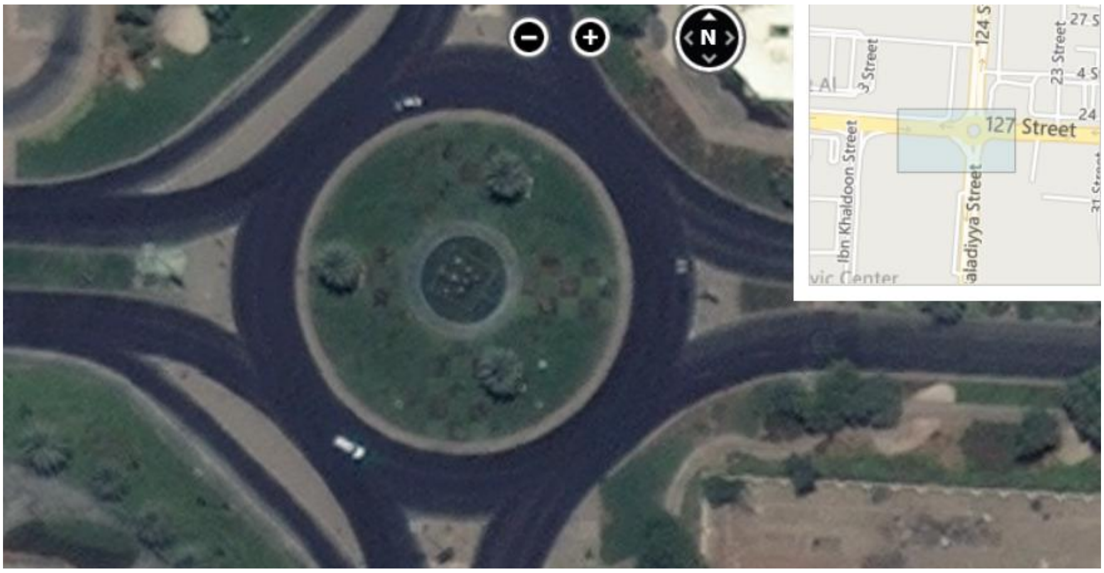


Figure 4-7: Roundabout 4 Location and Features

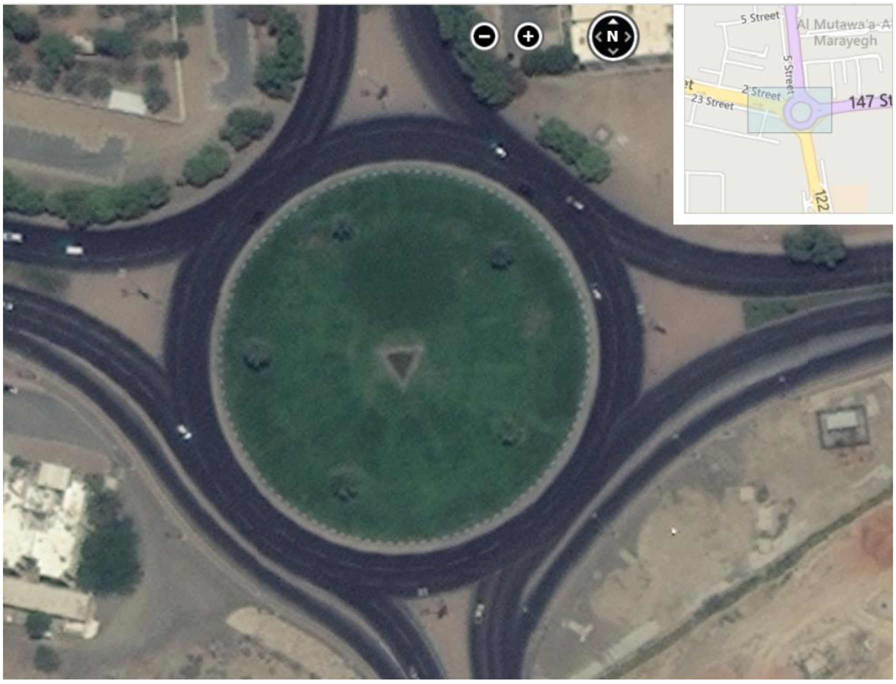


Figure 4-8: Roundabout 5 Location and Features

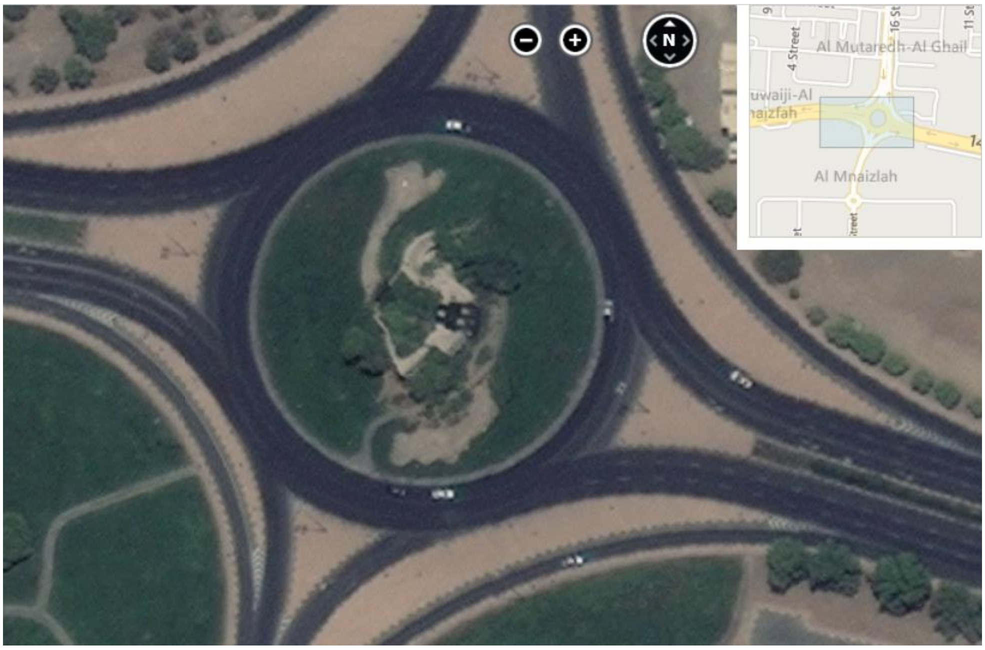


Figure 4-9: Roundabout 6 Location and Features

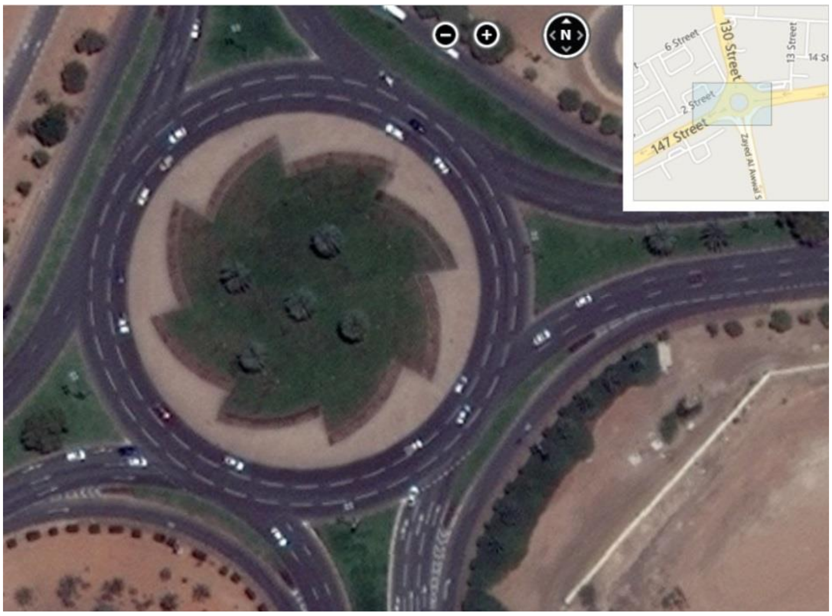


Figure 4-10: Roundabout 7 Location and Features

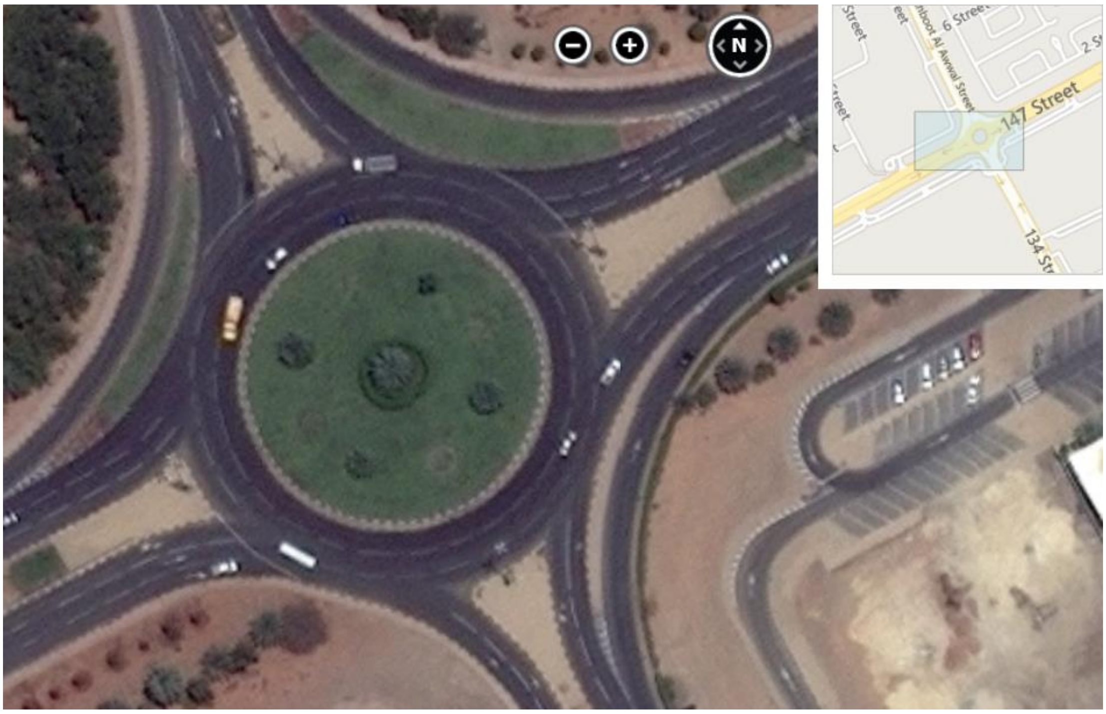


Figure 4-11: Roundabout 8 Location and Features

Figure 4-12: Roundabout 9 Location and Features

Figure 4-13: Roundabout 10 Location and Features

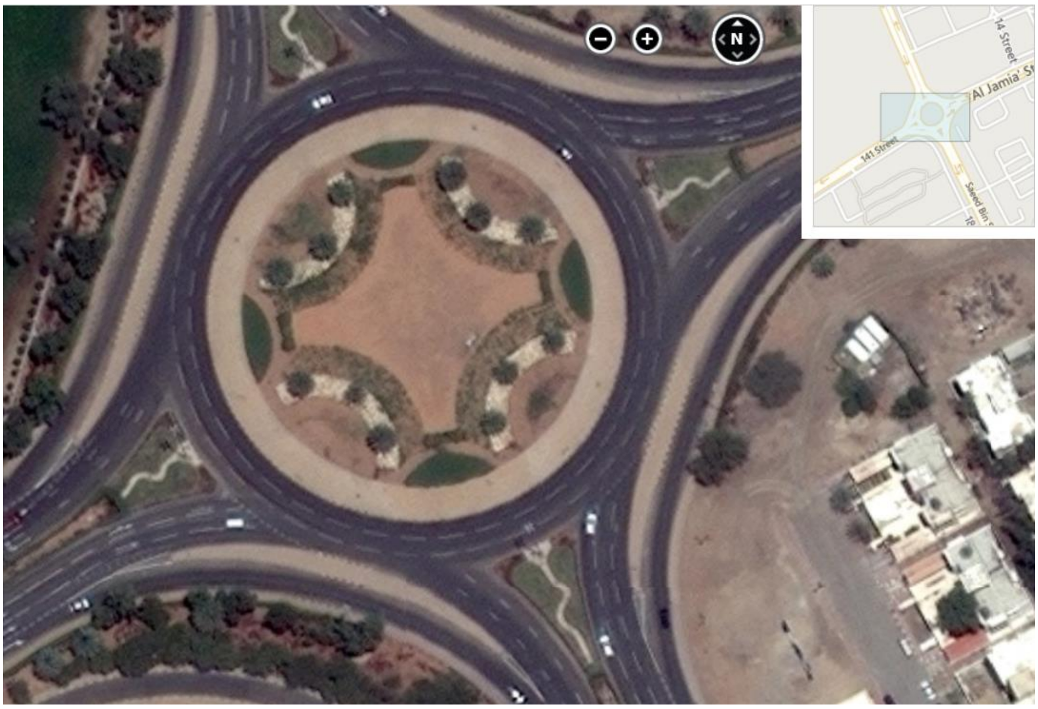


Figure 4-14: Roundabout 11 Location and Features

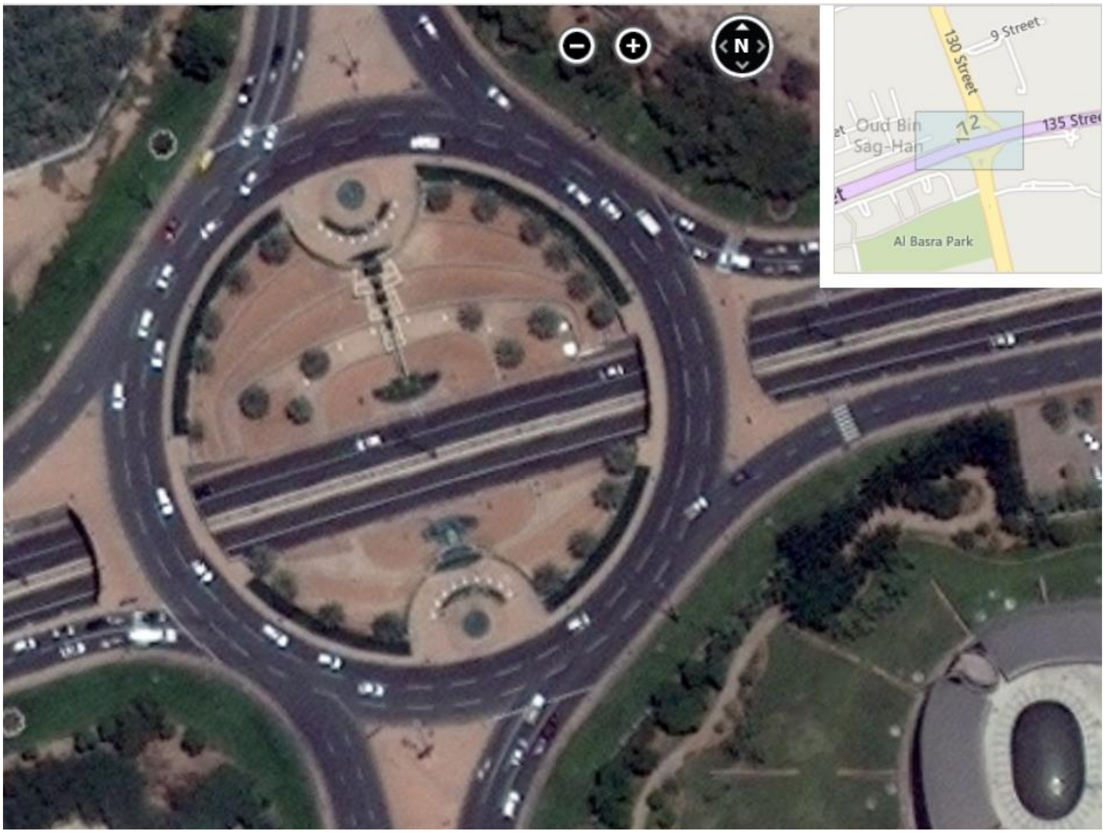


Figure 4-15: Roundabout 12 Location and Features

4.3. Data Collection

4.3.1. Type of Needed Data

The following types of data were needed for this study:

- The number of vehicles per 5-minute interval at the entry approach and vehicles per 5-minute interval circulating in front of the entry approach.
- Vehicles classification: light vehicles (LV), Buses, and Heavy Vehicles (HV). Figure 4-16 graphically shows the types of vehicles considered as LV, Buses, and HV.

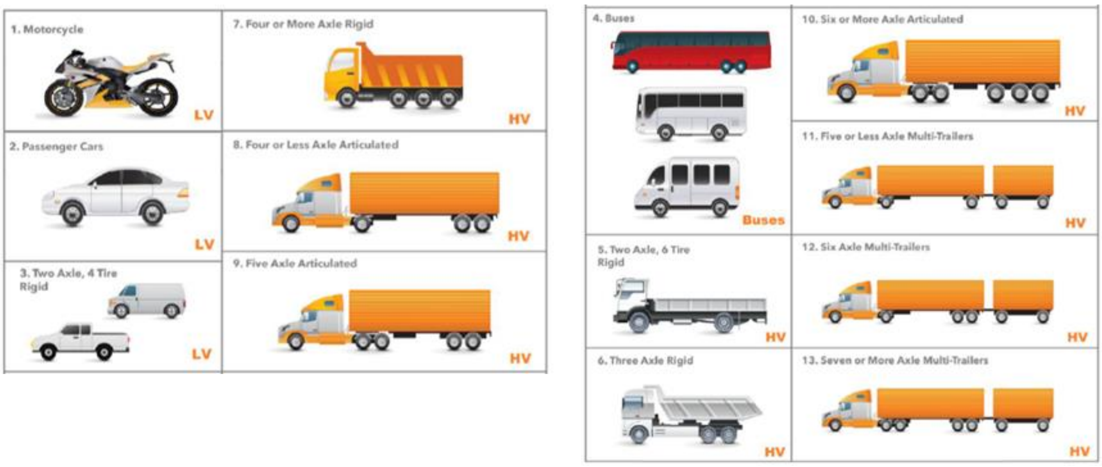


Figure 4-16: Vehicle Classifications

4.3.2. Data Collection Methodology

As discussed in the previous section, entry and conflicting circulating classified vehicle counts were required to do further analysis and capacity modeling. To ensure reliable data, data collection via video recording was used. The video cameras were installed on each leg of the roundabout in order to clearly capture the entry and circulating/conflicting traffic. The video-based traffic data collection software TRAIS [51] was later used to extract the data from the recorded videos. Therefore, TRAIS requirements and limitations were considered while recording the videos on each roundabout. For instance, the camera should be in the high-angle position and should be properly mounted so that it does not sway, move, or vibrate [51]. Moreover, to obtain high-quality video recordings, Scout video collection units [51] were used to record videos. Figure 4-17 shows the location of cameras installed on each leg of the roundabout and also the snapshot of an actual video recording. It is clear from the snapshot that entry vehicles from each lane of the entry approach and lane-by-lane circulating vehicles can be easily viewed. Similarly, camera schematics were used for all selected roundabouts for data collection.

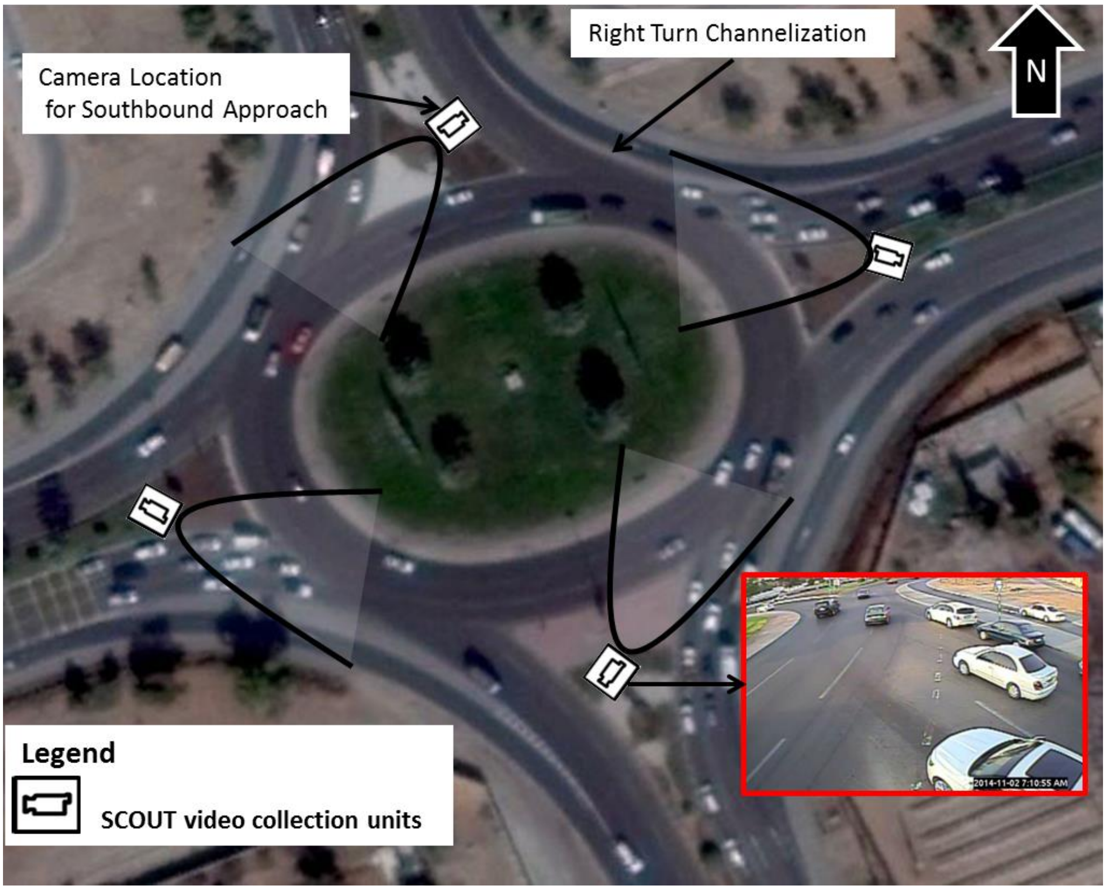


Figure 4-17: Camera Locations and Coverage

The video recordings were done for twelve hours continuously from 7 AM to 7 PM on all legs of the selected roundabouts during weekdays. This time period covers both AM and PM peak periods at the selected locations. The methodology adopted for the data extraction from the recorded videos and data analysis is presented in the proceeding chapters.

Chapter 5: Data Extraction and Analysis

5.1. Video Recording Screening

All of the selected roundabouts have three circulating lanes. However, some of these roundabouts do not have three entry lanes at all approaches as mentioned in the previous chapter. The scope of this research is limited to analysis of three lane approaches; therefore, only approaches that have three entry lanes were considered for data extraction.

A total of 168 hours of video was recorded for twelve roundabouts. To ensure reliable data are used for estimating capacity, time intervals satisfying the following two conditions were selected for data extraction:

- There should be continuous traffic demand on the entry lanes for at least five minutes (i.e., the vehicle queue should be present at the entry approach). HCM 2010 [1] recommends using fifteen-minute intervals for traffic analysis and also mentions that, in some situations, five-minute or one-minute intervals are valuable. In this research, it was observed that the traffic flow at the roundabouts stabilized for short intervals of time. Moreover, as compared to signalized intersections, roundabouts do not have a fixed number of cycles or green time periods. Therefore, five-minute intervals were used for data extraction and for the development of capacity models in this research.

- The traffic flow at the entry and circulating lanes should not be disturbed by any external factors. It was observed at two roundabouts that traffic police started controlling the traffic during peak morning hours. These time periods were not selected for data extraction.

Using the above conditions, out of 168 hours of total recorded data, only 28 hours of video recordings were selected for data extraction. Table 5-1 shows the details of all the video data collected and selected for data extraction from each roundabout.

Table 5-1: Details of Total Video Data Collected and Selected for Data Extraction for Each Roundabout

Roundabout ID	Recorded Video Data (min)	Minutes of Video Recording Selected for Extraction
1*	1,440	270
2*	1,440	210
3	720	120
4	720	60
5	720	60
6	720	120
7	720	210
8	720	120
9	720	120
10	720	170
11	720	210
12	720	60
Total	**10,080 (168 hours)**	**1,730 (28.3 hours)**

** For these roundabouts, data was collected for two days.*

5.2. Data Extraction Technique and Quality Assurance

Figure 5-1 shows the methodology adopted for data extraction from selected videos to ensure accuracy of the data. The traffic volume data were extracted from the selected videos using two techniques: one through TRAIS software [51] and another by manually reviewing the videos by multiple people. TRAIS video analysis software is one of the popular software tools used to extract the data automatically from video recordings. In this software, the area and type of data needed were defined, and the software provided the classified traffic counts as output. Moreover, the time interval can be defined for data extraction. The five-minute interval was coded in the TRAIS [51] software to extract the data from approximately twenty-eight hours of video recording. For extraction by reviewing the videos manually, undergraduate civil engineering students were hired to review the videos by playing them at slow speed. The results obtained from both techniques were compared and repeated if there were any significant discrepancies (i.e., difference of ± twenty vehicles).

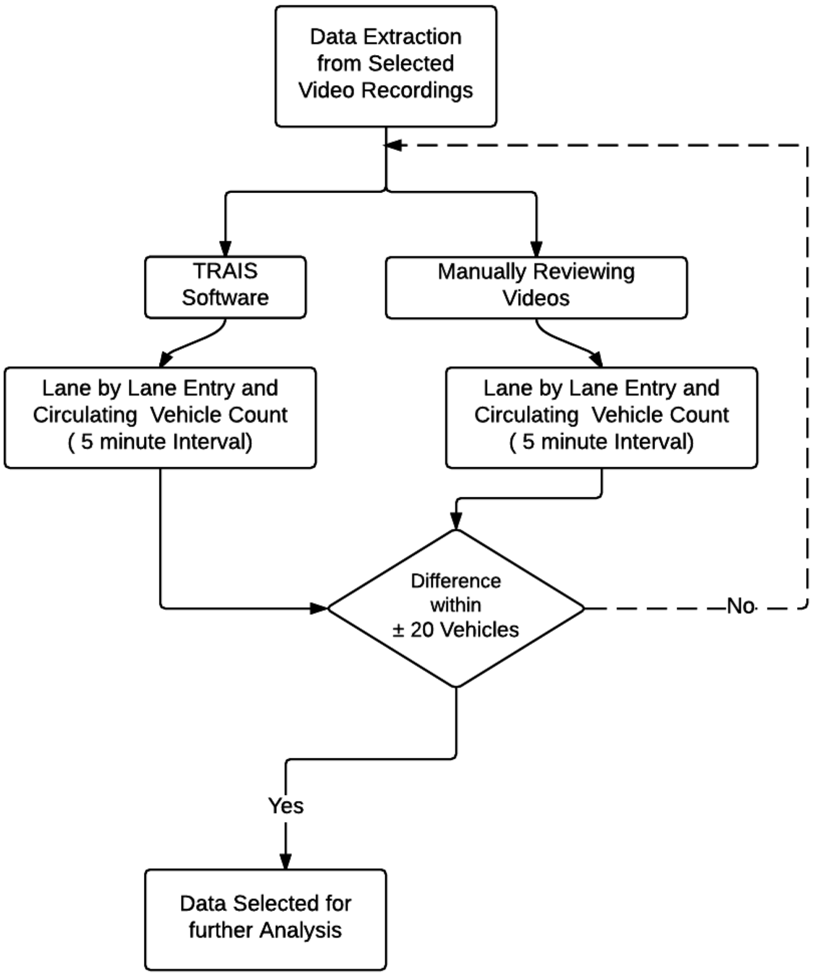


Figure 5-1: Methodology Flowchart for Data Extraction

5.3. Extracted Data

The entry lane-by-lane volume and circulating volume were extracted from the selected videos. The lanes were defined as the following:

- Entry-Lane 1 (E-Lane1) and Conflicting-Lane1 (C-Lane1): Adjacent to the median and the central island, respectively. Both lanes can be used for left and through movements.
- Entry-Lane 2 (E-Lane2) and Conflicting-Lane2 (C-Lane2): Located in the middle; only through movements are allowed on these lanes.

- Entry-Lane 3 (E-Lane3) and Conflicting-Lane3 (C-Lane3): Located close to the right-of-way boundary and median, respectively; only through movements are allowed on these lanes. The complete extracted data is provided in Appendix A.

Table 5-2 shows a sample of extracted data for both entry and circulating lanes for one hour at roundabout 1. The complete extracted data is provided in Appendix A.

Table 5-2: Roundabout 1 Lane-by-Lane Counts from 7:00 to 8:00 AM (EB Approach)

Time	Entry Volume (PCE)				Circulating Volume (PCE)			
	Lane 1 (Left-Through)	Lane 2 (Through)	Lane 3 (Through)	Total	Lane 1	Lane 2	Lane 3	Total
7:00	26	31	20	77	86	74	12	172
7:05	19	24	25	68	94	69	37	200
7:10	19	20	21	60	106	89	62	257
7:15	29	37	40	106	46	28	5	79
7:20	34	51	26	111	70	32	4	106
7:25	32	57	36	125	29	27	14	70
7:30	46	58	38	142	30	13	11	54
7:35	25	53	35	113	22	17	6	45
7:40	25	22	18	65	72	62	6	140
7:45	18	26	28	72	66	55	10	131

Time	Entry Volume (PCE)				Circulating Volume (PCE)			
	Lane 1 (Left-Through)	Lane 2 (Through)	Lane 3 (Through)	Total	Lane 1	Lane 2	Lane 3	Total
7:50	32	37	20	89	74	47	20	141
7:55	40	31	19	90	62	51	23	136

5.4. Data Analysis

5.4.1. Lane-by-Lane Average Traffic Volume

The data was extracted from the selected video recordings for all of the roundabouts. More than twenty-eight hours of video recording were analyzed. As discussed in the previous section, to ensure the accuracy of counts, extraction was done using two methods: manually by viewing the videos and also with TRAIS software. The traffic counts were classified as LV, Buses, and HV. Because all of the roundabouts were located in an urban area, the percentage of heavy vehicles was very low. The classified counts were converted into Passenger Car Equivalent (PCE) using the HCM methodology. Equation 5-1 was used for calculating the PCE:

$$f_{HV} = \frac{1}{1 + P_T(E_T - 1)} \qquad \text{Equation 5-1}$$

In this equation:

$f_{HV} = Heavy\ vehicle\ adjustment\ factor$

$P_T = Proportion\ of\ heavy\ vehicles$

$E_T = \; Passenger\; Car\; Equivalent\; for\; heavy\; vehicles = 2.0$

Figure 5-2 shows the detail of lane-by-lane average volumes per five minutes for each roundabout. On the entry approach, the highest average volume was observed on E-Lane2 (middle lane), whereas for the circulating lane, the maximum volume was on C-Lane1 (innermost lane). Similar graphs for each roundabout are provided in Appendix B.

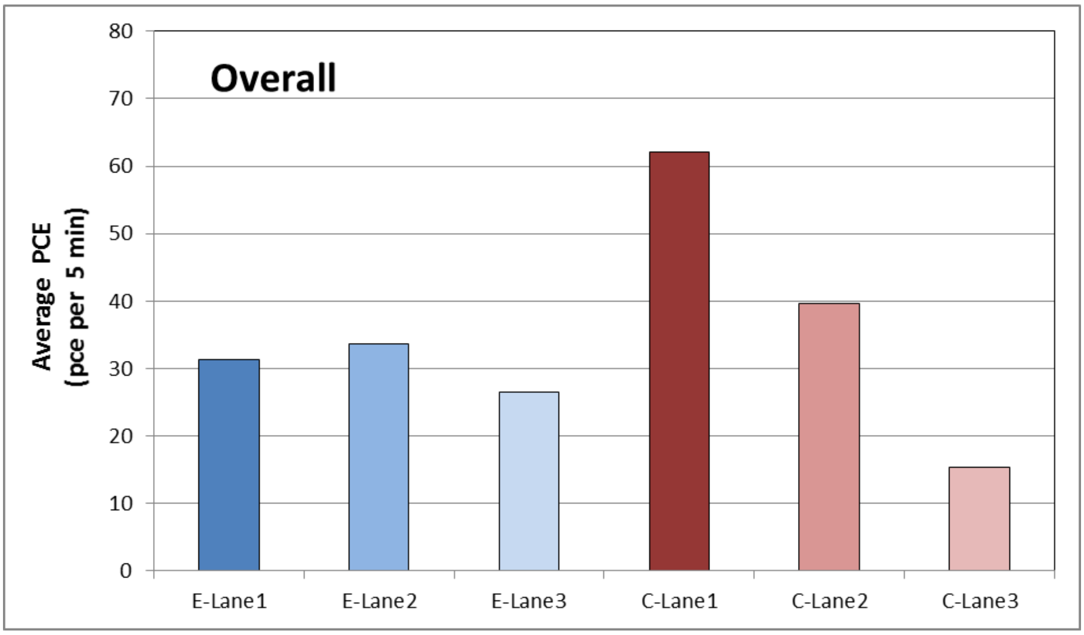


Figure 5-2: Overall Five-Minute Average Volumes at All Roundabouts (Lane by Lane)

5.4.2. Vehicle Distribution over the Lanes

5.4.2.1. Entry Lanes

The vehicle distribution over the lanes is important to understand the traffic operations analysis at the roundabout. The lane utilization also explains the drivers' perception and behavior related to the choice of lane while entering the roundabout. Figure 5-3 shows the lane distribution for through vehicles on the entry approach.

It is clear that drivers preferred to use the middle lane for the through movement. The center lane utilization was more than 50%. For roundabout 8, 41% of vehicles were using the rightmost lane for through movement due to the higher percentage of heavy vehicles at this roundabout. Heavy vehicles preferred to use the rightmost lane for through movement because of the turning radius and low speed. Note that “vehicle” refers to Passenger Car Equivalent (PCE), and only through vehicles were used to calculate the percentage.

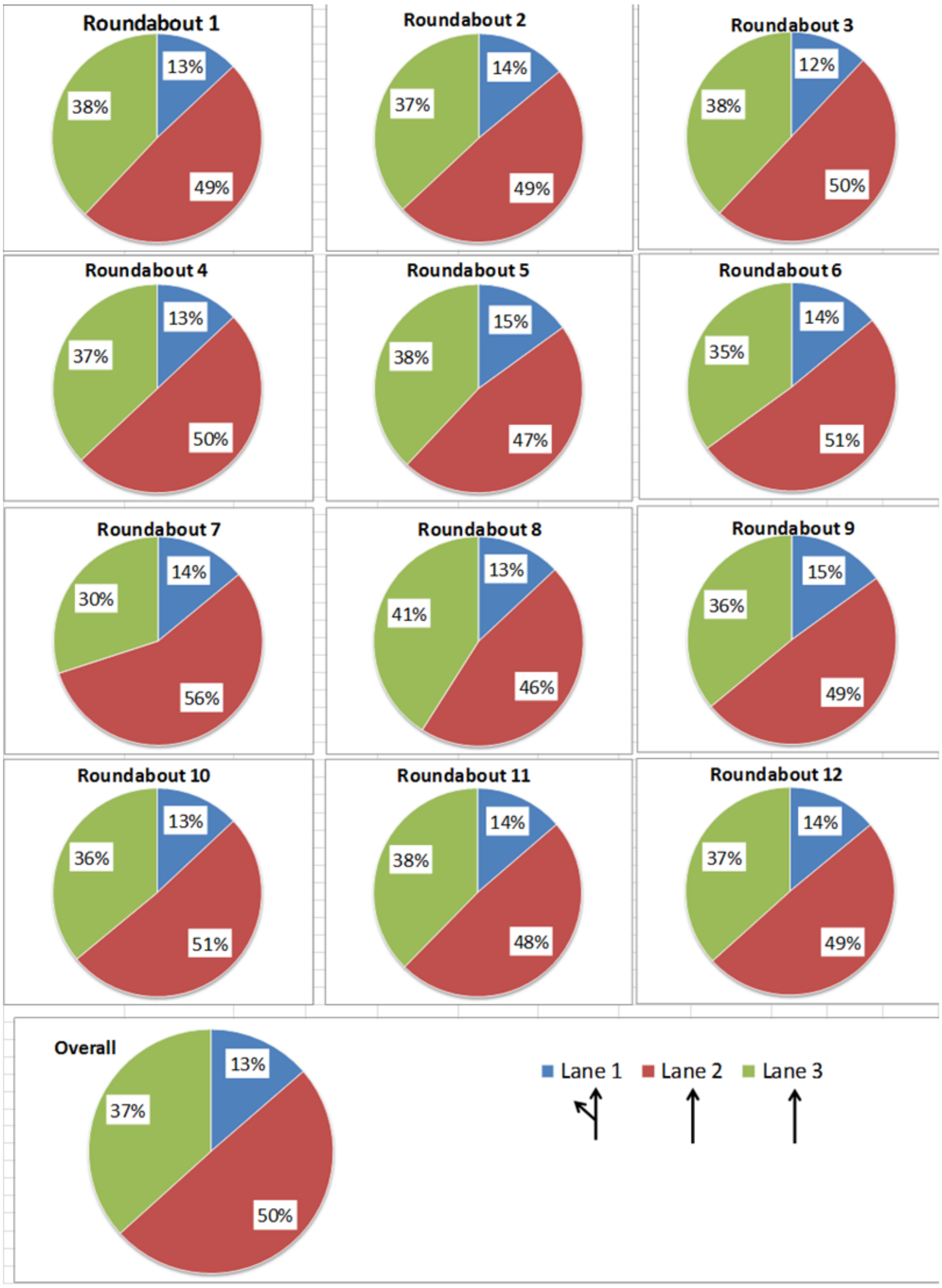


Figure 5-3: Through Vehicle Lane Utilization at Entry Approach

5.4.2.2. Circulating Lanes

All roundabouts under study have three circulating lanes. The lane utilization of vehicles on the circulating lanes is vital for developing capacity models for three-by-three–lane roundabouts. The uncertainty about the entry vehicle driver’s perception of gap between the circulating vehicles and whether he will look for a gap only on the inside or outside circulating lane makes the modeling process of multilane roundabouts more complex. Figure 5-4 shows the proportion of vehicles using each circulating lane. The innermost circulating lane carries the highest volume, which is expected because this lane is used by vehicles making a right turn on the immediate proceeding approach as well as for other directions. It was also observed that most of the time, leading vehicles waiting to enter the roundabout at the entry lanes were standing beyond the stop line. This reduces the available driving space of the outermost circulating lane, which impacts the driver’s comfort. That’s why the results showed that the outermost circulating lane was least used at a varying rate of 2% to 23%. This trend was observed on all of the roundabouts, as shown in Figure 5-4.

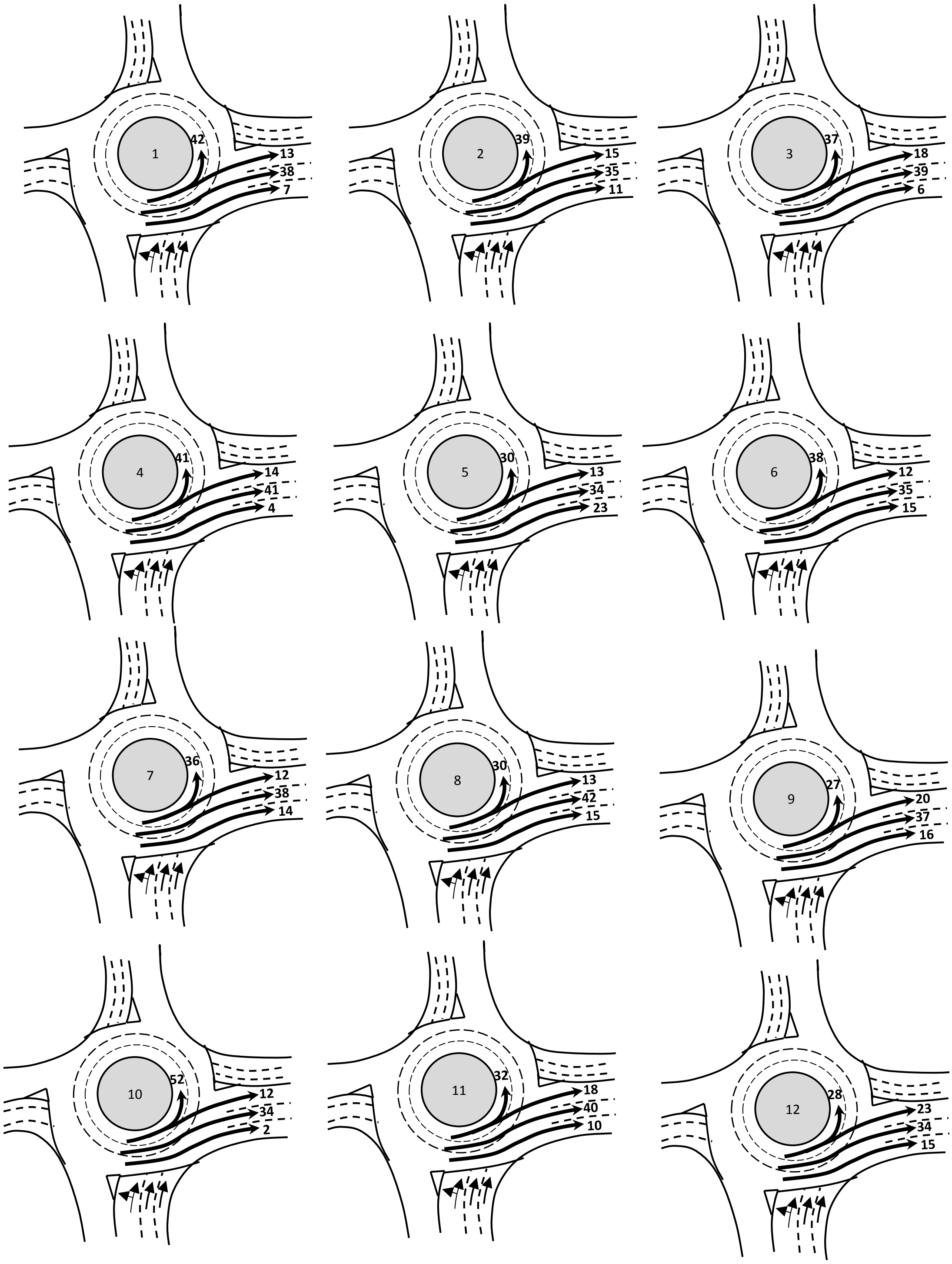


Figure 5-4: Circulating Vehicles Lane Utilization

5.4.3. Traffic Entry and Circulating Volume

The number of vehicles per 5-minute interval entering the roundabout depends on the number of vehicles circulating per 5-minute interval. Figure 5-5 shows the total entry volumes with total circulating volume. As expected, the number of vehicles entering decreases with the increase of circulating vehicles. Note that the volumes shown in the figure are PCEs at five-minute intervals. The maximum of 142 and 202 PCEs per five-minute interval was observed for the entry approach and circulating lanes, respectively.

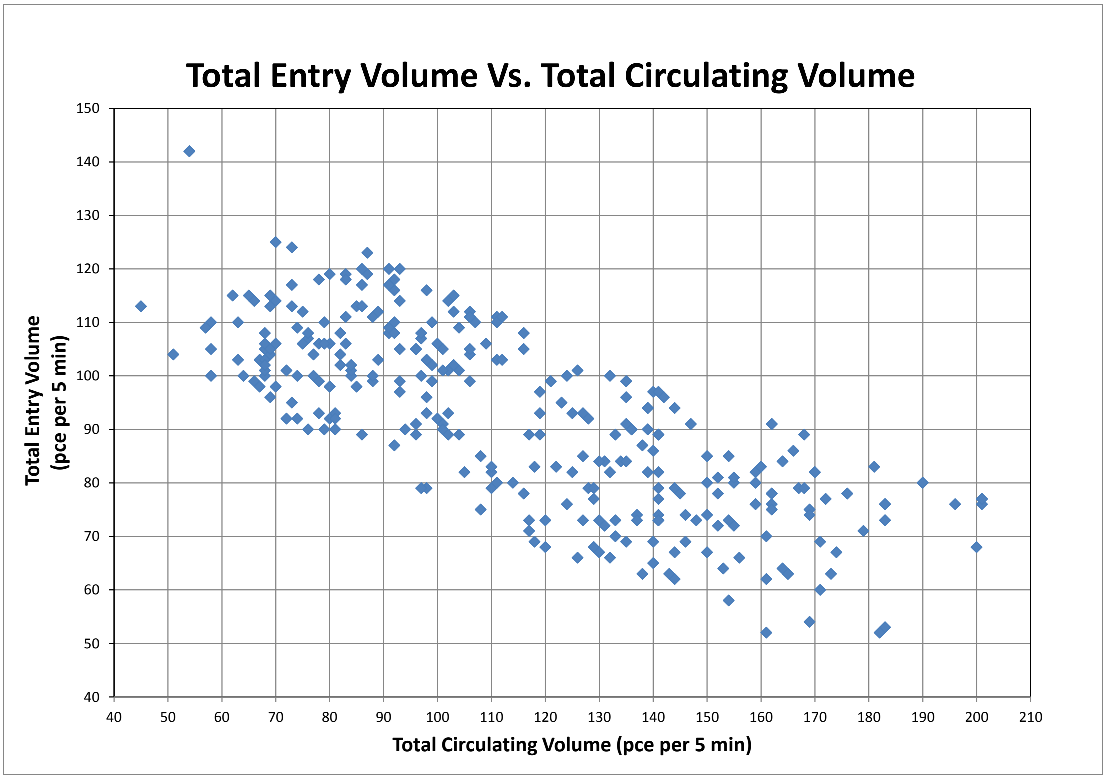


Figure 5-5: Total Entry Volume and Circulating Volume

5.4.4. Lane-by-Lane Traffic Volume Analysis

The scatter plots for entry lane 1, entry lane 2, and entry lane 3 versus the total conflicting traffic volumes are presented in Figure 5-6, Figure 5-7, and Figure 5-8, respectively. All the lanes showed similar trends. All entry lane volumes were inversely proportional to the circulating volume (i.e., with the increase of circulating volume, the entry lane volume decreases). These trends are as expected and are similar to previous studies. However, maximum variation in the data was observed in entry lane 3, for example, for a circulation volume of fifty PCEs per five minutes, an entry volume of between six PCEs and thirty-eight PCEs per five minutes was observed. This large variation was due to the high number of heavy vehicles using the rightmost lane and requiring more gap in the circulating traffic. This variation was highlighted more when capacity models were developed for entry lane 3. The methodology adopted for the development of capacity models is presented in the proceeding chapter.

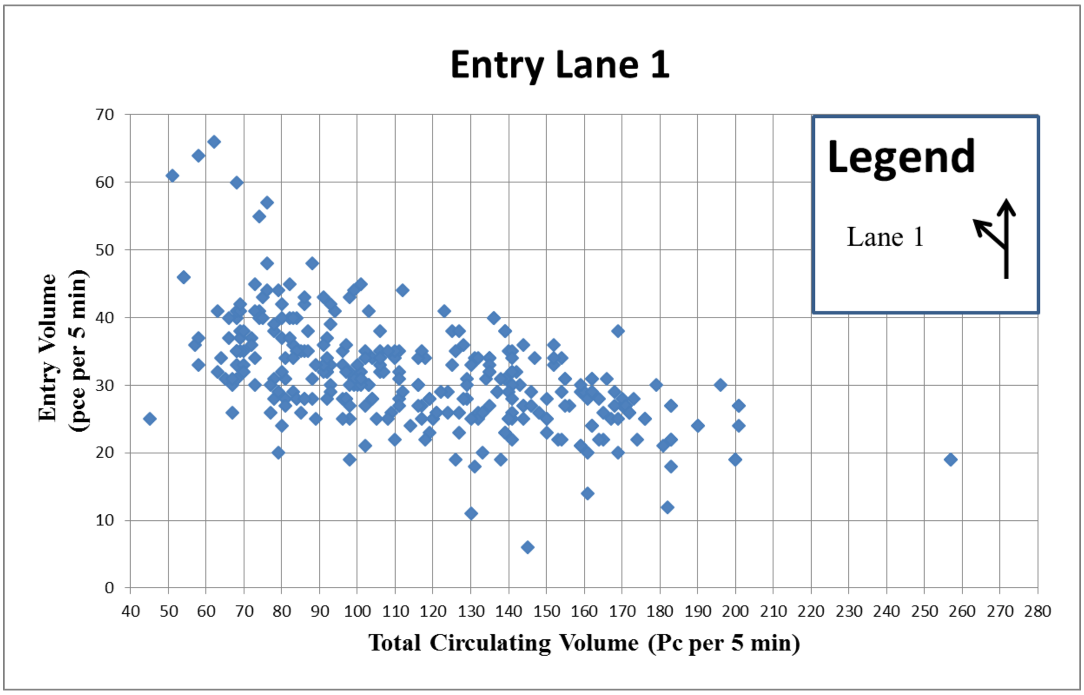


Figure 5-6: Scatter Plot for the First Entry Lane vs. the Total Conflicting Traffic

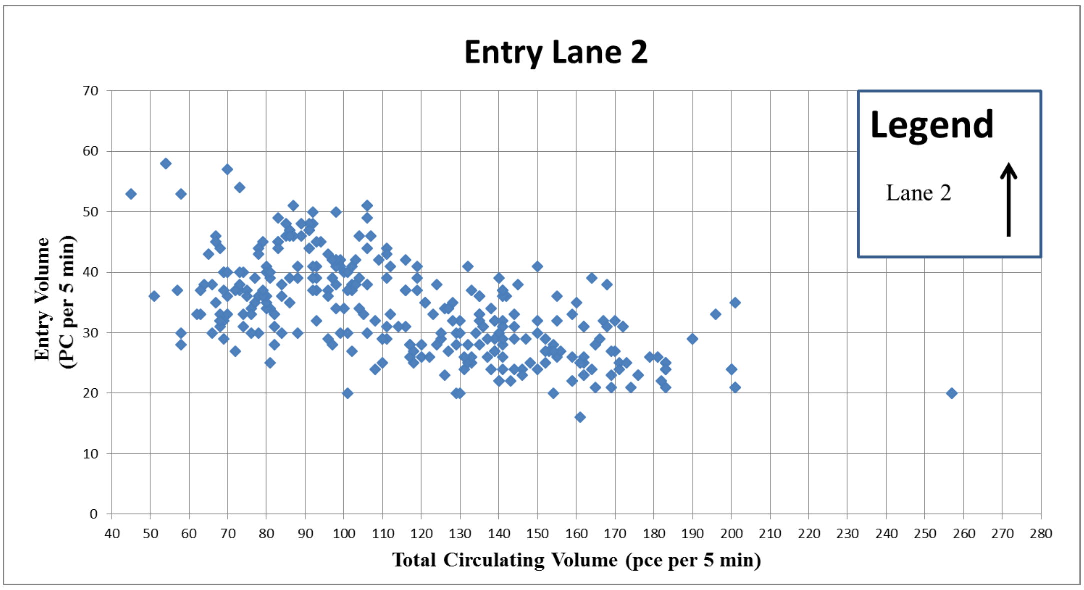


Figure 5-7: Scatter Plot for the Second Entry Lane vs. Total Conflicting Traffic

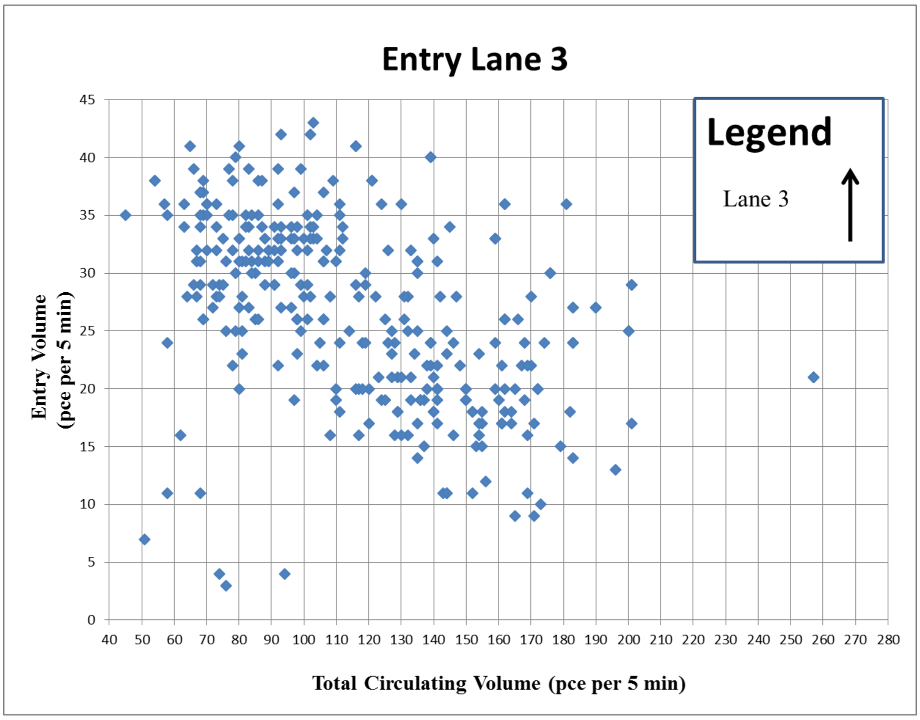


Figure 5-8: Scatter Plot for the Third Entry Lane vs. Total Conflicting Traffic

Chapter 6: Development of Capacity Models for Three-by-Three Lane Roundabouts

The lane-by-lane entry and circulating volumes were used to develop capacity models for the three-by-three–lane roundabouts. Different techniques were used to develop the models. The next section provides details on model development.

6.1. Data Setup and Hypothesis

The extracted data from the video recording was coded in the Statistical Package for Social Sciences (SPSS) [52]. The data coded in SPSS was divided into entry lanes and circulating lanes' volumes in five-minute intervals. The entry approach volume was divided into E-Lane1, E-Lane2, E-Lane 3, and total entry approach volume. Similarly, circulating volume was divided into C-Lane1, C-Lane2, C-Lance 3, and total circulating volume. The model was developed based on the hypothesis that the entry volume of each lane depends on the circulating volume. As the drivers approach the entry approach at roundabout they will be looking for gap to enter it. If there are no vehicles using the roundabout then the drivers will pass without any obstacle. Hence, the arrival rate will be more when there are not conflicting vehicles. On the other hand, if there are many vehicles inside the roundabout, the driver needs to wait certain gap to enter the roundabout. Therefore the entry volume is related to the circulating volume and it increases as the circulating volumes decreases and vice versa.

Following are general forms for the capacity models:

$$E - Total \ = f(C - Total)$$ Equation 6-1

$$E - Lane1 = f(C - Total)$$ Equation 6-2

$$E - Lane2 \ = f(C - Total)$$ Equation 6-3

$$E - Lane3 = f(C - Total)$$ Equation 6-4

$In\ these\ equations$:

$E - Total = Total\ Entry\ Volume\ (PCE\ per\ 5\ min)$

$C - Total \ = Total\ Circulating\ Volume\ (PCE\ per\ 5\ min)$

$E - Lane1 = \ Entry\ Lane\ 1\ \ Volume\ (PCE\ per\ 5\ min)$

$E - Lane2 \ = Entry\ Lane\ 2\ \ Volume\ (PCE\ per\ 5\ min)$

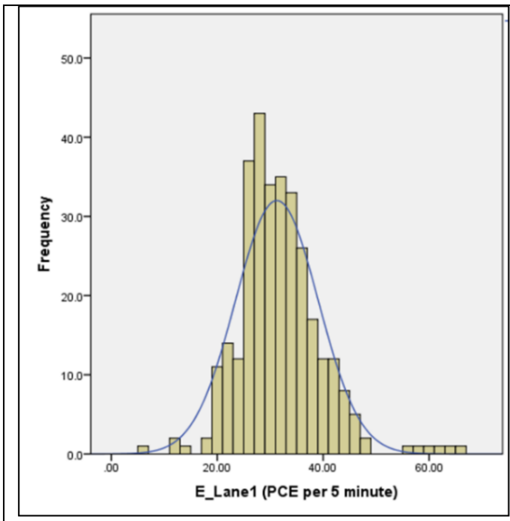
$E - Lane3 \ = Entry\ Lane\ 3\ \ Volume\ (PCE\ per\ 5\ min)$

6.2. Assumption Checking for Model Development

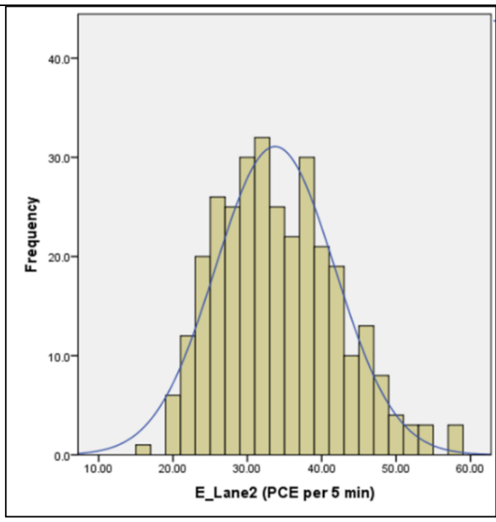
Most of the models, for example, linear and multiple regression, depend on certain assumptions related to independent and dependent variables. If these assumptions are not met, then the results or outputs of the models are not reliable and have Type I or II errors. As discussed in the previous section, total and lane-wise entry volumes were considered as dependent variable, whereas total and lane-wise circulating volumes were considered as independent variables. Two basic assumptions were checked, that is, normality and the correlation between independent and dependent variables.

6.2.1. Normality Check

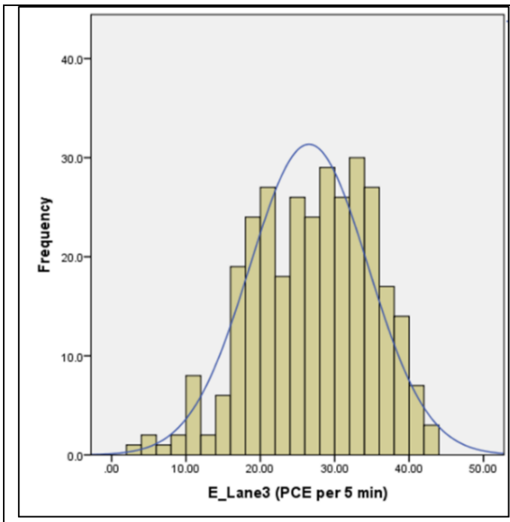
The independent and dependent variables normality checks were made to fulfill the basic assumption for statistical testing. Figure 6-1 shows the histogram and skewedness for both variables. The skewedness values of data distribution were calculated to check whether the variable distribution is comparable to normal distribution. According to a rule of thumb [53], normal distribution skewedness should be within the range of +1 and –1. All skewedness values for all variable were within the recommended range; therefore, it can be concluded that the collected data was normally distributed. Normality check were also done using Anderson-Darling method and the p-value shows that the data are normal as shown in Appendix D.



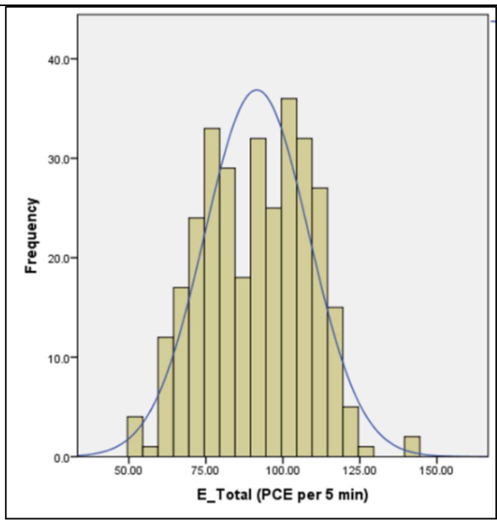
First Entry Lane (E-Lane1)



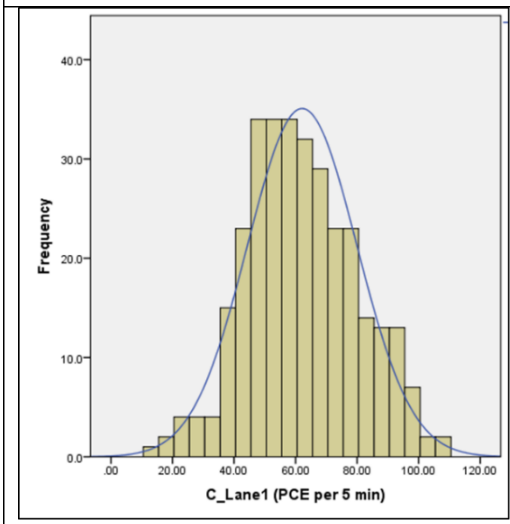
Second Entry Lane (E-Lane2)



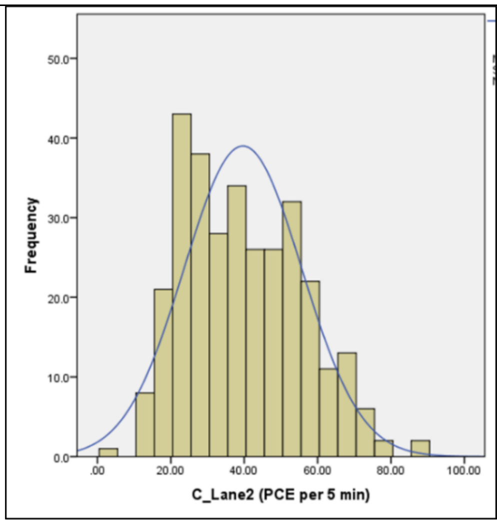
Third Entry Lane (E-Lane3)



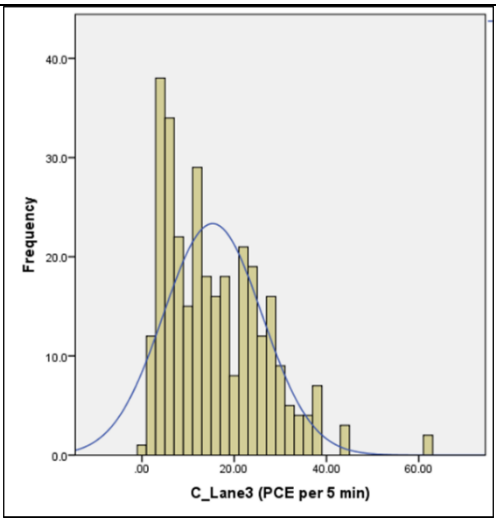
Total Entry Approach (E-Total)



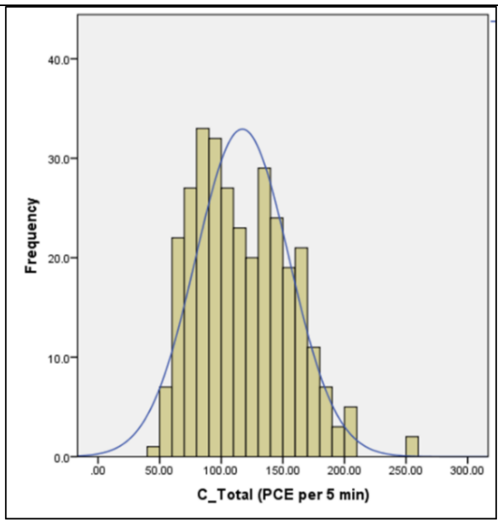
First Circulating Lane (C-Lane1)



Second Circulating Lane (C-Lane2)



Third Circulating Lane (C-Lane3)



Total Circulating Lanes (C-Total)

Figure 6-1: Normality Check for Independent and Dependent Variables

6.2.2. Multicollinearity Check

Multicollinearity occurs when two or more independent variables in the models are correlated to each other. The multicollinearity increases the standard error of the estimates and instability in the predication of models. On the other hand, correlation is required between dependent and independent variables. Table 6-1 shows the correlation matrix between entry and circulating volumes. It is clear that a significant correlation exists between the entry and circulating volumes. Moreover, circulating volumes on each lane also have significant correlation among themselves. Therefore, circulating volumes for each lane cannot be used together in the model for the prediction of entry volumes. Note that the correlation between entry and circulation volume are negative; that is, both are inversely proportional to each other.

Table 6-1: Correlation Matrix between Entry and Circulating Volumes

	C_Lane1	C_Lane2	C_Lane3	C_Total
E_Lane1	–.544**	–.473**	–.366**	–.559**
E_Lane2	–.506**	–.596**	–.436**	–.612**
E_Lane3	–.337**	–.413**	–.416**	–.450**
E_Total	–.649**	–.695**	–.571**	–.759**
C_Lane1	1	.661**	.456**	.877**
C_Lane2	.661**	1	.583**	.897**
C_Lane3	.456**	.583**	1	.742**
C_Total	.877**	.897**	.742**	1

***Correlation is significant at the 0.01 level (two-tailed).*

6.3. Capacity Models

The models were developed and studied for each entry lane as a function of the total circulating volume as well as for the total entry volume as a function of the total circulating volume. Based on previous studies, different types of regression models were used. Table 6-2 shows the results for linear, polynomial (quadratic and cubic), and exponential regression models. The R-squared for the models ranges from 0.20 to 0.59 approximately. The value of R^2 is not high for all models expect for models developed for total entry approach volumes. Particularly for entry lane 3 (rightmost lane), R^2 values for all models range from 0.20 to 0.23. This was an expected result because scatter plots for entry lane 3 shown in Figure 5-8 reveal significant variation in the entry volume for the same circulating volume. The other reason for this variation is the high percentage of heavy vehicles in this lane. The performance of all models was more or less similar to the others.

Based on the previous studies and for the purpose of calculating follow-up and critical headway using HCM 2010 functions, exponential models were selected for further analysis. Moreover, selection of the exponential models also enables the comparison of model output with HCM 2010 exponential models for multilane roundabouts.

Table 6-2: All Capacity Models

Entry	Model	Equation	R^2
For Entry Approach	Linear	E-Total = 131.25 – 0.34 C-Total	0.58
	Quadratic	E-Total = 145.15 – 0.58 C-Total + 0.0009 (C-Total)^2	0.59
	Cubic	E-Total = 122.4 – 0.014 C-Total – 0.003 C-Total^2 + 0.000010 C-Total^3	0.59
	Exponential	E-Total = 142.62 * EXP (–0.004 * C_Total)	0.59
Entry Lane 1	Linear	E-Lane1 = 44.73 – 0.15 C-Total	0.31
	Quadratic	E-Lane1 = 51.82 – 0.24 C-Total + 0.001 (C-Total)^2	0.33
	Cubic	E-Lane1 = 63.79 – 0.54 C-Total + 0.003 C-Total^2 – 0.00001 C-Total^3	0.33
	Exponential	E-Lane1 = 48.93 * EXP (–0.004 * C_Total)	0.32

Entry	Model	Equation	R^2
Entry Lane 2	Linear	E-Lane2 = 48.93 – 0.13 C-Total	0.37
	Quadratic	E-Lane2 = 50.66 – 0.16 C-Total + 0.00012 (C-Total)^2	0.38
	Cubic	E-Lane2 = 36.39 + 0.2 C-Total – 0.003 C-Total^2 + 0.00001 C-Total^3	0.39
	Exponential	E-Lane2 = 53.02 * EXP (–0.004 * C_Total)	0.38
Entry Lane 3	Linear	E-Lane3 = 37.60 – 0.01 C-Total	0.20
	Quadratic	E-Lane3 = 42.67 – 0.18 C-Total + 0.0004 (C-Total)^2	0.21
	Cubic	E-Lane3 = 22.24 + 0.33 C-Total – 0.004 C-Total^2 + 0.00001 C-Total^3	0.23
	Exponential	E-Lane3 = 40.68 * EXP (–0.004 * C_Total)	0.21

6.3.1. Exponential Regression Model

As discussed earlier, exponential regression models were selected based upon performance and suitability. Further analyses were performed to check the suitability and performance of these models for each entry lane as well as for total entry volume. Figure 6-2 shows the diagnostic analysis for the selected exponential model. The entry volumes were plotted against the selected exponential with the best fitted line plot for the linear model. A positive relationship was found between the entry volumes and the model. Moreover, correlation between the lane-by-lane entry volumes and selected exponential models ranges from 0.45 to 0.61. These results showed that exponential models were performing well to predict the entry volumes based on the circulating volumes. The details of diagnostic analysis of each entry lane are presented in Appendix C.

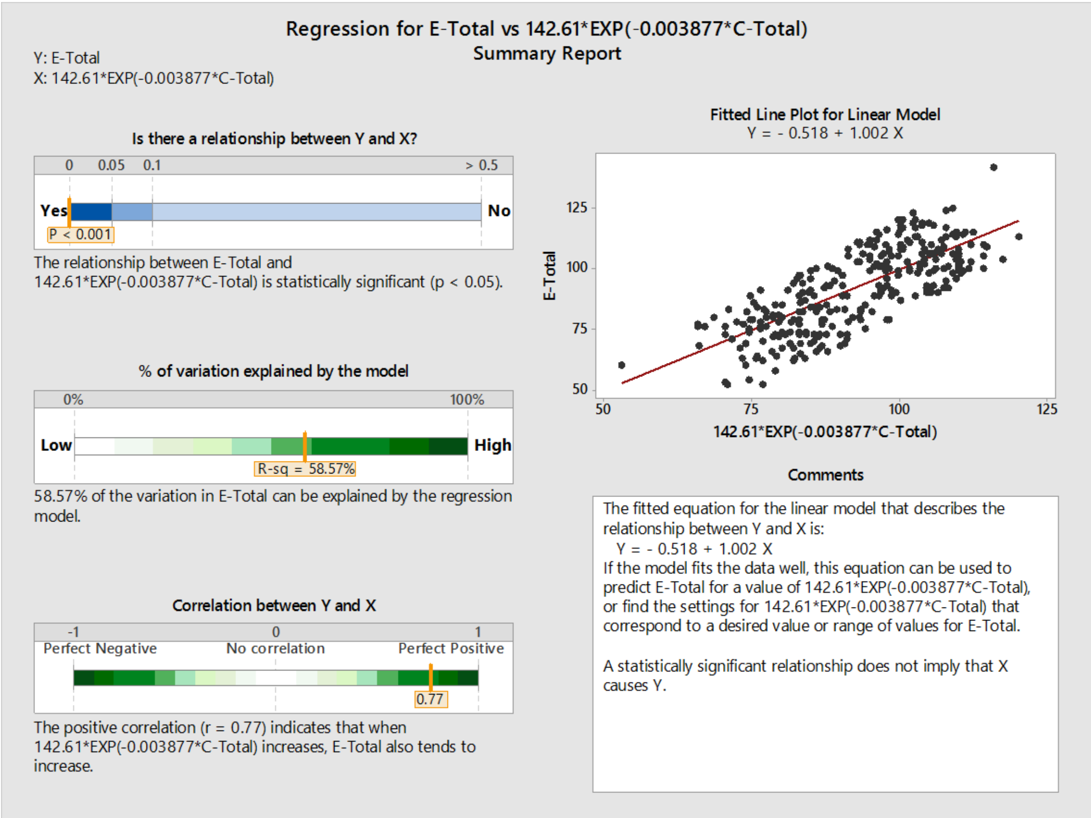


Figure 6-2: Diagnostic Analysis of the Exponential Model for E-Total

6.4. Capacity Curves for Each Entry Lane

Figure 6-3 shows each lane capacity curve for three-by-three–lane roundabouts. These capacity curves were developed using the selected exponential model. Note that the exponential models were developed for five-minute PCEs. For capacity curves, five-minute PCEs were converted into hourly PCEs.

With no conflicting traffic on the circulating lanes, maximum capacity was observed for the middle entry lane (E-Lane2), that is, 700 PCEs per hour. Minimum capacity was observed for the rightmost lane (E-Lane3), that is, 500 PCEs per hour. The capacity curves also show that as the circulating volume increases, the output of each lane becomes similar to the others. At the circulating volume of 2100 PCEs per hour, the outputs from E-Lane1, E-Lane2, and E-Lane3 were 295, 318, and 255 PCEs per hour, respectively. As expected, with the increase of circulating volume, the entry volume from each lane decreases. It is to be noted that the lower limit of the domain (range of hourly conflicting flow) is 540 PCE/hour, while the upper limit of the domain is 3,084 PCE/hour. Hence, the usage of the capacity curve between 0 to less than 540 PCE/hour is not warranted within this study.

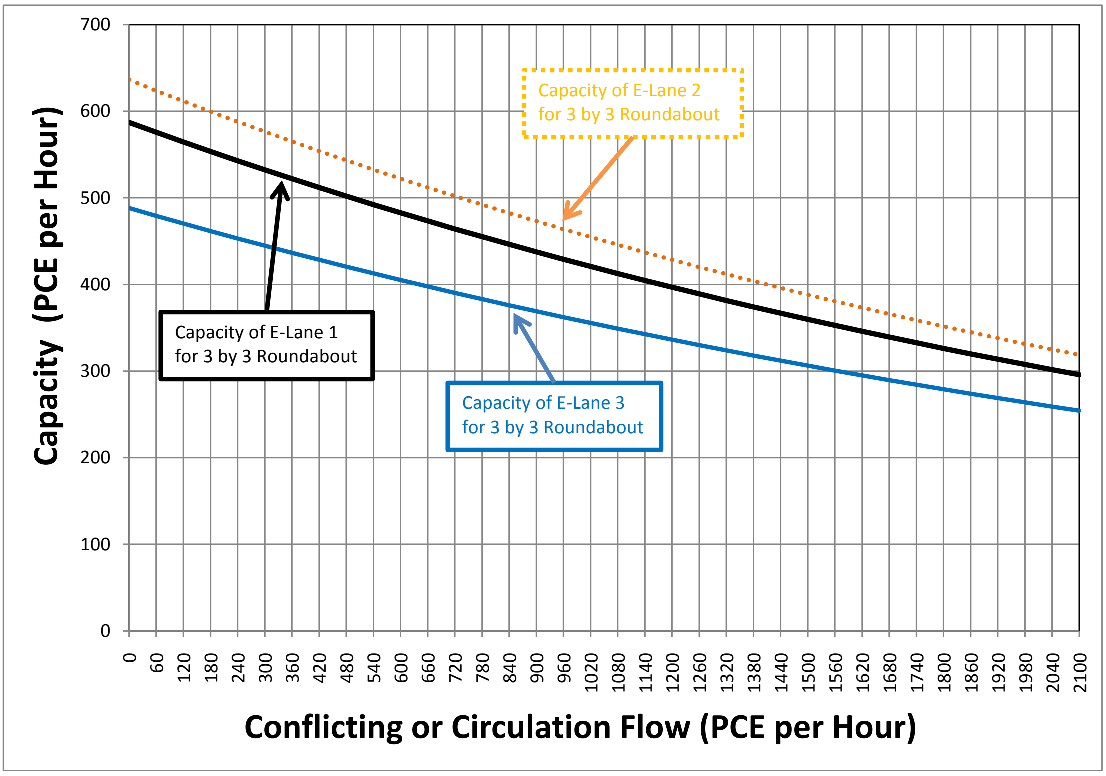


Figure 6-3: Capacity Curves for Three-by-Three-Lane Roundabouts

6.5. Capacity Curves for the Entry Approach

As compared to the lane-wise capacity of the three-by-three–lane roundabout, for transportation planners, the approach capacity has more importance in the initial planning stage when estimation of lane-by-lane volume is not possible. Figure 6-4 shows the capacity curve developed for the entry approach based on the selected exponential model. Maximum output of about 1700 PCEs per hour was estimated with no circulating vehicle. As the circulating volume increases, the entry approach volume decreases. For planning purposes, this curve will be very helpful to perform the capacity analysis with limited data. For example, after using travel demand modeling, the circulating and entry volumes were estimated as 1500 PCEs per hour and 1200 PCEs per hour, respectively. Using the capacity curve, it is clear for estimated entry and circulating volume, three-by-three–lane roundabouts will be performing at congested conditions.

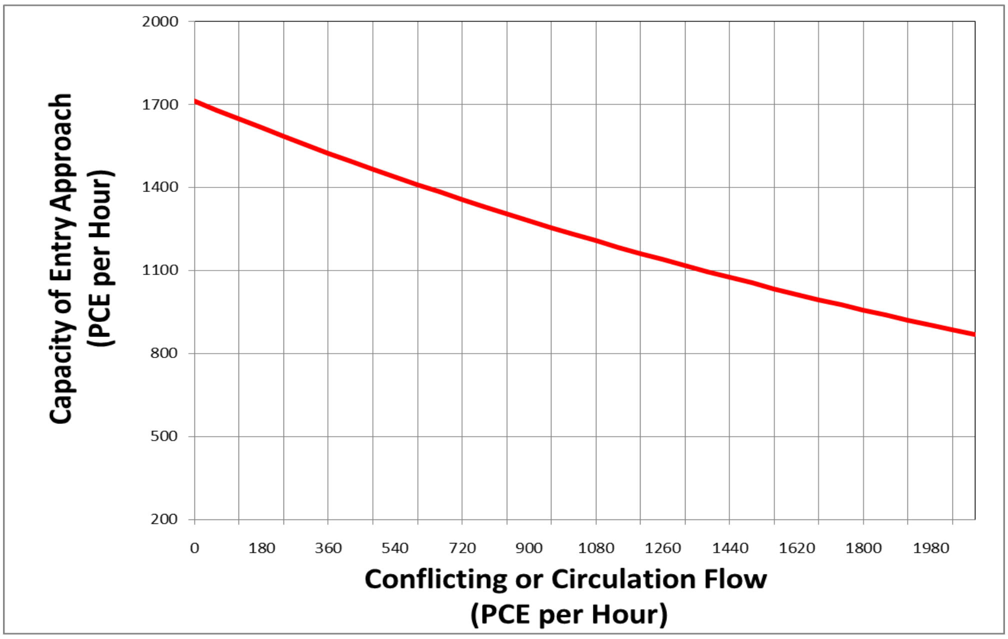


Figure 6-4: Capacity Curve for Entry Approach

6.5.1. Comparison with HCM 2010 for Two-by-Two-Lane Roundabouts

HCM 2010 provides multilane roundabout capacity models that were limited to two-by-two–lane roundabouts. In this research, capacity models for three-by-three–lane roundabouts were presented. Figure 6-5 shows the comparison of HCM 2010 multilane roundabout models with the proposed models.

It was interesting to note that with fewer circulating vehicles, the HCM 2010 models were estimating higher traffic output for each lane as compared to the proposed models. This may be because the drivers were more cautious on three-by-three–lane roundabouts and waiting for longer gaps. Both models showed similar results when the circulating traffic flow was higher than 1200 PCEs per hour. Figure 6-6 shows the comparison of total entry flow estimated by HCM 2010 and by the proposed model. Note that HCM 2010 did not provide any model for estimation of total entry approach flow; the values shown in the graph were calculated by adding the estimation of each lane. Similar trends were observed; at lower circulating volumes, HCM 2010 estimations were higher than the proposed model, whereas the proposed model estimated more entry flow when the circulating flows were higher than 700 PCEs per hour.

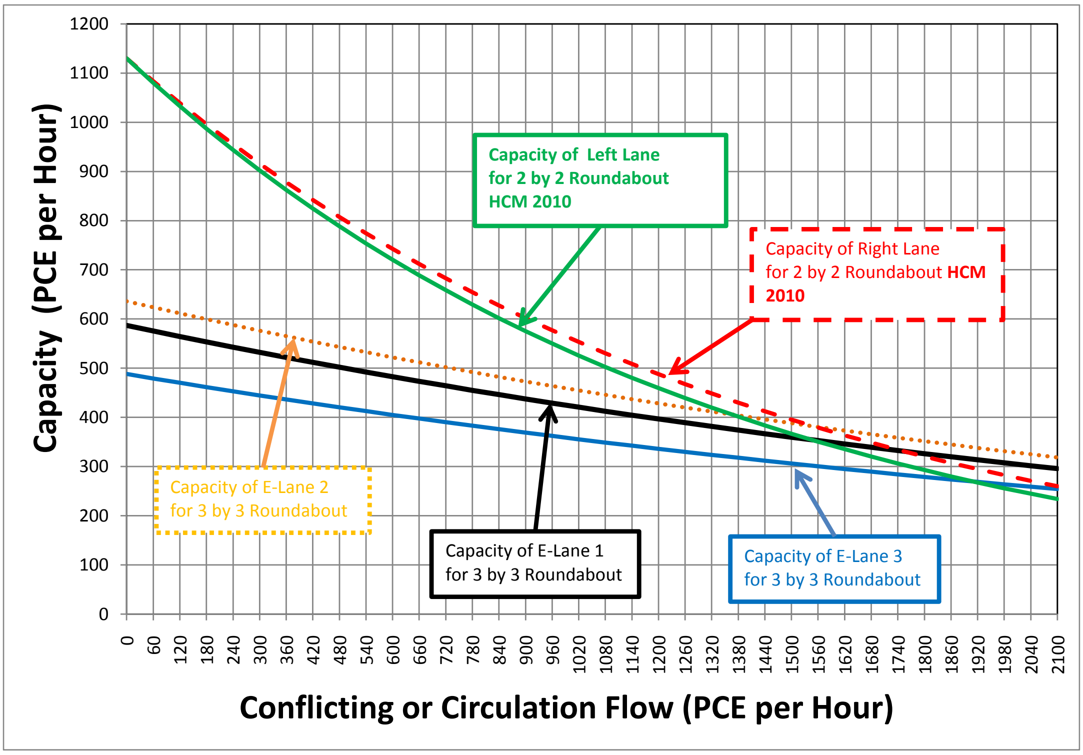


Figure 6-5: HCM 2010 Capacity Curves vs. Three-by-Three-Lane Roundabouts

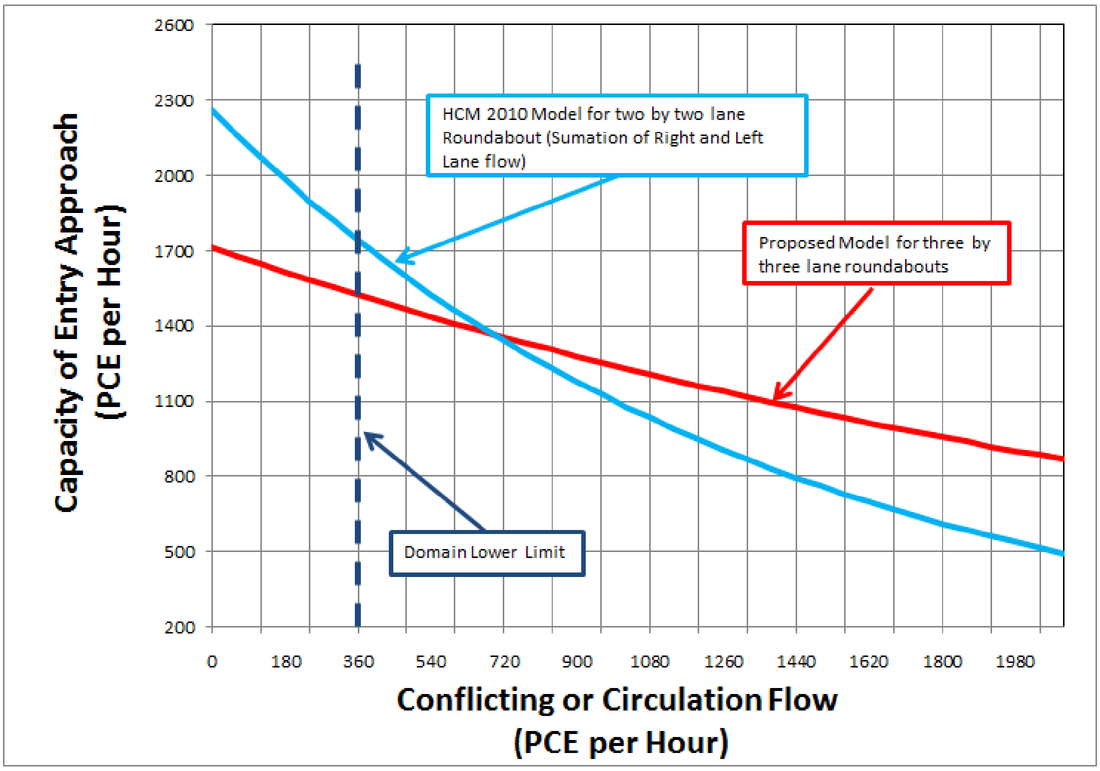


Figure 6-6: Total Entry Capacity Curves (HCM 2010 vs. Developed Models)

6.6. Estimation of Critical Gap and Follow-Up Headways

One of the important parameters that determines the behavior of the driver is the critical headway and follow-up headway. The minimum headway that the entry driver finds acceptable is called the critical headway, and the headway maintained by two consecutive entering vehicles using the same gap in the conflicting stream is called the follow-up headway. The higher these values are, the more serene the drivers will be; the lower the values, the more robust the drivers will be. From NCHRP Report-572 [21], the exponential model that is used to find the capacity is given in Equation 6-5. The constants in the equation are used to find the critical and follow-up headway for the intersection using the following general formula:

$$C_{pce} = A\, e^{(-B\nu_c)} \qquad \text{Equation 6-5}$$

Where: $A = \frac{3{,}600}{t_f}$, $B = \frac{t_c - (\frac{t_f}{2})}{3{,}600}$

v_c = conflicting flow (pc/h),

t_c = critical headway (s), and

t_f = follow-up headway (s).

Because the regression models obtained within this study were based on five-minute intervals, the above equations were modified to convert them for five-minute intervals:

$$C_{pce} = A\, e^{(-B\nu_c)}$$

Where: $A = \frac{300}{t_f}$, $B = \frac{t_c - (\frac{t_f}{2})}{300}$

v_c = conflicting flow (pce/5minutes),

t_c = critical headway (s), and

t_f = follow-up headway (s).

Using the above equations, the critical gap and follow-up headway were calculated for the entry approach and for each lane. Table 6-3 shows the estimated values of the critical gap and follow-up headway.

Table 6-3: Critical Gap and Follow-Up Headway Calculations Based on Field Data

Description	A	B	t_f (sec)	t_c (Sec)
E-Total	142.62	0.0039	2.104	2.215
E-Lane1	48.93	0.004	6.132	4.241
E-Lane2	53.02	0.004	5.659	4.015
E-Lane3	40.68	0.004	7.375	4.806

Figure 6-7 and Figure 6-8 show the comparison of the follow-up headway and the critical gap between HCM 2010 and the proposed model, respectively. The HCM follow-up headway was the same for both lanes, whereas the follow-up headway calculated based on the proposed model shows higher values ranging from 5.66 to 7.37 seconds. For the total entry approach, the follow-up headway was 2.10 seconds.

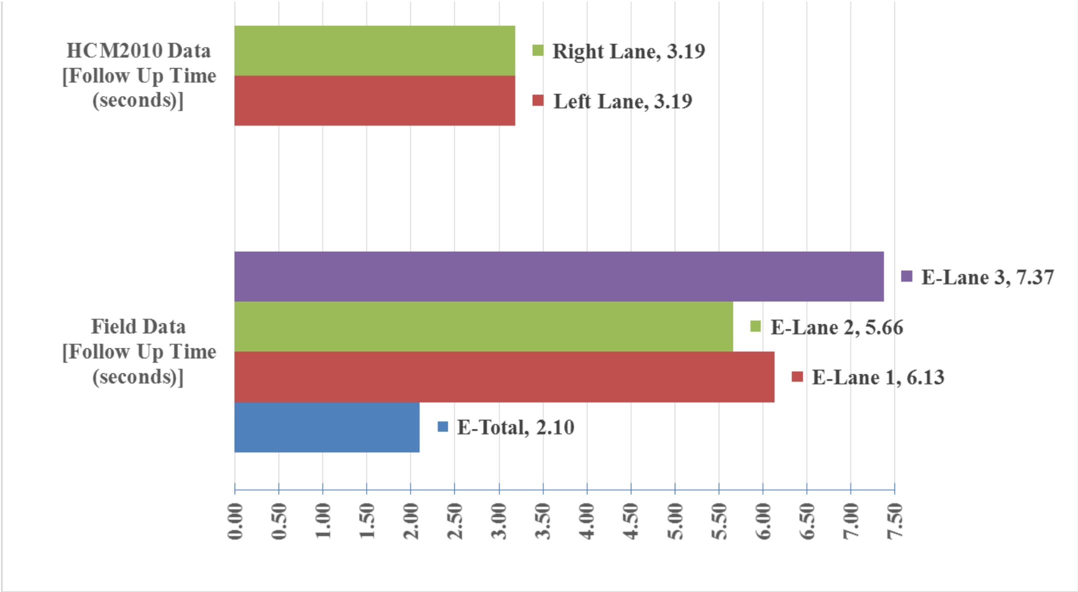


Figure 6-7: Field vs. HCM 2010 (Follow-Up Headway)

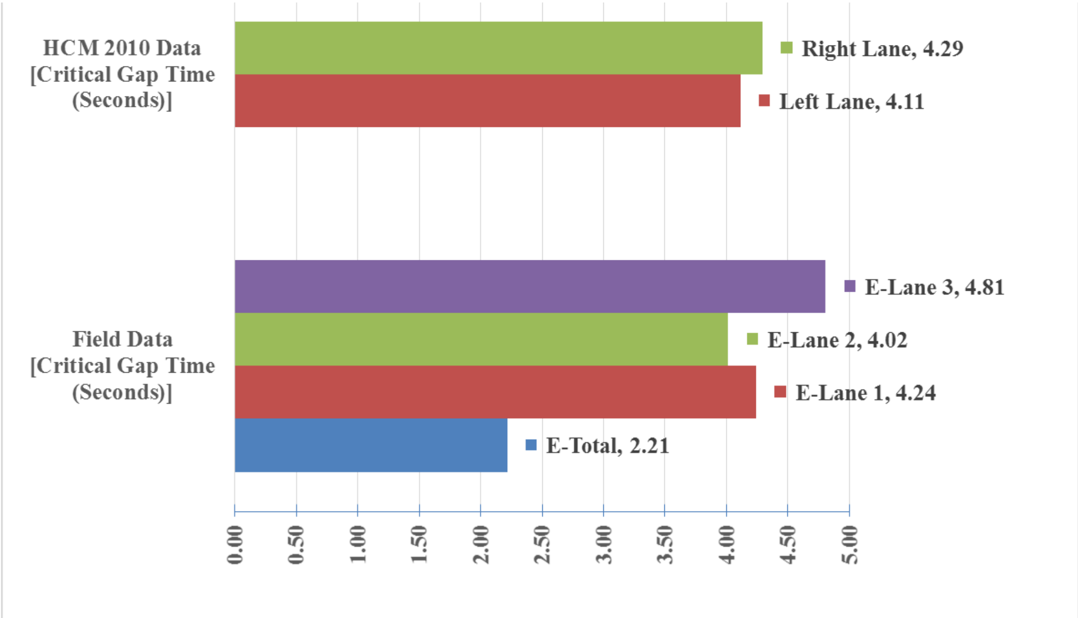


Figure 6-8: Field vs. HCM 2010 (Critical Gap Headway)

6.7. Application of Proposed Capacity Curves: How to Use the Capacity Curves to Estimate Capacity at the Entry Lanes

In this section, an experiment was created to explain how to use the proposed capacity curves to estimate the capacity of the entry approach as well as the entry lanes. Figure 6-9 shows the experimental setup and detail of the circulating flow. The capacity of the east approach was estimated using proposed capacity curves.

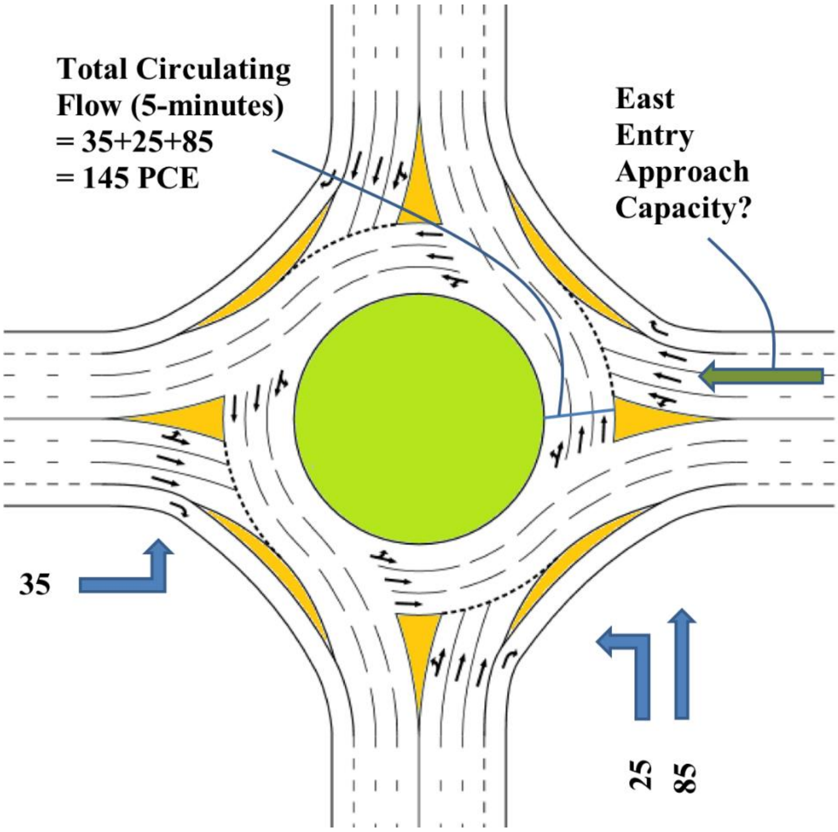


Figure 6-9: Five-Minute Traffic Flow (PCE) Example

The following steps were used to estimate the capacity:

1. Calculate the total circulating flow that conflicts with the east approach as shown in Figure 6-9. (Total Circulating Flow [5-minute] = 145 PCE).
2. Estimate the hourly circulating flow by converting the five-minute volume to an hour. If the peak hour factor is known, it can also be used to calculate hourly flow. Otherwise, assume that the five-minute flow will remain uniform for the entire hour, and the peak hour factor is 1 (Total Circulating Flow [60-minute] =145*12 = 1,740 PCE/Hour).

3. Use the capacity curves for each entry lane presented in the previous sections, and estimate the capacity at each lane as shown in Figure 6-10. The estimated capacities are E-Lane1 = 340 PCE/Hour, E-Lane2 = 360 PCE/Hour, and E-Lane3 = 290 PCE/hour. And as shown in Figure 6-11, the total approach capacity is 990 PCE/ Hour.

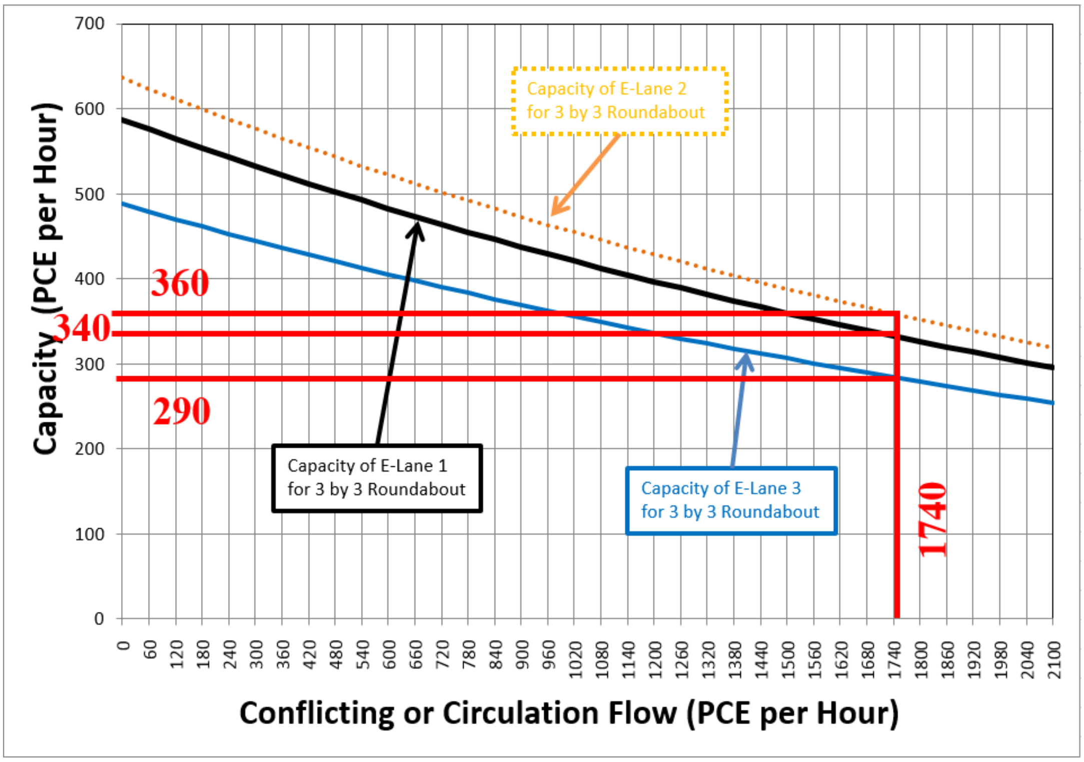


Figure 6-10: Estimate of Entry Lanes Capacity at the East Approach

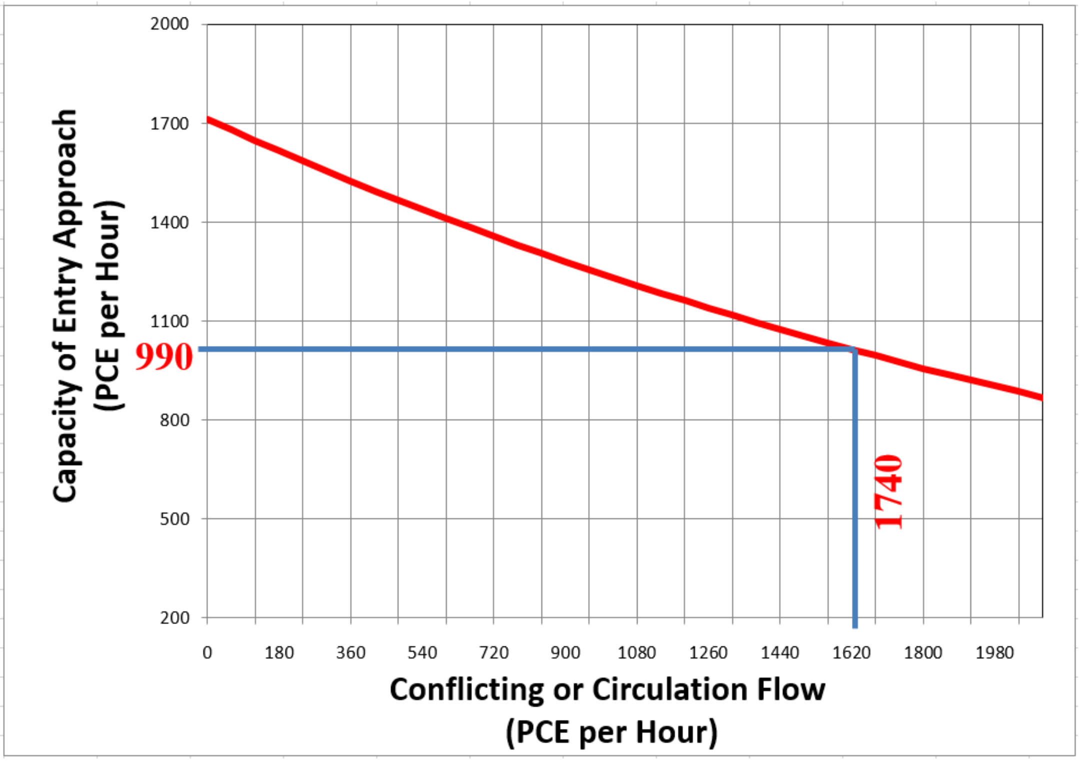


Figure 6-11: Estimate of Total Entry Capacity at the East Approach

Chapter 7: Validation of Proposed Capacity Curves Using Microscopic Simulation Models

7.1. Validation Process

The capacity models and curves were developed and presented in the previous section for each entry lane and approach of three-by-three–lane roundabouts. All the models were developed using actual field data. In this chapter, the validation of the proposed capacity models is presented. Figure 7-1 shows the methodology adopted for the validation process. The first task was to select the appropriate microscopic simulation software that can model the roundabout with the flexibility required for complex traffic-flow conditions. After the selection of software, the three-by-three–lane roundabout was coded in the software. A total of 313 simulation runs were conducted using field data. (Note that the field data includes lane-by-lane entry and circulating traffic volume extracted from the video recordings.) The output of the simulation software was compared with field data; if comparable, then the simulation output was used for further analysis; otherwise, simulation runs were repeated by changing default parameters in the simulation software. After obtaining acceptable simulation outputs, exponential regression models and capacity curves were developed for three-by-three–lane roundabouts using simulation data. These capacity curves were then compared with the proposed capacity curves presented in Chapter 7 of this thesis. Each task of this validation process is explained in the proceeding sections.

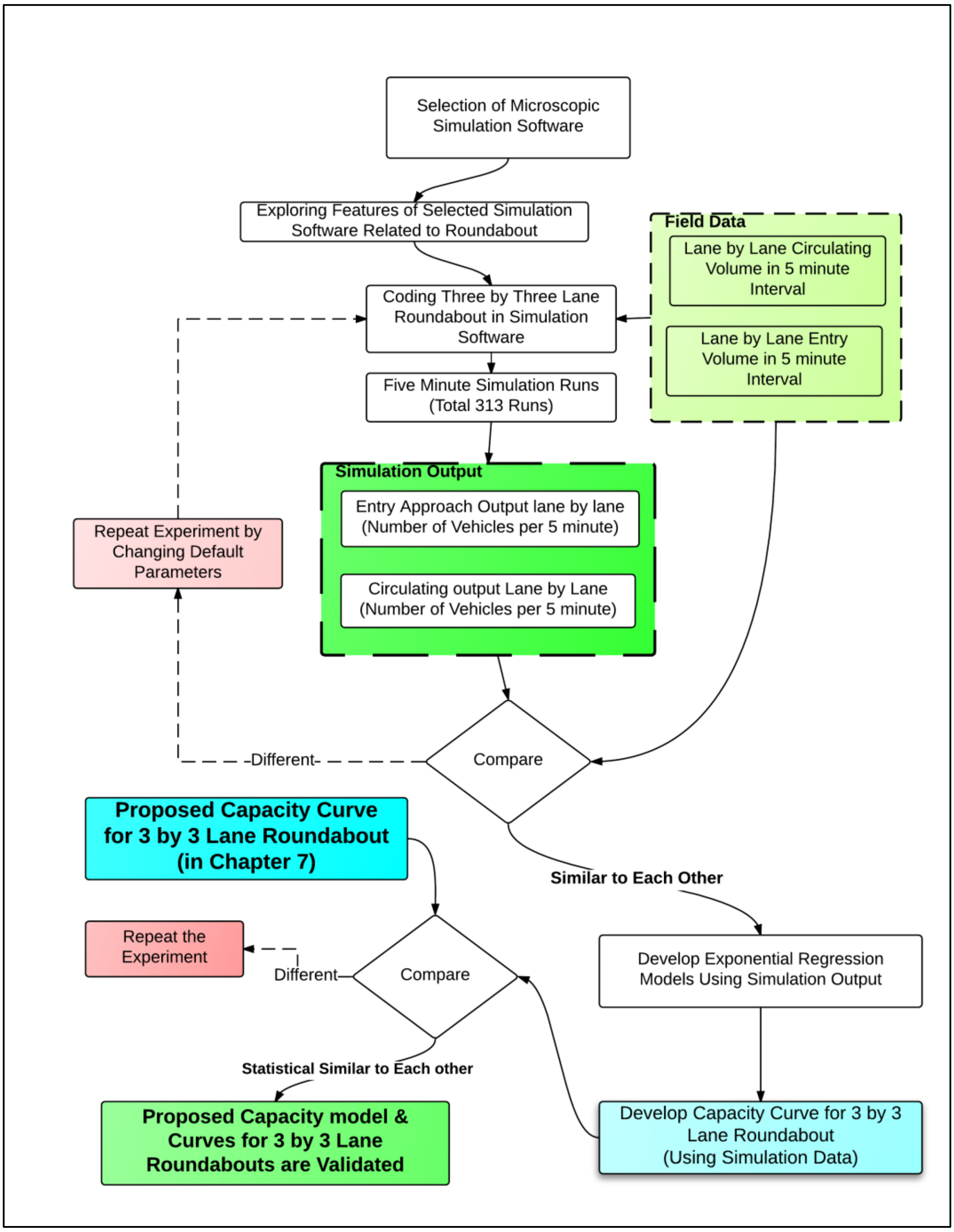


Figure 7-1: Flowchart for the Validation Process

7.2. Selection of Microscopic Simulation Software

A number of software products are available in the market to code the roundabouts, for example, SIDRA, Synchro, CORSIM, Aimsun, and VisSim. For validation purposes, software was needed that can code the roundabout, code the priority rules, and be flexible enough to code traffic parameters per the requirements. VisSim [54] microscopic simulation software was selected for the calibration of proposed capacity models. VisSim is one of the leading software products in the market for microscopic simulation. Most scholars used VisSim as their first choice for the microscopic simulation task within their studies.

7.2.1. VisSim Features

VisSim has multiple features related to roundabouts such as priority rules (PR) and conflict areas (CA). Because the microscopic simulation task within this research work was based on the CA, the features of CA and its attributes are discussed next.

7.2.2. Conflict Areas Features

Instead of using the priority rules feature, VisSim recommends using conflict areas because they are easier to handle, and driving behavior during simulation can be controlled. The conflicting area appears automatically when two intersecting links are coded in VisSim [54].

Figure 7-2 shows the possible scenarios that could be used for conflicted areas. The details of the color coding in the conflicting area are listed here:

- Green: main traffic flow (right of way)
- Red: minor traffic flow (yield)
- Both red: undetermined, both vehicles will see each other and will remain within their original sequence
- Both yellow: inactive conflict area without right of way/undetermined

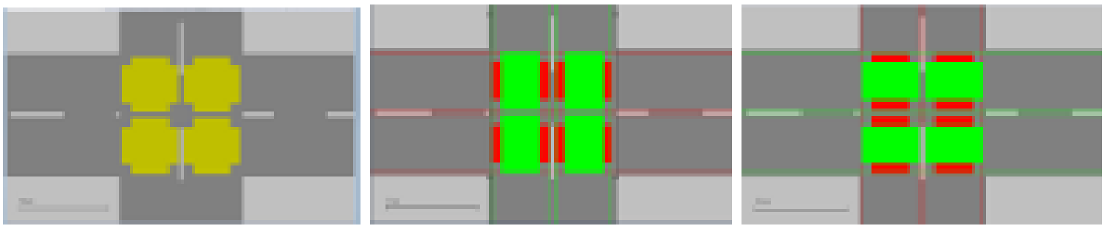


Figure 7-2: Conflict Areas Different Settings [54]

7.2.3. Conflict Areas Attributes

VisSim used different attributes related to the conflicting area. Each attribute's definition and details are provided here:

- Front gap: The least time difference in seconds between the back end of the vehicle and the vehicle front end for the major and minor traffic streams, respectively. The front gap is also defined "for the merging conflict" as the time needed for the waiting vehicle to enter the conflict area after the vehicle that has the priority has entered it. Figure 7-3 illustrates the position of the cars before and after for the major and minor traffic streams as they are approaching the conflict area and with the gap of 0.5 seconds [54].

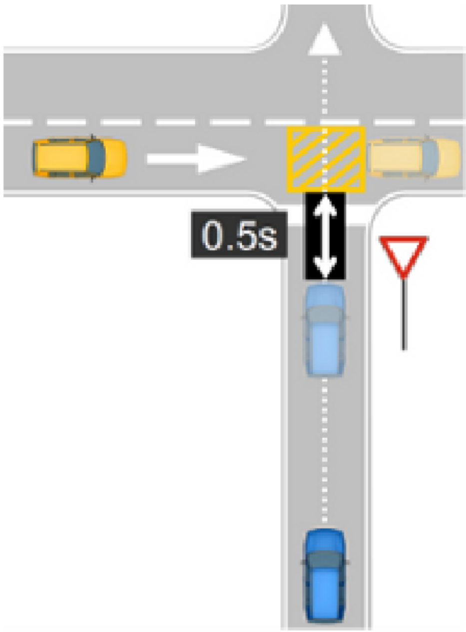


Figure 7-3: Front Gap in VisSim 7.0 [54]

- Rear gap: The least time gap in seconds between the back end of the vehicle and the front end of the vehicle in the minor and major traffic streams, respectively. This rear gap is used for the crossing conflicts and not for the merging conflicts. Figure 7-4 shows the rear gap with a minimum gap of 0.7 seconds [54].

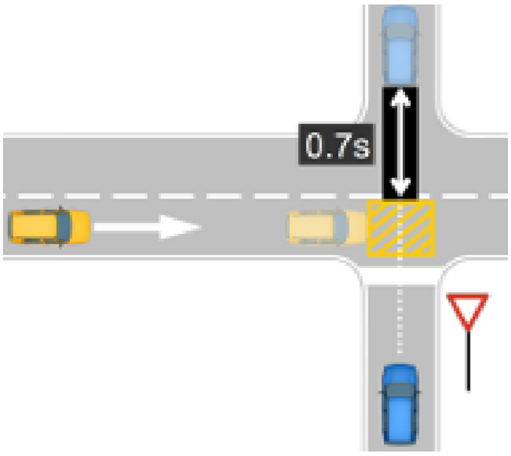


Figure 7-4: Rear Gap in VisSim 7.0 [54]

- Safety Distance Factor: VisSim suggests that this attribute should be used only for the merging conflict. It is defined as the factor to be multiplied by the preferred safety distance of the major stream vehicle so that the minimum distance of the yielding vehicle is calculated and known. Figure 7-5 shows the same scenarios with different safety distance factors (i.e., 1.0 and 0.5 seconds for top and bottom cases, respectively) [54].

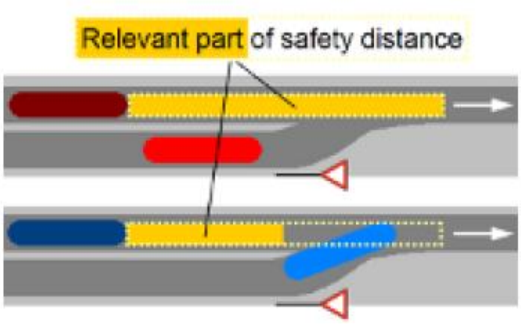


Figure 7-5: Different Safety Factor Values [54]

7.3. Experimental Setup

7.3.1. Coding of Three-by-Three–Lane Roundabouts

The main purpose of using microscopic simulation was to replicate the actual field and estimate the capacity of each entry lane and entry approach. The following steps were used to code three-by-three–lane roundabouts in VisSim [54]:

- Bing maps were imported as background to model the geometry of the roundabout.
- Links and connectors were coded to build the roundabout, as shown in Figure 7-6.

- Traffic volume, vehicle type, and composition were coded on the links. Note that each lane volume was input separately, as shown in pink lines in Figure 7-6.

Routing rules were assigned for each lane. Conflict areas were also defined, as shown in Figure 7-6. Conflict areas were highlighted in yellow, by default, which means the yield is undetermined. The priority was given to the circulating lanes as this is how modern roundabouts work. Red crossing bars indicate that the entering vehicles shall yield and give priority to the green crossing bars for circulating vehicles. This was the only change that was performed manually; the rest of the parameters have VisSim's default values.

Figure 7-6: Roundabout 2 – VisSim Model Coding

7.3.2. Data Collection Location

The main outputs from the simulation required were the entry approach traffic flow lane by lane and the circulating flow. Figure 7-7 illustrates the location of Data Collection (DC) points/detectors (DC1 to DC6). These DCs were used to count the vehicles crossing those points in the same manner that was done on the field data when analyzing the videos either manually or using the software as discussed earlier. To load the traffic on the roundabout, a warm-up period of five minutes was coded for each individual run. A total of twenty-seven hours of simulation runs were completed with different random seed numbers (i.e., 313 simulation files with five-minute time intervals).

Figure 7-7: Roundabout 2 Data Collection Locations

7.4. Simulation Output

Table 7-1 shows the simulation output sample (lane by lane) for both entry and circulating lanes for a one-hour simulation on roundabout 1. The whole simulation output data for the 313 simulation runs were performed in a similar manner and presented in Appendix A.

Table 7-1: Roundabout 1 Lane-by-Lane Counts from 7:00 to 8:00 AM (EB Approach)

Time	Entry Volume (PCE)				Circulating Volume (PCE)			
	DC4	DC5	DC6	Total	DC1	DC2	DC3	Total
7:00	23	23	20	66	85	66	14	165
7:05	18	20	16	54	96	63	36	195
7:10	17	8	7	32	121	82	58	261
7:15	24	37	37	98	42	30	5	77
7:20	31	45	26	102	66	38	3	107
7:25	30	51	32	113	34	28	18	80
7:30	52	57	33	142	34	10	13	57
7:35	25	55	33	113	32	14	4	50
7:40	25	23	23	71	67	57	4	128
7:45	19	21	27	67	63	55	10	128
7:50	29	35	22	86	69	51	22	142
7:55	38	33	21	92	59	50	23	132

7.5. Comparison between Field Data and Simulation Model

Before the simulation results were used for further analysis and to develop capacity curves, it was important to check whether the simulation software was replicating the field traffic flows or not. To check, the total entry and each lane vehicle output counted in the field were compared with simulation outputs. Table 7-2 shows the comparison of VisSim output with the field data. On average, 96% means that the VisSim output estimated 4% (100 – 96) less than field output for entry lane 1 and 4% more for entry lane 3. Moreover, there were 205 times out of 313 (65%) simulation outputs that were within 90 to 110% of the field data. Overall, simulation outputs were comparable to the field data. Note that only the priority rules were defined in the conflicting area in the VisSim software; all other parameters were kept as default values.

Table 7-2: VisSim Output versus Field Data Comparison Summary

	Entry Lanes			E-Total
	1	2	3	
Average %	96%	96%	104%	98%
100% Count	40	37	55	22
[90% to 110%] Count	205	223	183	258

7.6. Development of Capacity Models Using Simulation Output Data

Figure 7-8 shows a comparison of entry and circulating volume for the results obtained from the VisSim simulation. It is clear that with the increase of circulating volume, the entry volume decreases. Similar trends were observed when entry and circulating volume were compared for field data. Total entry volume ranges from 142 to 56 PCEs per five minutes, whereas the maximum circulating flow was 205

PCEs per five minutes. The entry lanes 1, 2, and 3 also showed the similar trends with the total circulating volume.

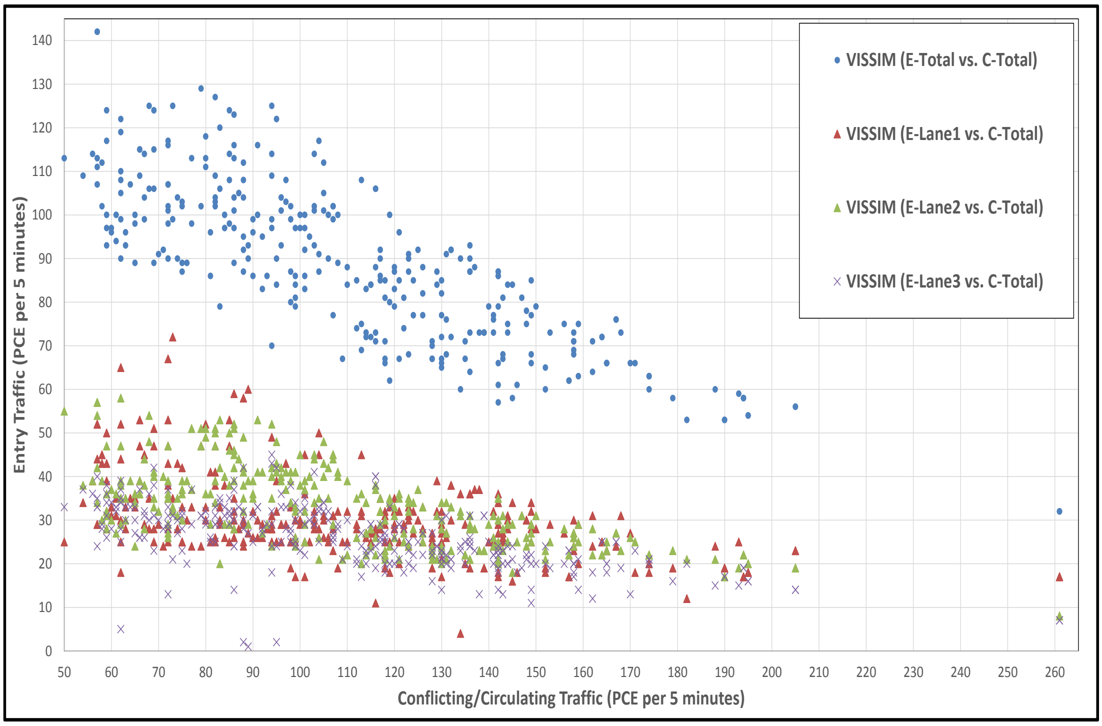


Figure 7-8: VisSim Output (Scatter Plot)

The outputs obtained from 313 simulation runs were coded in SPSS to develop the regression models. Table 7-3 shows the exponential models with R^2. The highest R^2 was observed for the estimation of total entry flow. Note that only exponential regression models were used to estimate the entry flow for approach and for each entry lane. These exponential models were then used to develop the capacity curve.

Table 7-3: Exponential Capacity Models for VisSim Output

Description	Exponential Model	
	Equation	R^2
For Entry Approach	V-E-Total = 149.60 * EXP (–0.005 * V-C_Total)	0.66
Entry Lane 1	V-E-Lane1 = 49.40 * EXP (–0.005 * V-C_Total)	0.27
Entry Lane 2	V-E-Lane2 = 57.10 * EXP (–0.005 * V-C_Total)	0.44
Entry Lane 3	V-E-Lane3 = 43.09 * EXP (–0.0047 * V-C_Total)	0.37

7.7. Comparison between Simulation Results and Proposed Models

The capacity curves, follow-up headway, and critical gap estimated using simulation results and the proposed model for three-by-three lane roundabouts were compared. Each comparison is presented in the following section.

7.7.1. Capacity Curves Comparison

Figure 7-9 shows the comparison of capacity curves developed using simulation output and the proposed model for the total entry approach of the three-by-three–lane roundabout. Overall, both curve trends are similar to each other. However, the capacity curve based on the simulation data shows 1800 PCEs per hour flow with no circulating traffic, whereas the proposed model shows 1720 PCEs per hour flow. To compare whether curves were statistically similar to each other or not, the outputs from both capacity models were plotted versus each other, as shown in Figure 7-10. The results showed that both outputs are highly correlated and explaining variation by 96%. This showed that statistically, there is no significant difference between the proposed model and models developed using simulation output. This provides the validation to the proposed models presented in this study. Similar results were found for the proposed capacity curves for entry lane 1, 2, and 3. The graphs are provided in Appendix D.

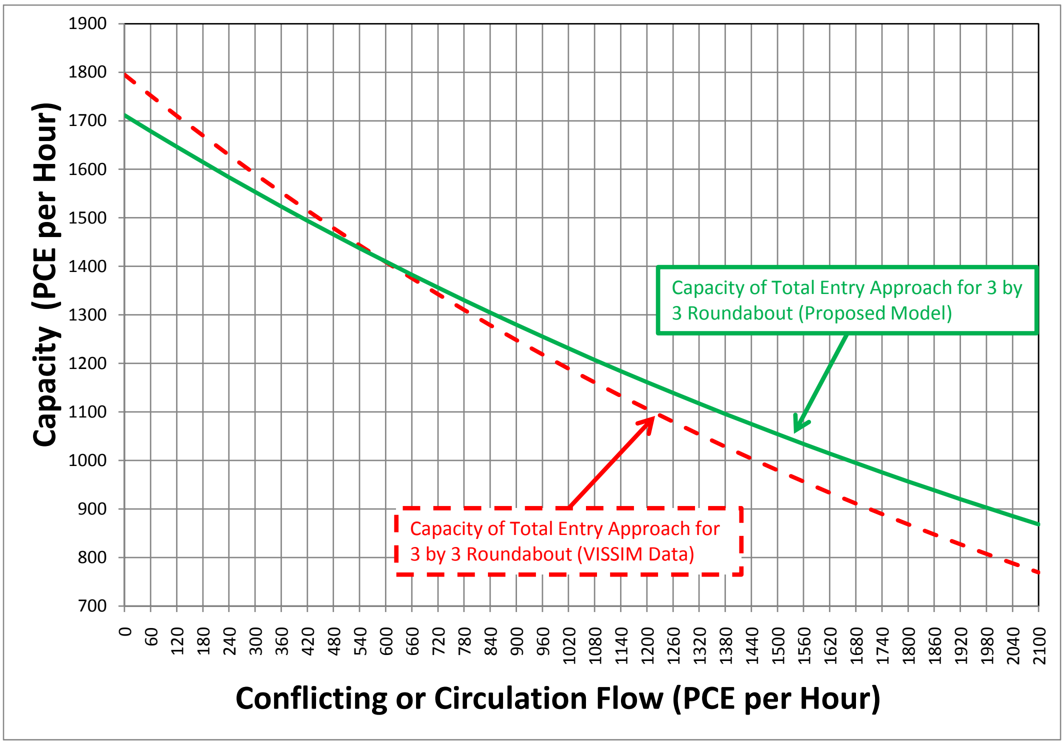


Figure 7-9: Capacity Curve Comparisons for Total Entry Approach (Proposed Model vs. VisSim Output)

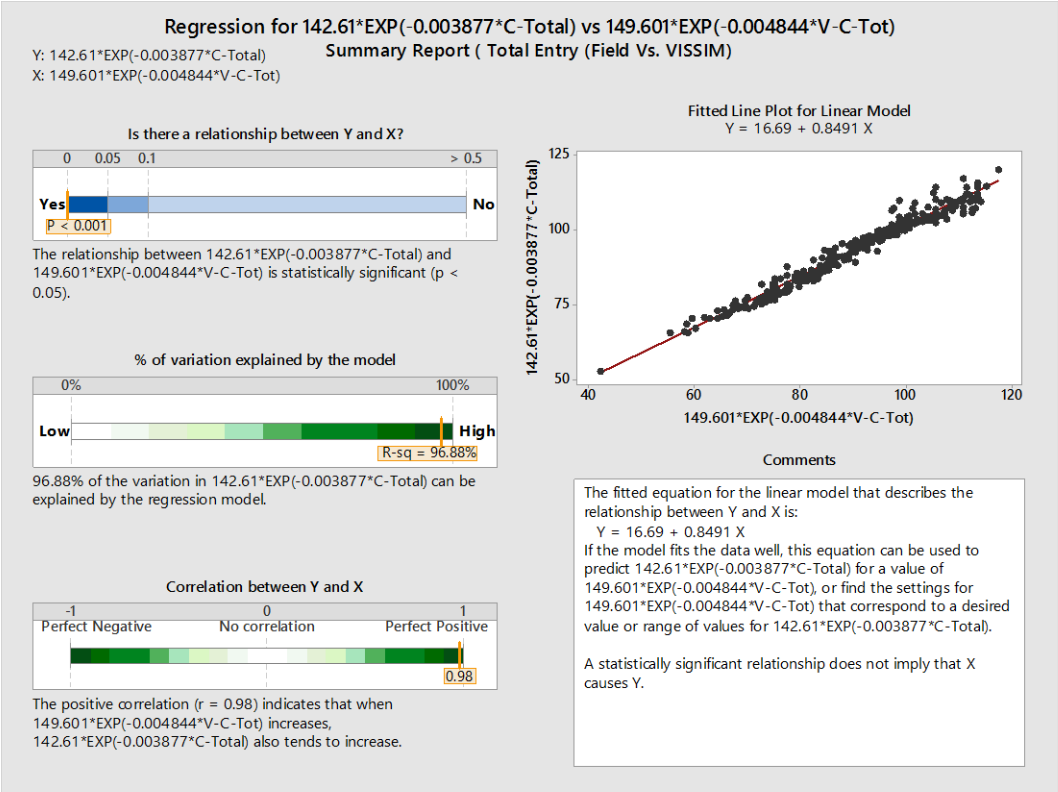


Figure 7-10: Proposed Model vs. VisSim Output for Total Entry

7.7.2. Critical Gap and Follow-Up Headways Comparison

Figure 7-11 and Figure 7-12 show the comparison of critical gap and follow-up headway, respectively. The calculated critical gap from the proposed model for total entry approach was 2.21 seconds, whereas VisSim's model estimate was 2.46 seconds. All the estimated critical gap and follow-up headway using the proposed and VisSim models were comparable to each other.

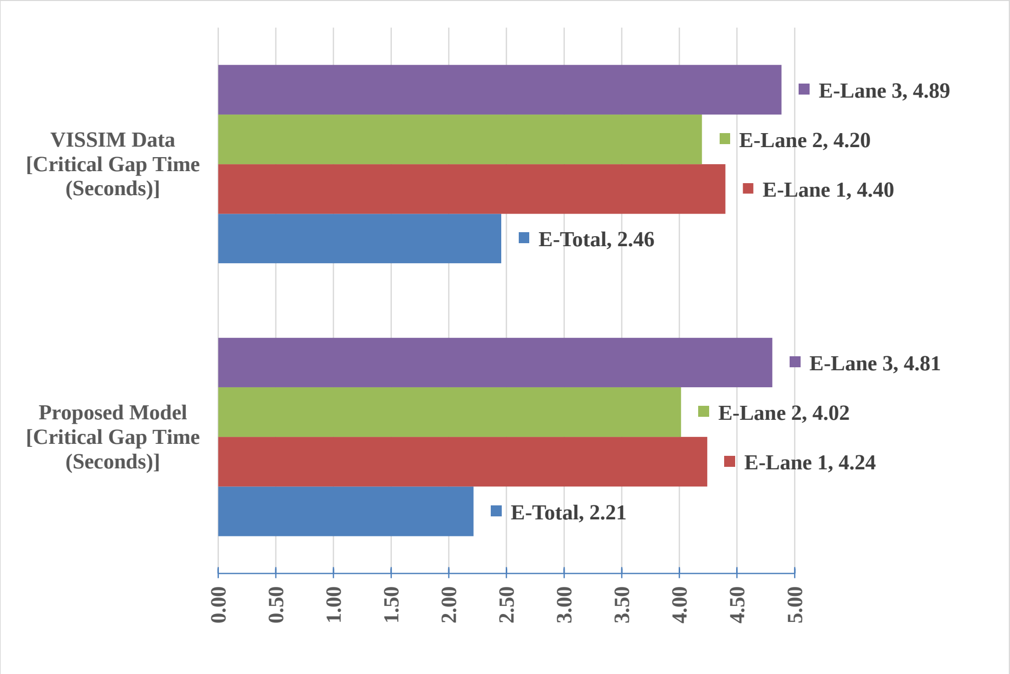


Figure 7-11: Critical Gap Comparison (Proposed Model vs. VisSim Data)

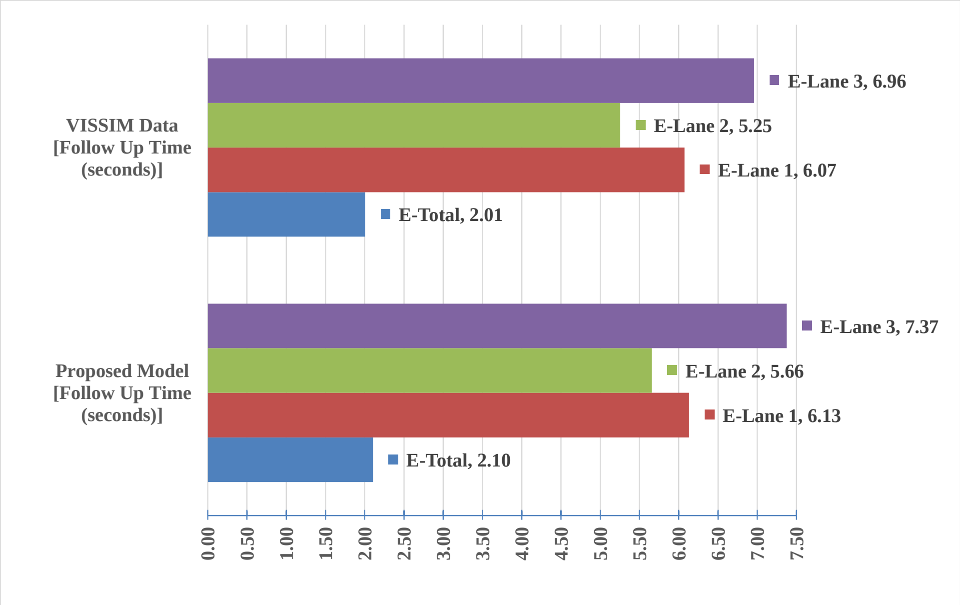


Figure 7-12: Follow-Up Headway Comparison (Proposed Model vs. VisSim Output)

Chapter 8: Conclusions and Recommendations

8.1. Introduction

Current standard models for roundabout capacity estimation are not valid for three-by-three–lane roundabouts. The traffic flow parameters and operations at three-by-three–lane roundabouts are different and have a significant effect on the determination of roundabout capacity. This research presents models to estimate the capacity of three-by-three–lane roundabouts. The capacity models were formulated in terms of circulating traffic flow on the roundabout that is commonly available or can be easily collected. The capacity curves were also developed, which can be used to perform the capacity analysis of the three-by-three–lane roundabout. The models presented in this research are a step in the direction to understanding the traffic flow characteristic on the three-by-three–lane roundabout.

8.2. Conclusion

Following are the main conclusions of this research:

- The traffic characteristic and flow parameters of three-by-three–lane roundabouts are different from the two-by-two–lane roundabouts.
- The lane utilization of the outermost circulating lane in three-by-three–lane roundabouts is low as compared to the other circulating lanes.
- Drivers preferred to use the middle entry lane for the through movement as compared to the other two entry lanes in three-by-three–lane roundabouts.

- Exponential regression models explain variations in the entry flow in terms of circulating traffic flow better than other regression models for multilane roundabouts.

- Highest values of follow-up headway and critical gap time were found for the outermost entry lane (E-lane 3) as compare to the middle and innermost entry lanes.

- Critical gap time for each entry lane estimated using proposed capacity models and HCM 2010 models were similar to each other.

- Capacity curves were developed for each entry lane and for the entry approach. These capacity curves will help transportation engineers and planners perform capacity analysis of three-by-three–lane roundabouts. The application of the proposed capacity models was also presented.
- The proposed capacity models and curves were validated using well-established microscopic traffic-simulation model, that is VisSim. The validation results show close agreement between the outcomes of the models of this research and those of the microscopic simulation models.

8.3. Recommendations

New capacity models are proposed for three-by-three–lane roundabouts. These models should be added to the HCM 2010 multilane roundabout capacity analysis chapter after some refinement and validation of field data from other countries. Following are some suggestion for further research:

- Before the models of this research are finally adopted, more consistency tests and evaluations will have to be conducted, including field validation for other regions and countries.

- A four-by-four–lane roundabout is already operating in the emirate of Dubai (intersection of Jebel Ali-Lahbab Road and Emirates Road). So, scholars might want to work on four-by-four–lane roundabout capacity models in the future.

- Other microscopic simulation software can also be used to validate the proposed capacity models for three-by-three–lane roundabouts.

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Appendix A

Extracted Field Data

Table A-1 presented below shows the collected passenger car volumes for each of the three entering and circulating lanes.

Table A-1: Extracted Lane by Lane Volume Counts

Entry Volume (PCE)				Circulating Volume (PCE)			
Lane 1 (Left-Through)	Lane 2 (Through)	Lane 3 (Through)	Total (Approach Demand Volume)	Lane 1	Lane 2	Lane 3	Total
28	28	21	77	64	49	16	129
26	28	28	82	63	43	26	132
36	33	25	94	75	41	28	144
38	29	26	93	69	34	22	125
34	29	28	91	77	47	23	147
34	24	26	84	57	50	24	131
29	33	20	82	74	48	37	159
28	39	17	84	78	52	34	164
29	24	16	69	67	50	29	146
27	28	16	71	65	34	18	117
35	30	21	86	76	40	24	140
25	26	17	68	61	40	19	120
28	35	16	79	67	40	21	128
25	30	19	74	74	43	33	150

Entry Volume (PCE)				Circulating Volume (PCE)			
Lane 1 (Left-Through)	Lane 2 (Through)	Lane 3 (Through)	Total (Approach Demand Volume)	Lane 1	Lane 2	Lane 3	Total
26	25	19	70	67	36	30	133
31	30	18	79	69	34	26	129
22	27	15	64	79	38	36	153
27	24	11	62	84	34	26	144
25	32	22	79	89	40	38	167
38	21	16	75	86	47	36	169
23	27	23	73	54	49	24	127
29	26	19	74	70	40	27	137
34	25	24	83	64	34	20	118
28	39	23	90	34	31	16	81
26	46	31	103	24	29	14	67
35	47	35	117	38	37	11	86
37	48	31	116	51	35	6	92
32	36	28	96	50	54	38	142
34	32	30	96	64	40	31	135
26	46	26	98	38	34	13	85
28	41	24	93	57	31	31	119
41	38	33	112	58	25	20	103
30	41	39	110	56	21	22	99
31	39	29	99	39	31	18	88

Entry Volume (PCE)				Circulating Volume (PCE)			
Lane 1 (Left-Through)	Lane 2 (Through)	Lane 3 (Through)	Total (Approach Demand Volume)	Lane 1	Lane 2	Lane 3	Total
27	41	33	101	52	39	11	102
25	33	24	82	51	42	12	105
32	44	35	111	53	52	6	111
26	42	38	106	61	36	12	109
25	32	28	85	55	41	12	108
21	38	34	93	55	31	16	102
35	39	36	110	58	36	17	111
30	34	28	92	48	37	15	100
43	50	23	116	52	36	10	98
34	34	33	101	48	35	21	104
32	49	31	112	52	37	17	106
27	29	23	79	84	33	27	144
29	35	19	83	85	53	22	160
31	29	22	82	76	48	15	139
25	25	16	66	78	36	18	132
31	34	22	87	60	59	19	138
33	27	18	78	63	67	22	152
31	26	15	72	69	63	23	155
31	29	26	86	76	66	24	166
30	26	15	71	82	68	29	179

Entry Volume (PCE)				Circulating Volume (PCE)			
Lane 1 (Left-Through)	Lane 2 (Through)	Lane 3 (Through)	Total (Approach Demand Volume)	Lane 1	Lane 2	Lane 3	Total
30	22	11	63	74	53	16	143
31	25	20	76	76	58	28	162
31	26	18	75	83	55	24	162
34	28	23	85	73	52	29	154
24	35	17	76	93	71	37	201
30	33	13	76	95	69	32	196
27	25	17	69	75	58	38	171
22	20	16	58	70	56	28	154
20	25	17	62	78	61	22	161
20	37	32	89	60	47	26	133
23	37	29	89	60	42	17	119
25	39	33	97	68	48	24	140
28	39	30	97	59	43	17	119
32	50	36	118	51	28	13	92
28	43	32	103	61	35	15	111
29	41	33	103	48	42	22	112
33	39	42	114	40	36	17	93
30	42	43	115	49	38	16	103
27	27	28	82	82	54	34	170
30	36	31	97	61	53	27	141

Entry Volume (PCE)				Circulating Volume (PCE)			
Lane 1 (Left-Through)	Lane 2 (Through)	Lane 3 (Through)	Total (Approach Demand Volume)	Lane 1	Lane 2	Lane 3	Total
26	34	25	85	44	54	29	127
31	34	28	93	48	26	7	81
30	37	32	99	46	37	10	93
32	39	39	110	42	39	11	92
29	41	27	97	43	36	14	93
28	47	38	113	46	30	10	86
31	30	38	99	49	20	9	78
28	42	37	107	57	28	12	97
29	45	32	106	48	25	10	83
28	43	34	105	57	29	10	96
35	37	33	105	58	25	13	96
35	37	42	114	64	29	9	102
31	42	29	102	61	26	12	99
28	39	33	100	58	28	11	97
32	44	32	108	54	27	10	91
33	47	29	109	56	24	11	91
25	46	32	103	55	25	9	89
33	29	27	89	54	24	18	96
34	42	29	105	50	43	23	116
6	38	34	78	73	47	25	145

Entry Volume (PCE)				Circulating Volume (PCE)			
Lane 1 (Left-Through)	Lane 2 (Through)	Lane 3 (Through)	Total (Approach Demand Volume)	Lane 1	Lane 2	Lane 3	Total
27	28	14	69	68	41	26	135
22	32	20	74	73	46	22	141
25	26	22	73	71	51	19	141
31	30	23	84	69	44	21	134
26	28	19	73	72	48	21	141
27	23	24	74	74	53	19	146
26	26	21	73	65	51	17	133
30	20	18	68	68	43	18	129
31	32	17	80	85	49	21	155
29	22	18	69	76	47	17	140
34	29	18	81	77	53	22	152
27	27	12	66	82	52	22	156
26	28	9	63	81	58	26	165
30	26	24	80	79	56	24	159
28	32	22	82	84	59	27	170
22	21	20	63	79	58	28	165
22	24	18	64	81	54	29	164
25	27	22	74	83	57	29	169
29	31	19	79	82	59	27	168
22	21	24	67	91	39	44	174

Entry Volume (PCE)				Circulating Volume (PCE)			
Lane 1 (Left-Through)	Lane 2 (Through)	Lane 3 (Through)	Total (Approach Demand Volume)	Lane 1	Lane 2	Lane 3	Total
27	38	24	89	81	43	44	168
32	37	32	101	54	31	16	101
33	40	33	106	47	39	14	100
26	38	36	100	49	42	33	124
35	38	31	104	49	34	23	106
30	41	32	103	45	36	17	98
28	41	31	100	49	27	12	88
30	37	28	95	52	3	18	73
30	38	34	102	46	36	21	103
38	36	32	106	43	27	8	78
34	41	33	108	50	29	13	92
32	46	32	110	55	36	16	107
14	16	22	52	63	55	43	161
11	20	36	67	59	49	22	130
21	26	36	83	92	62	27	181
35	34	32	101	71	38	17	126
33	30	21	84	76	40	14	130
25	32	16	73	69	45	16	130
41	33	21	95	64	47	12	123
38	34	21	93	67	43	17	127

Entry Volume (PCE)				Circulating Volume (PCE)			
Lane 1 (Left-Through)	Lane 2 (Through)	Lane 3 (Through)	Total (Approach Demand Volume)	Lane 1	Lane 2	Lane 3	Total
34	33	17	84	67	46	22	135
33	33	25	91	65	49	21	135
29	29	15	73	61	51	25	137
34	41	25	100	63	45	24	132
36	32	24	92	60	43	25	128
28	29	20	77	67	47	27	141
35	24	20	79	69	49	23	141
36	25	11	72	72	56	24	152
23	24	20	67	74	55	21	150
28	25	17	70	77	58	26	161
26	25	22	73	73	51	24	148
27	36	18	81	75	52	28	155
29	27	17	73	76	47	31	154
25	41	19	85	73	45	32	150
43	48	29	120	58	29	4	91
36	47	34	117	54	29	8	91
35	48	30	113	49	28	8	85
33	44	31	108	37	24	7	68
30	45	28	103	34	26	7	67
27	31	20	78	47	54	15	116

Entry Volume (PCE)				Circulating Volume (PCE)			
Lane 1 (Left-Through)	Lane 2 (Through)	Lane 3 (Through)	Total (Approach Demand Volume)	Lane 1	Lane 2	Lane 3	Total
29	28	19	76	52	56	16	124
33	30	19	82	55	57	13	125
34	31	17	82	56	72	13	141
28	32	20	80	70	64	16	150
19	24	20	63	58	59	21	138
25	42	26	93	63	28	7	98
19	34	26	79	62	22	14	98
32	38	26	96	66	28	4	98
27	42	34	103	59	28	11	98
28	46	35	109	62	37	5	104
36	49	34	119	53	23	7	83
34	54	36	124	49	19	5	73
33	53	24	110	31	20	7	58
12	22	18	52	96	75	11	182
20	23	11	54	91	66	12	169
27	24	9	60	89	69	13	171
18	21	14	53	94	74	15	183
28	25	10	63	92	67	14	173
25	31	11	67	87	45	12	144
39	44	35	118	52	18	8	78

Entry Volume (PCE)				Circulating Volume (PCE)			
Lane 1 (Left-Through)	Lane 2 (Through)	Lane 3 (Through)	Total (Approach Demand Volume)	Lane 1	Lane 2	Lane 3	Total
36	42	30	108	67	28	2	97
24	41	33	98	57	23	1	80
33	44	22	99	80	19	7	106
32	40	20	92	62	15	3	80
27	29	24	80	78	21	12	111
24	31	25	80	90	19	5	114
32	28	19	79	58	32	7	97
19	23	24	66	80	34	12	126
38	40	35	113	50	13	6	69
37	40	38	115	43	21	5	69
37	38	39	114	40	22	4	66
34	38	28	100	38	21	5	64
36	37	36	109	39	15	3	57
35	36	35	106	40	20	10	70
37	28	35	100	32	22	4	58
35	32	37	104	42	20	7	69
40	30	30	100	52	26	6	84
41	33	36	110	39	19	5	63
34	25	20	79	48	58	4	110
44	33	34	111	45	58	9	112

Entry Volume (PCE)				Circulating Volume (PCE)			
Lane 1 (Left-Through)	Lane 2 (Through)	Lane 3 (Through)	Total (Approach Demand Volume)	Lane 1	Lane 2	Lane 3	Total
35	26	28	89	56	50	11	117
34	25	31	90	44	30	7	81
29	26	28	83	53	59	10	122
38	30	37	105	47	54	5	106
34	27	28	89	44	53	5	102
22	29	31	82	50	53	7	110
48	30	33	111	49	31	8	88
45	28	35	108	51	27	4	82
28	38	35	101	41	37	6	84
39	32	34	105	57	26	10	93
25	28	20	73	56	46	15	117
25	28	20	73	65	41	14	120
35	46	38	119	55	29	3	87
41	45	4	90	66	25	3	94
33	48	31	112	58	28	3	89
42	45	33	120	72	20	1	93
28	37	22	87	67	23	2	92
41	40	28	109	54	15	5	74
28	39	22	89	67	34	3	104
27	40	25	92	60	18	3	81

Entry Volume (PCE)				Circulating Volume (PCE)			
Lane 1 (Left-Through)	Lane 2 (Through)	Lane 3 (Through)	Total (Approach Demand Volume)	Lane 1	Lane 2	Lane 3	Total
22	27	20	69	65	41	12	118
42	39	32	113	54	25	7	86
41	38	34	113	47	22	4	73
35	36	31	102	52	27	5	84
37	37	27	101	45	21	6	72
32	37	34	103	38	22	3	63
38	40	36	114	39	19	12	70
35	33	37	105	47	14	7	68
31	32	37	100	45	17	6	68
40	32	29	101	45	15	8	68
40	30	29	99	42	20	4	66
37	34	27	98	49	22	9	80
40	31	31	102	50	21	11	82
40	35	31	106	48	29	3	80
45	20	26	91	64	32	5	101
33	33	32	98	44	23	3	70
44	30	25	99	59	33	7	99
45	40	32	117	51	19	3	73
48	34	25	107	49	21	6	76
42	36	41	119	52	24	4	80

Entry Volume (PCE)				Circulating Volume (PCE)			
Lane 1 (Left-Through)	Lane 2 (Through)	Lane 3 (Through)	Total (Approach Demand Volume)	Lane 1	Lane 2	Lane 3	Total
37	33	34	104	52	25	5	82
44	36	30	110	43	32	4	79
31	31	18	80	64	34	13	111
35	29	19	83	62	36	12	110
35	24	16	75	59	37	12	108
30	40	35	105	72	26	3	101
34	45	39	118	60	21	2	83
43	46	31	120	58	24	4	86
38	51	34	123	59	22	6	87
40	44	27	111	59	21	3	83
28	35	26	89	61	21	4	86
28	43	22	93	53	22	3	78
20	45	25	90	57	18	4	79
31	30	29	90	70	23	8	101
25	36	30	91	75	17	4	96
55	33	4	92	24	32	18	74
57	30	3	90	26	29	21	76
61	36	7	104	13	27	11	51
60	32	11	103	20	31	17	68
66	33	16	115	22	27	13	62

Entry Volume (PCE)				Circulating Volume (PCE)			
Lane 1 (Left-Through)	Lane 2 (Through)	Lane 3 (Through)	Total (Approach Demand Volume)	Lane 1	Lane 2	Lane 3	Total
64	30	11	105	19	26	13	58
30	35	39	104	51	20	6	77
26	39	35	100	49	24	4	77
31	43	41	115	42	19	4	65
41	31	34	106	39	22	7	68
31	35	32	98	41	21	5	67
36	27	29	92	43	23	6	72
40	31	29	100	41	30	3	74
41	29	26	96	40	24	5	69
40	37	29	106	43	28	4	75
42	37	26	105	40	24	5	69
43	36	33	112	54	17	4	75
35	32	35	102	42	22	4	68
44	33	31	108	48	23	5	76
24	31	36	91	92	68	2	162
25	23	30	78	87	61	28	176
40	31	19	90	62	51	23	136
26	35	38	99	69	51	1	121
38	32	24	94	89	45	5	139
26	31	20	77	86	74	12	172

Entry Volume (PCE)				Circulating Volume (PCE)			
Lane 1 (Left-Through)	Lane 2 (Through)	Lane 3 (Through)	Total (Approach Demand Volume)	Lane 1	Lane 2	Lane 3	Total
46	58	38	142	30	13	11	54
27	25	24	76	102	57	24	183
32	36	31	99	94	40	1	135
29	23	26	78	97	62	3	162
21	22	33	76	78	56	25	159
19	24	25	68	94	69	37	200
19	20	21	60	106	89	62	257
32	37	20	89	74	47	20	141
23	27	40	90	86	52	1	139
27	21	29	77	98	68	35	201
24	29	27	80	98	63	29	190
30	37	41	108	65	45	6	116
22	24	27	73	79	76	28	183
34	51	26	111	70	32	4	106
38	32	24	94	89	45	5	139
29	23	26	78	97	62	3	162
32	36	31	99	94	40	1	135
27	25	24	76	102	57	24	183
25	23	30	78	87	61	28	176
21	22	33	76	78	56	25	159

Entry Volume (PCE)				Circulating Volume (PCE)			
Lane 1 (Left-Through)	Lane 2 (Through)	Lane 3 (Through)	Total (Approach Demand Volume)	Lane 1	Lane 2	Lane 3	Total
24	29	27	80	98	63	29	190
22	24	27	73	79	76	28	183
27	21	29	77	98	68	35	201
26	35	38	99	69	51	1	121
24	31	36	91	92	68	2	162
23	27	40	90	86	52	1	139
30	37	41	108	65	45	6	116
26	31	20	77	86	74	12	172
19	24	25	68	94	69	37	200
19	20	21	60	106	89	62	257
29	37	40	106	46	28	5	79
34	51	26	111	70	32	4	106
32	57	36	125	29	27	14	70
46	58	38	142	30	13	11	54
25	53	35	113	22	17	6	45
25	22	18	65	72	62	6	140
18	26	28	72	66	55	10	131
32	37	20	89	74	47	20	141
40	31	19	90	62	51	23	136

VisSim Simulation Output

Table A-2 presented below shows the complete set of the simulation output data obtained from VisSim.

Table A-2: Extracted Data Lane by Lane Counts

Entry Volume (PCE)				Circulating Volume (PCE)			
Lane 1 (Left-Through)	Lane 2 (Through)	Lane 3 (Through)	Total (Approach Demand Volume)	Lane 1	Lane 2	Lane 3	Total
29	30	26	85	62	36	20	118
28	25	28	81	60	32	30	122
36	31	26	93	71	32	33	136
35	26	26	87	66	28	26	120
36	31	23	90	71	35	28	134
32	22	27	81	53	36	29	118
30	26	22	78	70	36	42	148
31	31	19	81	71	37	39	147
29	22	20	71	64	36	35	135
28	26	20	74	64	28	20	112
30	23	19	72	72	31	29	132
25	21	21	67	57	31	21	109
28	31	20	79	64	31	25	120
24	31	22	77	71	32	38	141
27	21	20	68	64	31	36	131

Entry Volume (PCE)				Circulating Volume (PCE)			
Lane 1 (Left-Through)	Lane 2 (Through)	Lane 3 (Through)	Total (Approach Demand Volume)	Lane 1	Lane 2	Lane 3	Total
27	28	22	77	66	28	30	124
18	25	18	61	74	31	41	146
27	20	14	61	84	28	30	142
23	25	18	66	92	31	42	165
31	22	18	71	86	35	41	162
19	23	25	67	53	36	29	118
25	20	20	65	68	31	31	130
31	20	24	75	62	28	23	113
26	39	24	89	39	27	20	86
28	48	30	106	28	23	17	68
32	52	39	123	42	31	13	86
35	51	30	116	52	29	5	86
32	30	23	85	49	39	42	130
32	31	24	87	62	31	36	129
28	45	24	97	42	28	16	86
27	37	24	88	53	27	36	116
43	37	28	108	54	20	23	97
25	40	36	101	53	17	26	96
27	39	27	93	42	27	20	89
29	41	33	103	52	32	13	97

Entry Volume (PCE)				Circulating Volume (PCE)			
Lane 1 (Left-Through)	Lane 2 (Through)	Lane 3 (Through)	Total (Approach Demand Volume)	Lane 1	Lane 2	Lane 3	Total
25	32	24	81	52	32	15	99
32	48	42	122	53	37	5	95
28	45	41	114	57	31	15	103
25	32	29	86	54	32	15	101
17	37	29	83	54	27	20	101
31	40	34	105	54	31	20	105
25	34	28	87	48	31	19	98
49	52	24	125	52	31	11	94
30	34	29	93	48	30	25	103
29	44	29	102	52	31	20	103
25	23	20	68	84	28	31	143
28	31	20	79	86	38	26	150
28	27	27	82	72	35	19	126
25	21	21	67	70	31	20	121
32	35	29	96	56	44	21	121
37	28	23	88	60	51	26	137
32	24	20	76	66	47	28	141
34	29	22	85	71	49	29	149
31	23	19	73	80	53	35	168
29	23	14	66	71	39	20	130

Entry Volume (PCE)				Circulating Volume (PCE)			
Lane 1 (Left-Through)	Lane 2 (Through)	Lane 3 (Through)	Total (Approach Demand Volume)	Lane 1	Lane 2	Lane 3	Total
30	24	21	75	72	43	33	148
32	25	20	77	80	40	29	149
36	25	18	79	70	37	35	142
25	19	15	59	95	56	42	193
24	21	15	60	97	54	37	188
27	28	20	75	71	43	42	156
17	21	19	57	68	41	33	142
18	24	24	66	71	45	26	142
20	36	29	85	56	35	30	121
19	41	29	89	56	32	20	108
26	34	31	91	67	35	29	131
28	44	27	99	55	32	20	107
30	53	33	116	52	23	16	91
26	43	32	101	57	29	19	105
25	35	30	90	48	32	26	106
29	40	45	114	42	32	20	94
25	39	38	102	47	31	20	98
30	26	17	73	80	39	39	158
33	33	22	88	57	38	31	126
28	32	25	85	43	39	35	117

Entry Volume (PCE)				Circulating Volume (PCE)			
Lane 1 (Left-Through)	Lane 2 (Through)	Lane 3 (Through)	Total (Approach Demand Volume)	Lane 1	Lane 2	Lane 3	Total
28	35	27	90	47	21	6	74
25	38	32	95	46	31	11	88
29	41	42	112	42	33	13	88
26	41	28	95	44	31	17	92
26	50	33	109	46	25	11	82
28	29	33	90	47	16	9	72
26	41	33	100	53	23	15	91
24	47	31	102	48	20	11	79
28	44	33	105	53	23	11	87
32	36	31	99	54	20	16	90
31	35	43	109	62	23	9	94
28	42	29	99	58	21	15	94
26	39	31	96	54	23	13	90
30	42	32	104	53	22	11	86
29	50	29	108	53	19	13	85
25	47	31	103	53	20	9	82
29	27	27	83	53	19	20	92
32	40	28	100	48	32	28	108
4	32	24	60	70	35	29	134
27	24	16	67	66	32	30	128

Entry Volume (PCE)				Circulating Volume (PCE)			
Lane 1 (Left-Through)	Lane 2 (Through)	Lane 3 (Through)	Total (Approach Demand Volume)	Lane 1	Lane 2	Lane 3	Total
17	34	21	72	70	34	26	130
25	25	27	77	69	36	21	126
30	32	25	87	66	32	25	123
27	28	22	77	70	35	25	130
28	24	30	82	71	38	21	130
29	26	28	83	64	36	20	120
25	21	20	66	66	32	20	118
34	29	21	84	85	35	25	145
26	22	22	70	73	35	20	128
36	29	25	90	72	38	26	136
26	28	13	67	80	37	26	143
28	29	11	68	76	43	30	149
31	29	24	84	74	41	29	144
29	25	21	75	84	44	31	159
18	23	24	65	75	44	33	152
19	21	20	60	78	39	35	152
23	26	20	69	82	41	35	158
29	25	19	73	78	44	31	153
18	22	20	60	95	32	47	174
26	24	18	68	79	32	47	158

Entry Volume (PCE)				Circulating Volume (PCE)			
Lane 1 (Left-Through)	Lane 2 (Through)	Lane 3 (Through)	Total (Approach Demand Volume)	Lane 1	Lane 2	Lane 3	Total
30	38	32	100	53	27	20	100
29	42	33	104	47	32	17	96
28	35	29	92	47	32	38	117
32	38	31	101	47	28	28	103
25	40	32	97	43	31	20	94
26	40	31	97	47	22	15	84
25	36	28	89	53	2	20	75
25	40	30	95	46	31	25	102
38	35	29	102	43	22	7	72
30	42	32	104	49	23	16	88
30	48	34	112	54	31	20	105
16	18	24	58	60	40	45	145
11	22	38	71	55	35	26	116
18	25	23	66	95	45	31	171
33	34	33	100	68	31	20	119
32	33	23	88	72	31	17	120
25	35	20	80	66	33	20	119
45	36	27	108	63	35	15	113
35	29	22	86	65	32	20	117
32	34	19	85	64	34	26	124

Entry Volume (PCE)				Circulating Volume (PCE)			
Lane 1 (Left-Through)	Lane 2 (Through)	Lane 3 (Through)	Total (Approach Demand Volume)	Lane 1	Lane 2	Lane 3	Total
30	37	25	92	64	36	25	125
29	27	18	74	56	37	29	122
31	34	25	90	61	33	29	123
32	32	26	90	56	32	29	117
27	27	22	76	65	35	31	131
39	21	24	84	66	35	28	129
37	23	13	73	68	41	29	138
20	22	25	67	70	40	25	135
28	25	20	73	71	43	30	144
28	21	24	73	71	36	29	136
25	29	25	79	70	37	33	140
30	25	20	75	73	35	36	144
25	26	22	73	71	33	37	141
47	51	29	127	54	23	5	82
33	53	34	120	53	23	7	83
33	51	29	113	47	23	7	77
29	44	31	104	36	24	7	67
25	47	29	101	37	28	7	72
27	34	22	83	43	53	18	114
26	27	20	73	42	54	18	114

Entry Volume (PCE)				Circulating Volume (PCE)			
Lane 1 (Left-Through)	Lane 2 (Through)	Lane 3 (Through)	Total (Approach Demand Volume)	Lane 1	Lane 2	Lane 3	Total
29	35	21	85	45	53	14	112
33	35	23	91	46	63	14	123
27	31	23	81	66	59	18	143
21	23	23	67	54	53	23	130
25	41	24	90	61	30	4	95
19	34	27	80	59	21	18	98
29	39	25	93	63	30	3	96
26	41	30	97	56	30	13	99
26	42	32	100	58	43	5	106
35	54	36	125	42	22	4	68
30	58	34	122	42	15	5	62
29	54	24	107	36	17	4	57
12	21	20	53	102	67	13	182
20	29	14	63	88	57	14	159
24	28	12	64	85	63	14	162
19	23	16	58	94	67	18	179
27	26	13	66	92	60	18	170
25	27	14	66	85	50	14	149
39	47	38	124	42	11	6	59
33	41	25	99	63	30	5	98

Entry Volume (PCE)				Circulating Volume (PCE)			
Lane 1 (Left-Through)	Lane 2 (Through)	Lane 3 (Through)	Total (Approach Demand Volume)	Lane 1	Lane 2	Lane 3	Total
24	40	28	92	48	22	1	71
29	45	23	97	81	15	4	100
30	39	20	89	59	11	6	76
27	22	23	72	80	20	14	114
23	29	25	77	87	15	5	107
28	24	18	70	52	38	4	94
19	21	24	64	81	41	14	136
39	39	36	114	42	10	4	56
35	39	33	107	39	20	5	64
35	38	37	110	38	21	3	62
31	37	28	96	35	20	5	60
34	38	37	109	37	11	6	54
33	34	33	100	38	17	10	65
35	27	32	94	37	21	3	61
33	30	34	97	39	17	4	60
43	31	30	104	42	28	4	74
44	34	35	113	37	15	5	57
30	24	25	79	42	54	3	99
50	35	32	117	41	54	9	104
32	22	30	84	47	50	13	110

Entry Volume (PCE)				Circulating Volume (PCE)			
Lane 1 (Left-Through)	Lane 2 (Through)	Lane 3 (Through)	Total (Approach Demand	Lane 1	Lane 2	Lane 3	Total
30	20	29	79	42	37	4	83
28	26	33	87	42	52	10	104
36	29	35	100	43	53	5	101
30	26	30	86	41	53	5	99
17	33	34	84	42	53	4	99
53	29	32	114	42	37	6	85
53	26	37	116	41	28	3	72
25	38	35	98	38	43	4	85
38	29	33	100	46	28	10	84
25	24	23	72	47	50	18	115
24	24	20	68	61	44	18	123
30	46	37	113	46	34	6	86
39	43	2	84	63	26	6	95
29	49	30	108	52	30	6	88
47	46	31	124	67	17	1	85
26	35	25	86	63	22	5	90
45	39	28	112	42	11	5	58
25	39	24	88	63	41	6	110
25	39	23	87	58	11	6	75
18	24	20	62	61	44	14	119

Entry Volume (PCE)				Circulating Volume (PCE)			
Lane 1 (Left-Through)	Lane 2 (Through)	Lane 3 (Through)	Total (Approach Demand Volume)	Lane 1	Lane 2	Lane 3	Total
47	39	31	117	42	26	4	72
44	38	32	114	43	21	3	67
33	37	32	102	42	28	5	75
35	36	27	98	41	20	4	65
31	36	33	100	34	21	6	61
39	39	37	115	37	15	14	66
32	32	36	100	43	12	4	59
28	31	34	93	41	14	4	59
43	30	29	102	41	11	6	58
43	28	26	97	39	17	3	59
35	35	28	98	42	21	9	72
42	30	31	103	42	20	13	75
41	34	29	104	42	34	6	82
45	21	25	91	61	38	5	104
29	32	30	91	42	22	6	70
45	25	22	92	56	41	4	101
52	39	28	119	41	15	6	62
53	36	26	115	42	20	4	66
47	35	42	124	42	24	3	69
35	33	31	99	42	26	5	73

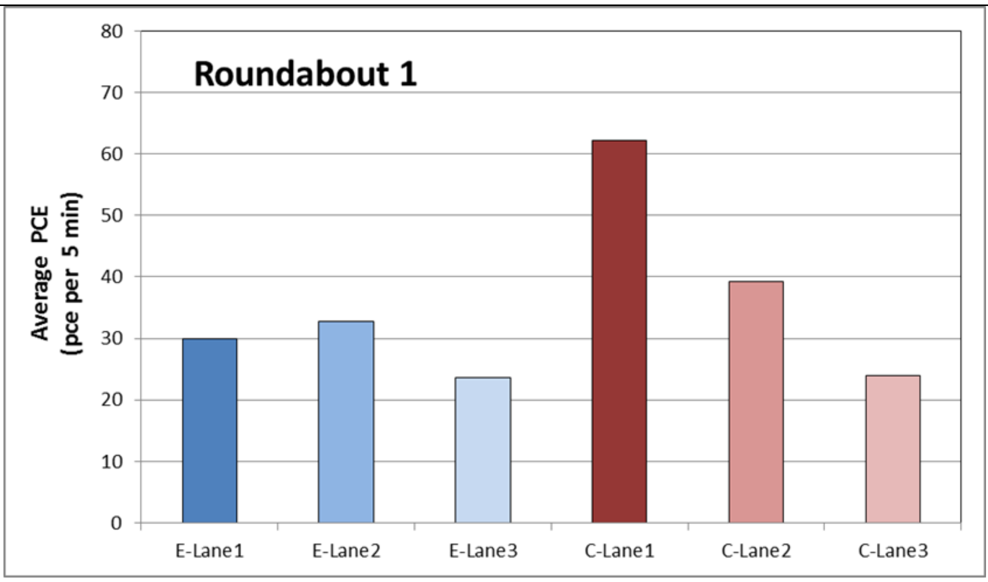
Entry Volume (PCE)				Circulating Volume (PCE)			
Lane 1 (Left-Through)	Lane 2 (Through)	Lane 3 (Through)	Total (Approach Demand Volume)	Lane 1	Lane 2	Lane 3	Total
52	36	30	118	39	38	3	80
28	26	19	73	61	41	14	116
31	22	18	71	59	45	14	118
32	20	17	69	56	43	14	113
25	39	33	97	67	28	6	101
29	42	35	106	58	20	5	83
47	51	31	129	52	24	3	79
33	49	29	111	55	21	4	80
38	39	25	102	56	20	6	82
25	36	25	86	58	20	3	81
25	41	23	89	42	21	6	69
18	47	25	90	48	11	3	62
28	29	29	86	65	22	6	93
24	35	28	87	71	14	3	88
58	32	2	92	31	38	19	88
60	29	1	90	32	34	23	89
65	35	5	105	21	28	13	62
59	28	14	101	31	37	18	86
72	32	21	125	31	28	14	73
67	27	13	107	30	28	14	72

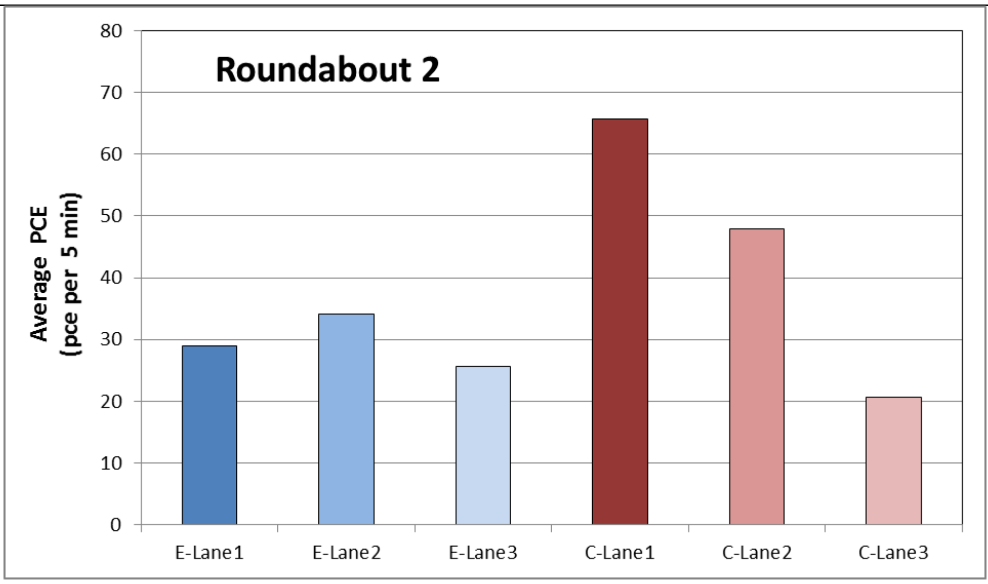
Entry Volume (PCE)				Circulating Volume (PCE)			
Lane 1 (Left-Through)	Lane 2 (Through)	Lane 3 (Through)	Total (Approach Demand Volume)	Lane 1	Lane 2	Lane 3	Total
25	35	39	99	41	17	4	62
28	40	38	106	42	24	3	69
29	42	40	111	39	15	3	57
44	29	35	108	37	21	4	62
28	35	30	93	38	20	5	63
35	24	30	89	39	22	4	65
41	29	26	96	38	37	6	81
45	28	26	99	38	24	5	67
43	36	28	107	39	30	3	72
47	36	26	109	38	23	5	66
50	36	31	117	42	14	3	59
33	30	33	96	39	21	3	63
51	33	31	115	42	22	5	69
24	27	20	71	91	62	5	158
24	27	25	76	85	55	27	167
38	33	21	92	59	50	23	132
28	38	40	106	65	50	1	116
34	30	23	87	87	50	5	142
23	23	20	66	85	66	14	165
52	57	33	142	34	10	13	57

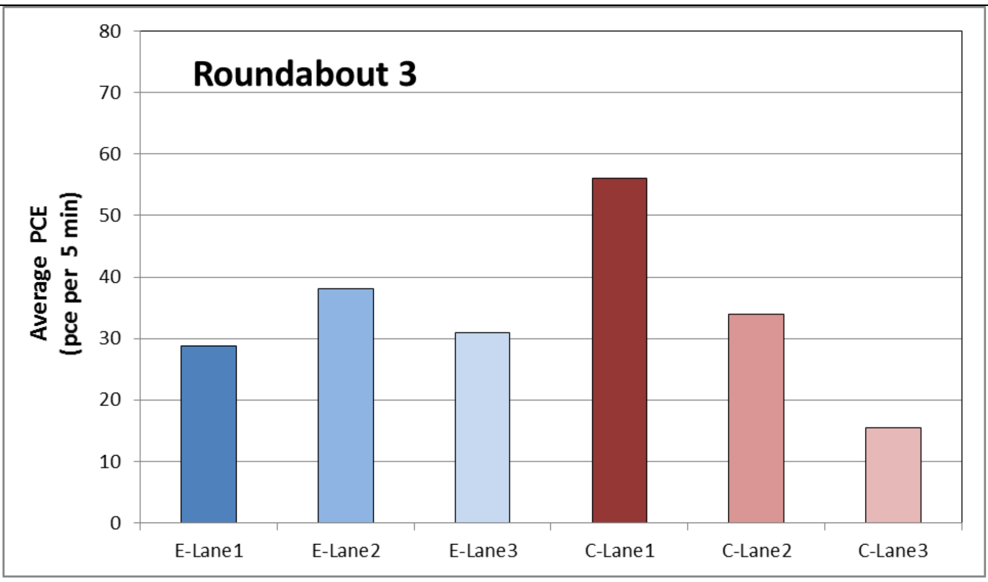
Entry Volume (PCE)				Circulating Volume (PCE)			
Lane 1 (Left-Through)	Lane 2 (Through)	Lane 3 (Through)	Total (Approach Demand Volume)	Lane 1	Lane 2	Lane 3	Total
19	17	17	53	113	54	23	190
28	28	31	87	92	43	1	136
25	22	25	72	101	57	6	164
17	22	23	62	78	54	25	157
18	20	16	54	96	63	36	195
17	8	7	32	121	82	58	261
29	35	22	86	69	51	22	142
19	23	31	73	86	52	1	139
23	19	14	56	109	62	34	205
17	22	19	58	109	58	27	194
27	28	29	84	61	50	4	115
20	22	21	63	79	68	27	174
31	45	26	102	66	38	3	107
34	30	23	87	87	50	5	142
25	22	25	72	101	57	6	164
28	28	31	87	92	43	1	136
19	17	17	53	113	54	23	190
24	27	25	76	85	55	27	167
17	22	23	62	78	54	25	157
17	22	19	58	109	58	27	194

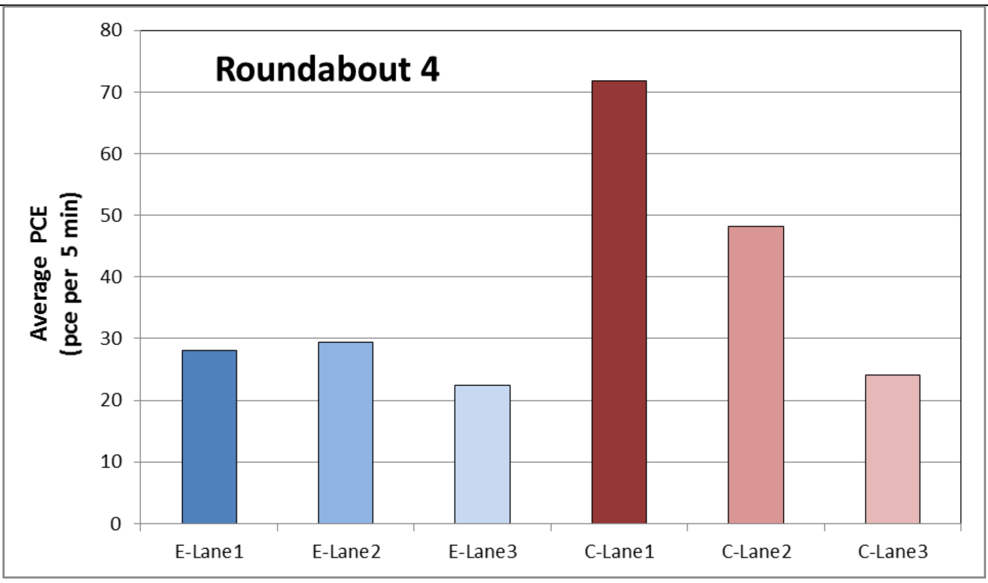
Entry Volume (PCE)				Circulating Volume (PCE)			
Lane 1 (Left-Through)	Lane 2 (Through)	Lane 3 (Through)	Total (Approach Demand Volume)	Lane 1	Lane 2	Lane 3	Total
20	22	21	63	79	68	27	174
23	19	14	56	109	62	34	205
28	38	40	106	65	50	1	116
24	27	20	71	91	62	5	158
19	23	31	73	86	52	1	139
27	28	29	84	61	50	4	115
23	23	20	66	85	66	14	165
18	20	16	54	96	63	36	195
17	8	7	32	121	82	58	261
24	37	37	98	42	30	5	77
31	45	26	102	66	38	3	107
30	51	32	113	34	28	18	80
52	57	33	142	34	10	13	57
25	55	33	113	32	14	4	50
25	23	23	71	67	57	4	128
19	21	27	67	63	55	10	128
29	35	22	86	69	51	22	142
38	33	21	92	59	50	23	132

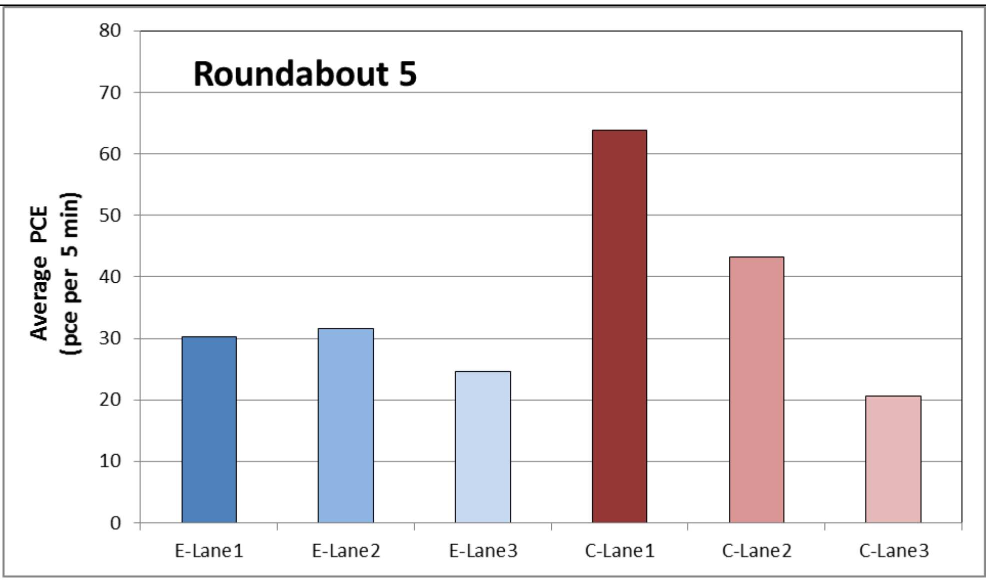
Appendix B

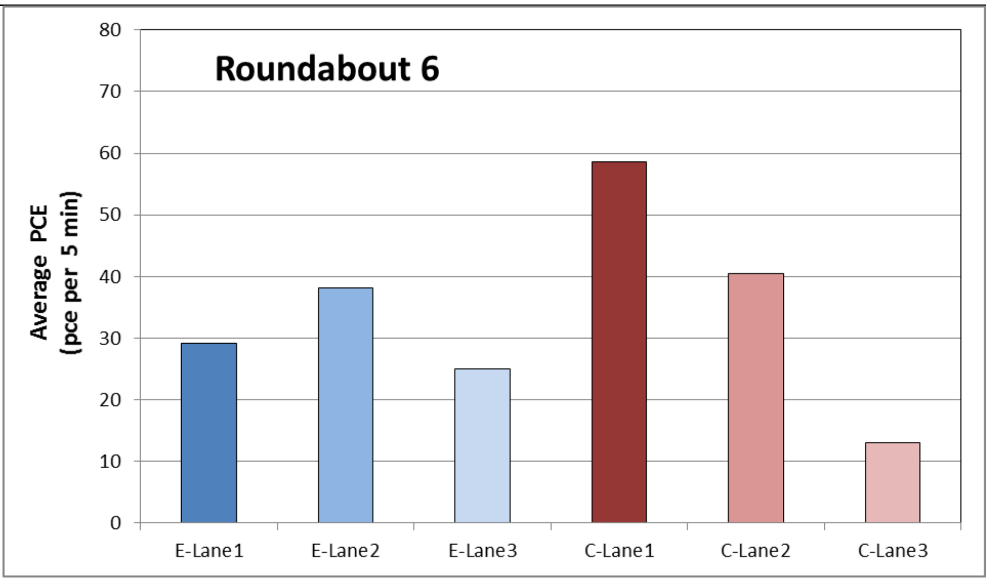

Roundabout 1
Average PCE
(pce per 5 min)
80
70
60
50
40
30
20
10
0
E-Lane1
E-Lane2
E-Lane3
C-Lane1
C-Lane2
C-Lane3

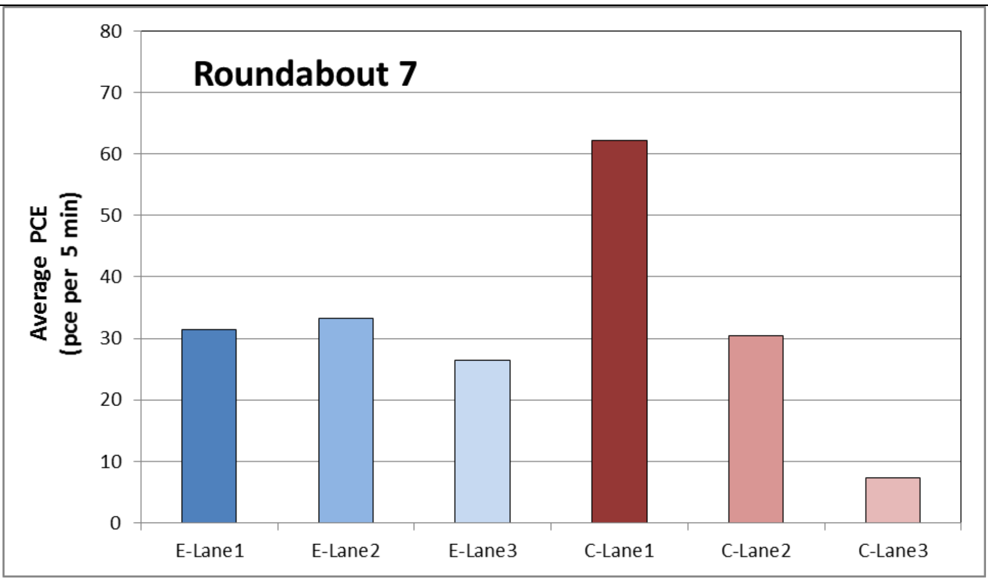

Roundabout 2
Average PCE
(pce per 5 min)
80
70
60
50
40
30
20
10
0
E-Lane1
E-Lane2
E-Lane3
C-Lane1
C-Lane2
C-Lane3

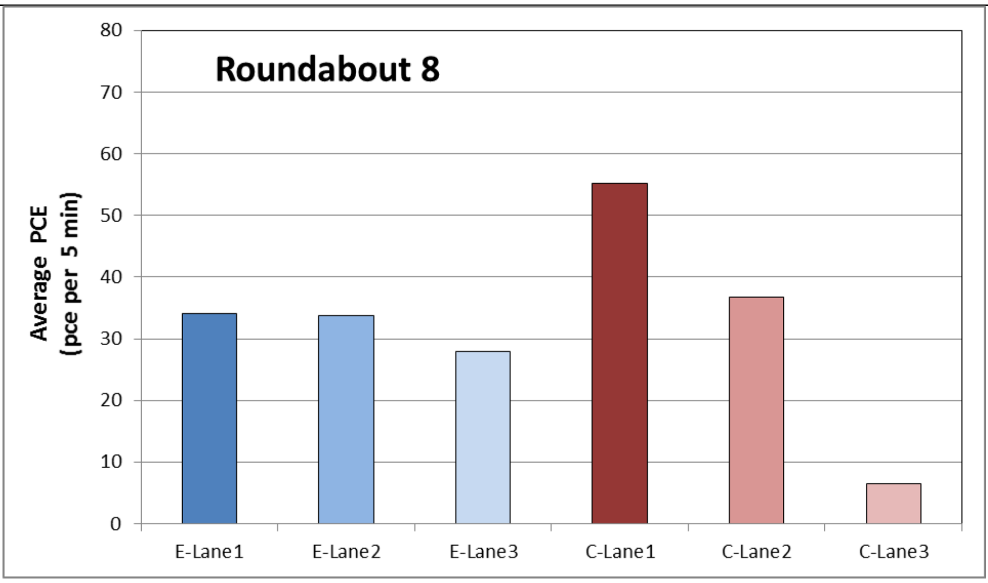

Roundabout 3
Average PCE
(pce per 5 min)
80
70
60
50
40
30
20
10
0
E-Lane1
E-Lane2
E-Lane3
C-Lane1
C-Lane2
C-Lane3

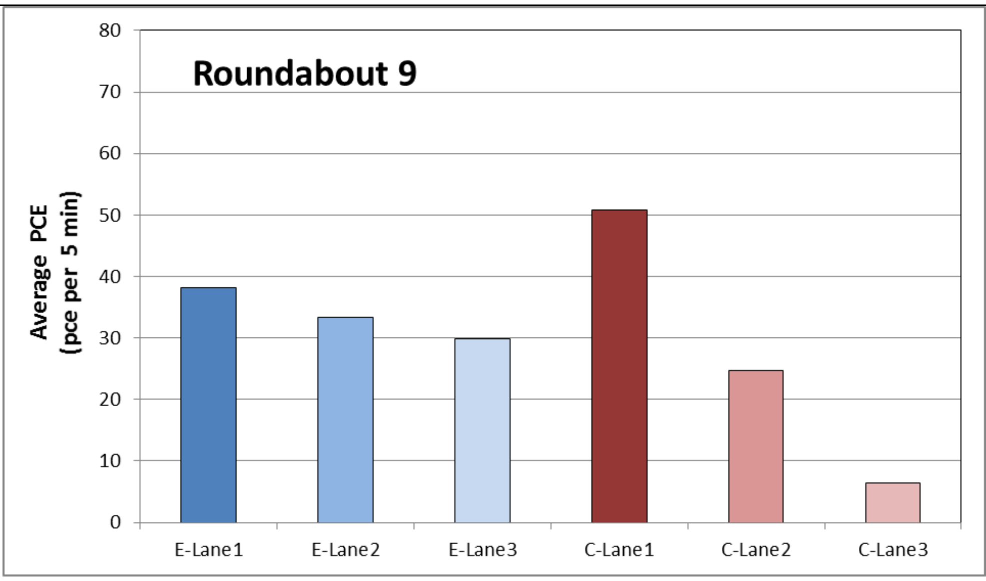

Roundabout 4
Average PCE
(pce per 5 min)
80
70
60
50
40
30
20
10
0
E-Lane1
E-Lane2
E-Lane3
C-Lane1
C-Lane2
C-Lane3

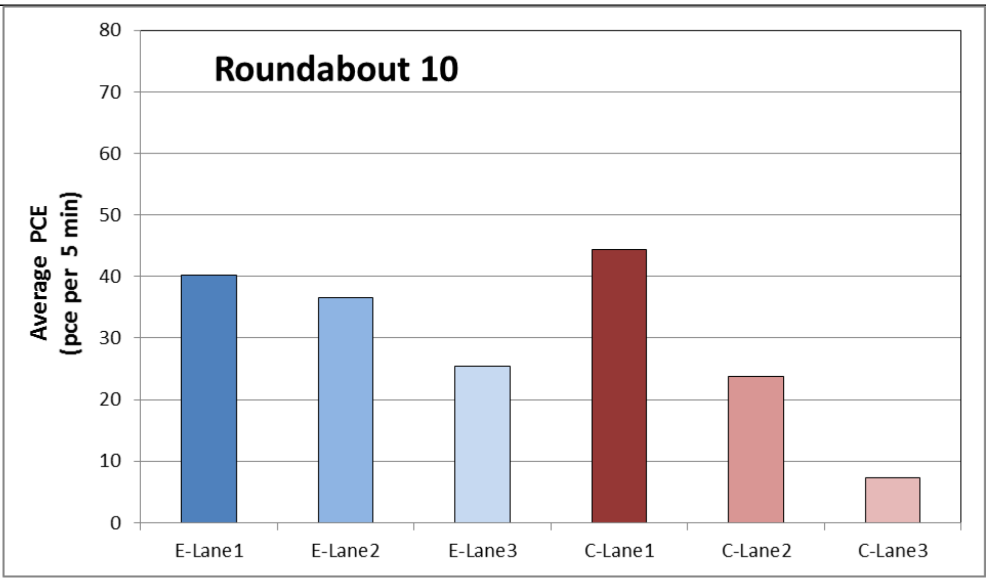

Roundabout 5
Average PCE (pce per 5 min)
80
70
60
50
40
30
20
10
0
E-Lane1
E-Lane2
E-Lane3
C-Lane1
C-Lane2
C-Lane3

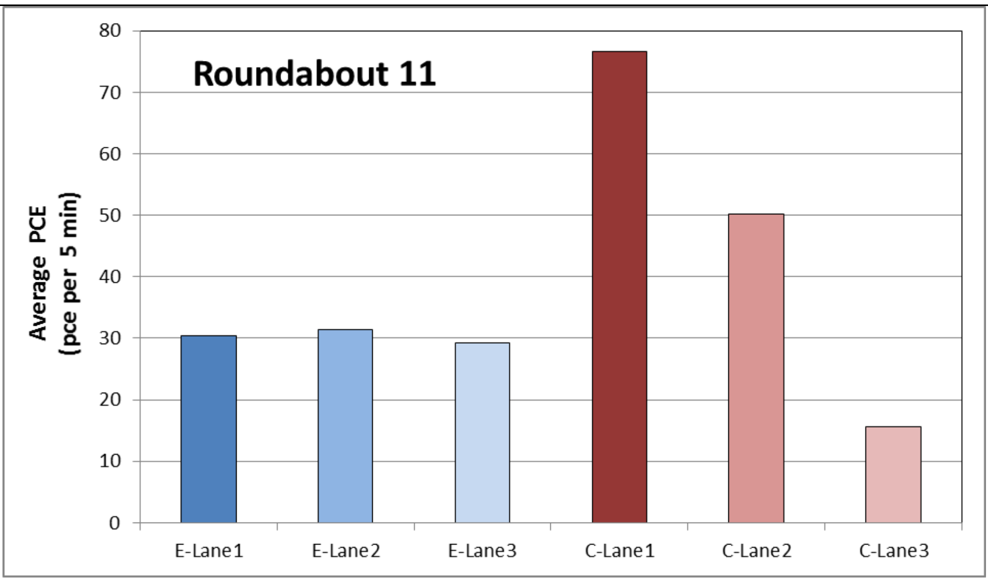

Roundabout 6
Average PCE (pce per 5 min)
80
70
60
50
40
30
20
10
0
E-Lane1
E-Lane2
E-Lane3
C-Lane1
C-Lane2
C-Lane3

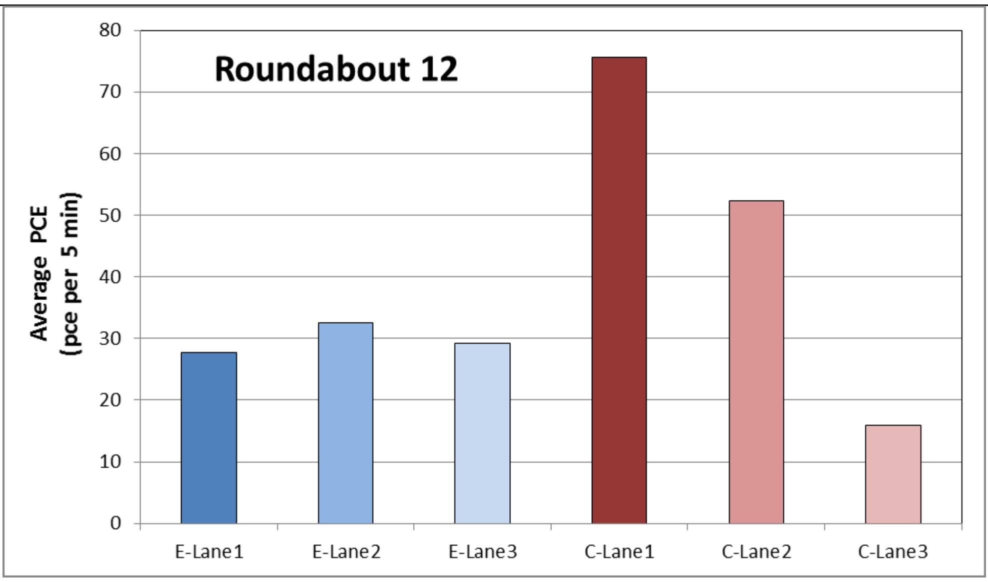

Roundabout 7
Average PCE (pce per 5 min)
0
10
20
30
40
50
60
70
80
E-Lane1
E-Lane2
E-Lane3
C-Lane1
C-Lane2
C-Lane3


Roundabout 8
Average PCE (pce per 5 min)
0
10
20
30
40
50
60
70
80
E-Lane1
E-Lane2
E-Lane3
C-Lane1
C-Lane2
C-Lane3


Roundabout 9
Average PCE (pce per 5 min)
80
70
60
50
40
30
20
10
0
E-Lane1
E-Lane2
E-Lane3
C-Lane1
C-Lane2
C-Lane3


Roundabout 10
Average PCE (pce per 5 min)
80
70
60
50
40
30
20
10
0
E-Lane1
E-Lane2
E-Lane3
C-Lane1
C-Lane2
C-Lane3


Roundabout 11
Average PCE
(pce per 5 min)
80
70
60
50
40
30
20
10
0
E-Lane1
E-Lane2
E-Lane3
C-Lane1
C-Lane2
C-Lane3


Roundabout 12
Average PCE
(pce per 5 min)
80
70
60
50
40
30
20
10
0
E-Lane1
E-Lane2
E-Lane3
C-Lane1
C-Lane2
C-Lane3

Appendix C

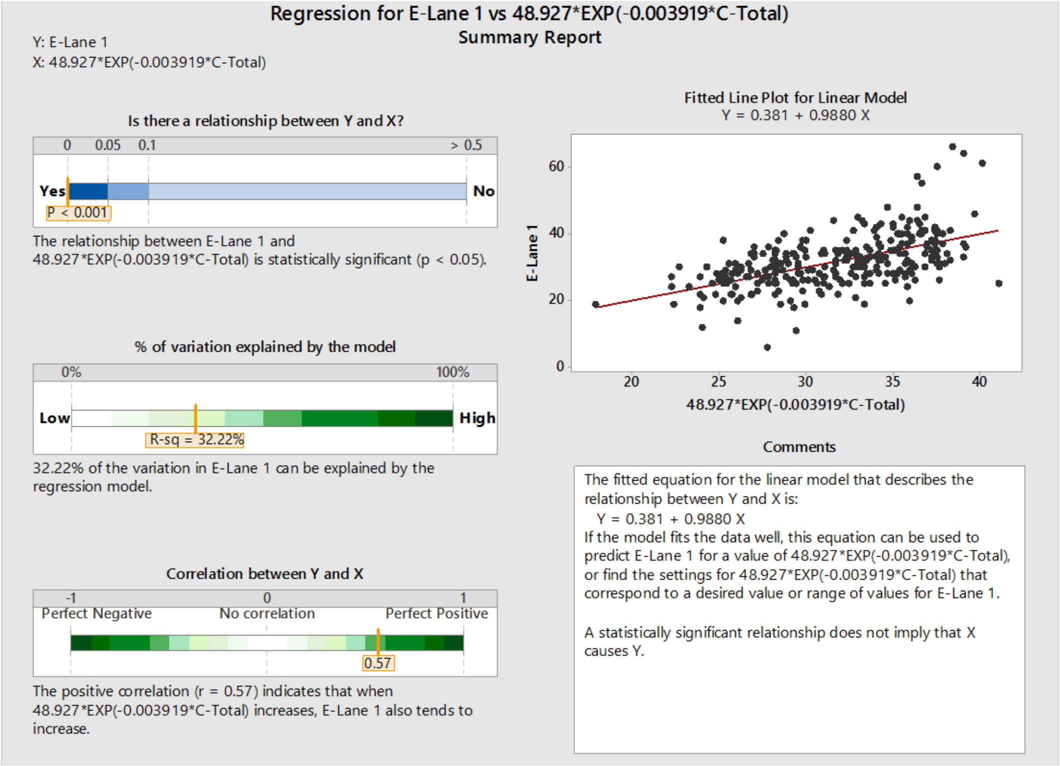


Figure *C*-1: Diagnostic Analysis of Exponential Model for E-Lane 1

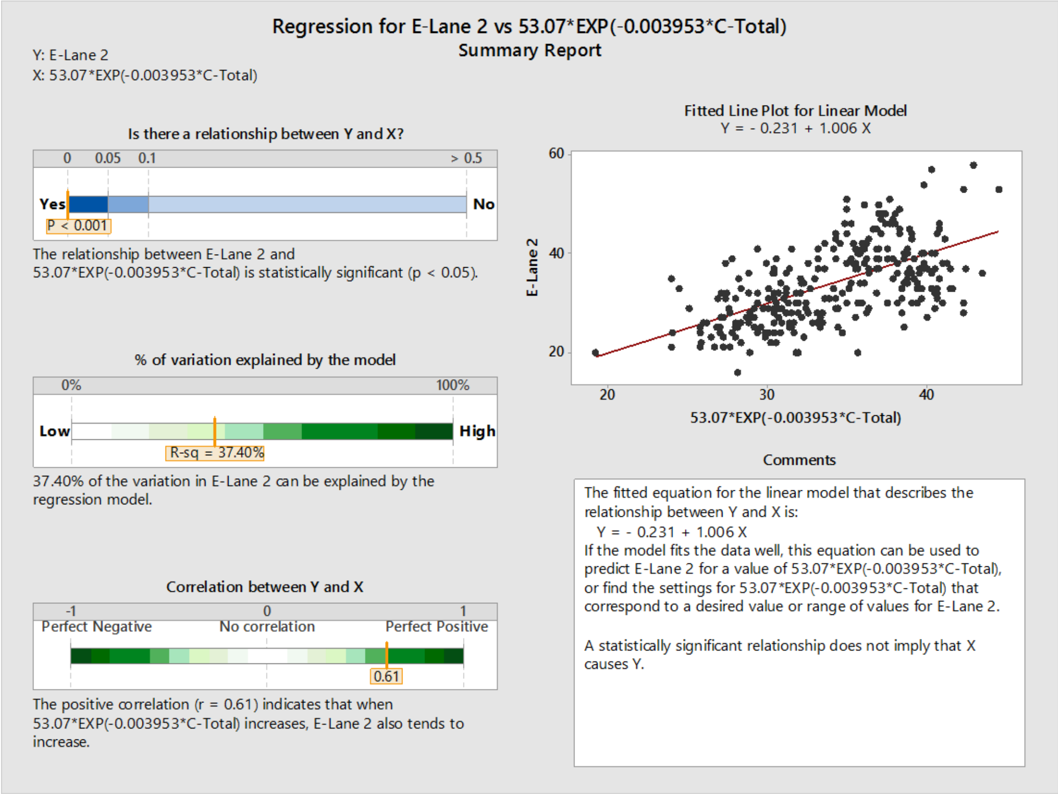


Figure *C*-2: Diagnostic Analysis of Exponential Model for E-Lane 2

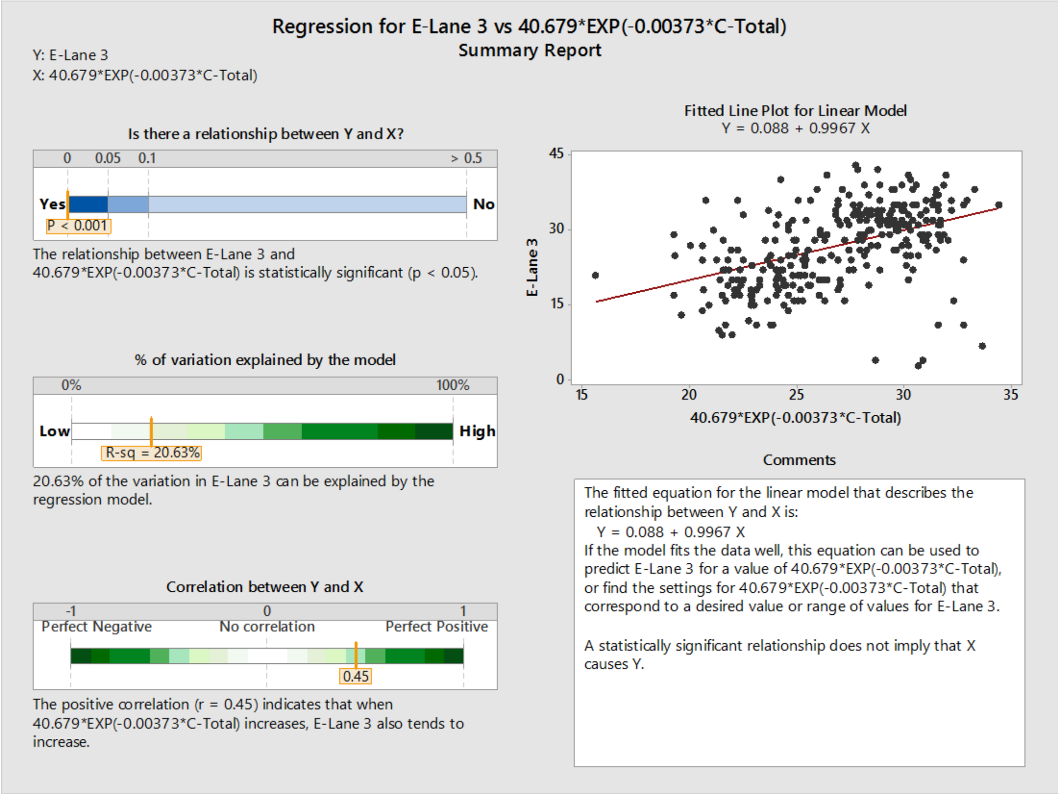


Figure *C*-3: Diagnostic Analysis of Exponential Model for E-Lane 3

Appendix D

Proposed Model vs. VisSim Data

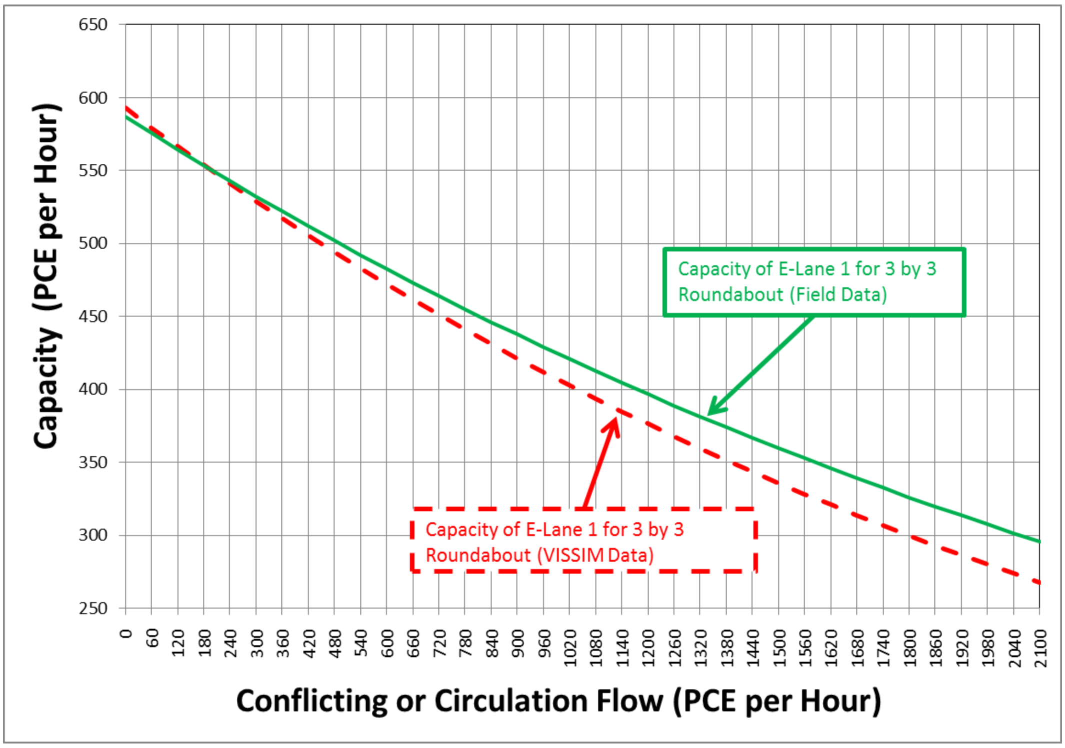


Figure D-1: Capacity Curve Comparisons for Entry Lane 1

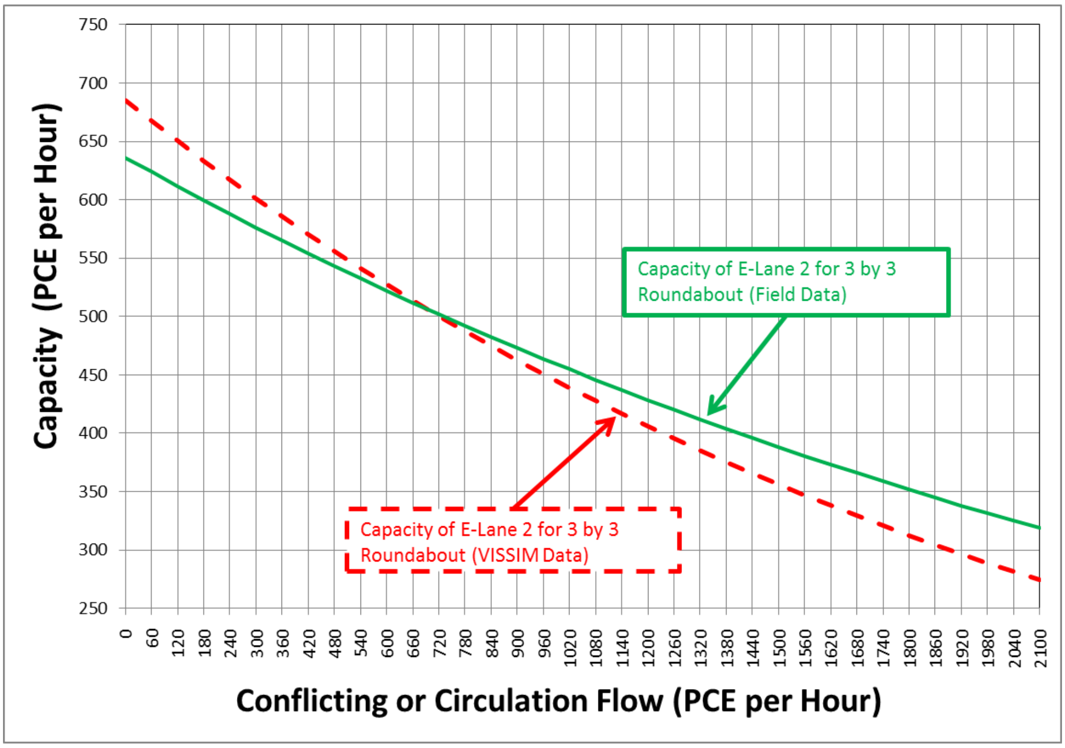


Figure D-2: Capacity Curve Comparisons for Entry Lane 2

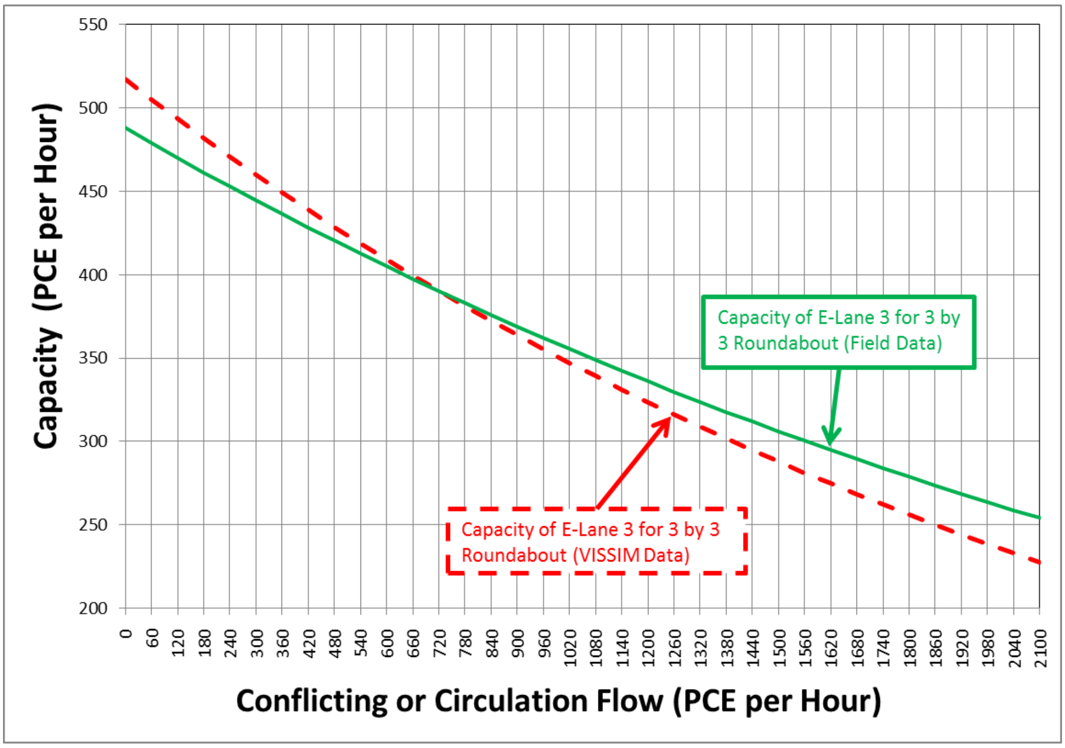


Figure D-3: Capacity Curve Comparisons for Entry Lane 3

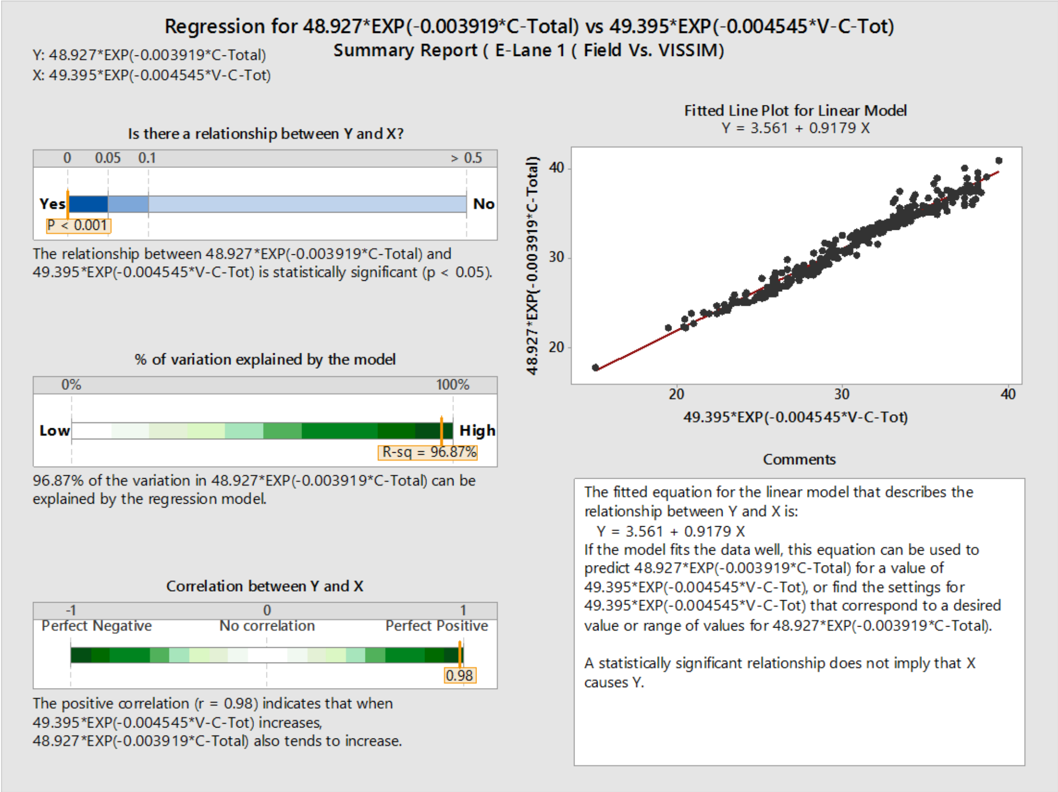


Figure D-4: First Entry Lane (Proposed Model vs. VisSim Data)

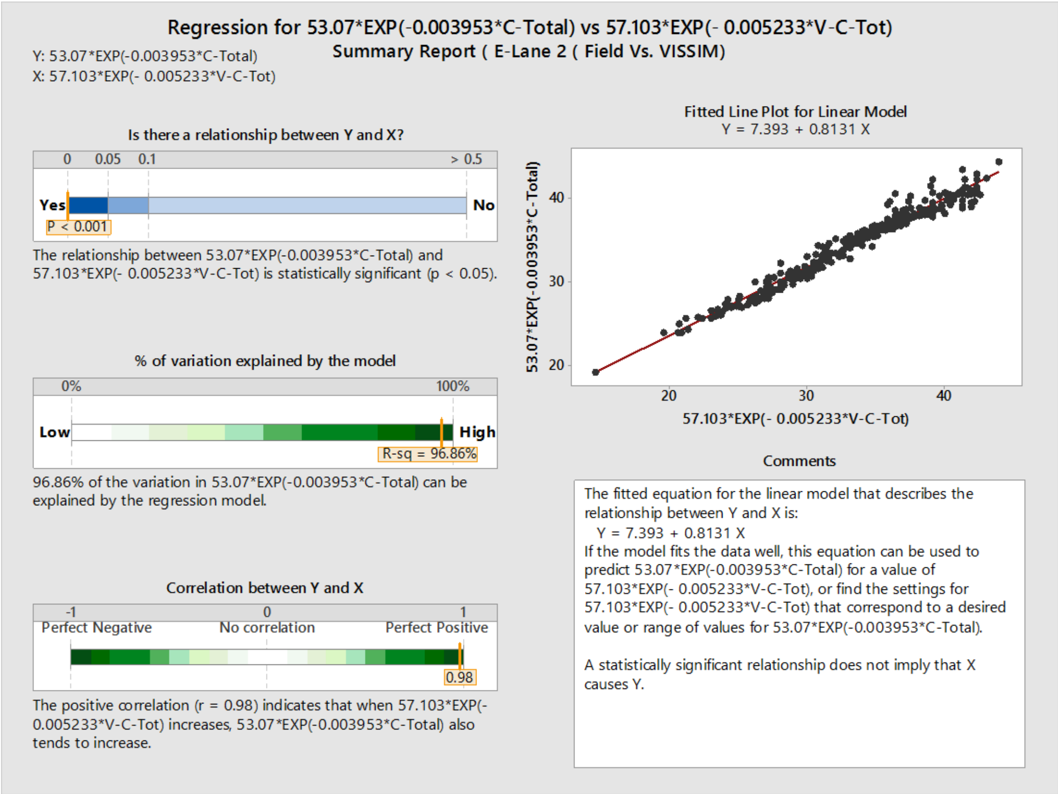


Figure D-5: Second Entry Lane (Proposed Model vs. VisSim Data)

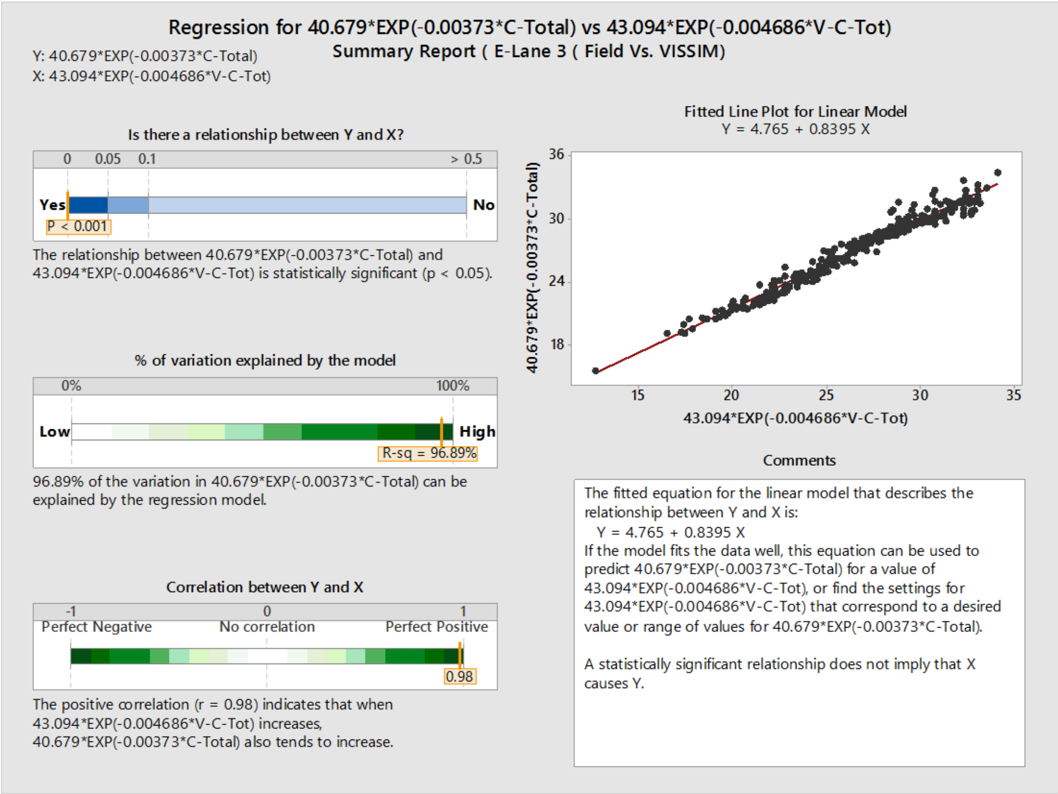


Figure D-6: Third Entry Lane (Proposed Model vs. VisSim Data)

SPSS outputs

Exponential Model Output for E-Lane 1

```
* NonLinear Regression.
MODEL PROGRAM  A=100 B=-0.008.
COMPUTE  PRED_=A*EXP(B*C_Total).
NLR E_Lane_1
  /OUTFILE='C:\Users\Mohamad\AppData\Local\Temp\spss4500\SPSSFNLR.TMP'
  /PRED PRED_
  /CRITERIA ITER 500 SSCONVERGENCE 1E-10 PCON 1E-10.
```

Nonlinear Regression Analysis

Iteration History[b]

Iteration Number[a]	Residual Sum of Squares	Parameter	
		A	B
1.0	57916.546	100.000	-.008
1.1	25844.011	43.391	-.005
2.0	25844.011	43.391	-.005
2.1	13044.495	48.753	-.004
3.0	13044.495	48.753	-.004
3.1	12878.549	48.880	-.004
4.0	12878.549	48.880	-.004
4.1	12878.481	48.926	-.004
5.0	12878.481	48.926	-.004
5.1	12878.481	48.927	-.004
6.0	12878.481	48.927	-.004
6.1	12878.481	48.927	-.004

Derivatives are calculated numerically.

a. Major iteration number is displayed to the left of the decimal, and minor iteration number is to the right of the decimal.

b. Run stopped after 12 model evaluations and 6 derivative evaluations because the relative reduction between successive residual sums of squares is at most SSCON = 1.00E-010.

Parameter Estimates

Parameter	Estimate	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
A	48.927	1.820	45.347	52.507
B	-.004	.000	-.005	-.003

Correlations of Parameter Estimates

	A	B
A	1.000	-.951
B	-.951	1.000

ANOVA[a]

Source	Sum of Squares	df	Mean Squares
Regression	311955.519	2	155977.759
Residual	12878.481	311	41.410
Uncorrected Total	324834.000	313	
Corrected Total	18998.038	312	

Dependent variable: E_Lane_1[a]

a. R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .322.

Exponential Model Output for E-Lane 2

ANOVA[a]

Source	Sum of Squares	df	Mean Squares
Regression	363667.656	2	181833.828
Residual	12604.344	311	40.528
Uncorrected Total	376272.000	313	
Corrected Total	20133.457	312	

Dependent variable: E_Lane_2[a]

a. R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .374.

```
* NonLinear Regression.
MODEL PROGRAM  A=100 B=-0.008.
COMPUTE  PRED_=A*EXP(B*C_Total).
NLR E_Lane_2
  /OUTFILE='C:\Users\Mohamad\AppData\Local\Temp\spss4500\SPSSFNLR.TMP'
  /PRED PRED_
  /CRITERIA ITER 500 SSCONVERGENCE 1E-10 PCON 1E-10.
```

Nonlinear Regression Analysis

Iteration History[b]

Iteration Number[a]	Residual Sum of Squares	Parameter	
		A	B
1.0	43173.924	100.000	-.008
1.1	26226.311	45.531	-.005
2.0	26226.311	45.531	-.005
2.1	12681.290	52.841	-.004
3.0	12681.290	52.841	-.004
3.1	12604.347	53.022	-.004
4.0	12604.347	53.022	-.004
4.1	12604.344	53.017	-.004
5.0	12604.344	53.017	-.004
5.1	12604.344	53.017	-.004

Derivatives are calculated numerically.

a. Major iteration number is displayed to the left of the decimal, and minor iteration number is to the right of the decimal.

b. Run stopped after 10 model evaluations and 5 derivative evaluations because the relative reduction between successive residual sums of squares is at most SSCON = 1.00E-010.

Parameter Estimates

Parameter	Estimate	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
A	53.017	1.807	49.462	56.572
B	-.004	.000	-.005	-.003

Correlations of Parameter Estimates

	A	B
A	1.000	-.951
B	-.951	1.000

Exponential Model Output for E-Lane 3

```
* NonLinear Regression.
MODEL PROGRAM  A=100 B=-0.008.
COMPUTE  PRED_=A*EXP(B*C_Total).
NLR E_Lane_3
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  /PRED PRED_
  /CRITERIA ITER 500 SSCONVERGENCE 1E-10 PCON 1E-10.
```

Nonlinear Regression Analysis

Iteration History[b]

Iteration Number[a]	Residual Sum of Squares	Parameter	
		A	B
1.0	100486.489	100.000	-.008
1.1	32448.593	34.526	-.005
2.0	32448.593	34.526	-.005
2.1	16302.255	40.098	-.003
3.0	16302.255	40.098	-.003
3.1	15706.498	40.593	-.004
4.0	15706.498	40.593	-.004
4.1	15705.949	40.679	-.004
5.0	15705.949	40.679	-.004
5.1	15705.949	40.679	-.004
6.0	15705.949	40.679	-.004

Derivatives are calculated numerically.

a. Major iteration number is displayed to the left of the decimal, and minor iteration number is to the right of the decimal.

b. Run stopped after 11 model evaluations and 6 derivative evaluations because the relative reduction between successive parameter estimates is at most PCON = 1.00E-008.

Parameter Estimates

Parameter	Estimate	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
A	40.679	1.969	36.805	44.553
B	-.004	.000	-.005	-.003

Correlations of Parameter Estimates

	A	B
A	1.000	-.951
B	-.951	1.000

ANOVA[a]

Source	Sum of Squares	df	Mean Squares
Regression	224549.051	2	112274.525
Residual	15705.949	311	50.501
Uncorrected Total	240255.000	313	
Corrected Total	19787.751	312	

Dependent variable: E_Lane_3[a]

a. R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .206.

Exponential Model Output for E-Total

Correlations of Parameter Estimates

	A	B
A	1.000	-.951
B	-.951	1.000

ANOVA[a]

Source	Sum of Squares	df	Mean Squares
Regression	2674649.461	2	1337324.731
Residual	37065.539	311	119.182
Uncorrected Total	2711715.000	313	
Corrected Total	89461.962	312	

Dependent variable: E_Total[a]

a. R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .586.

```
* NonLinear Regression.
MODEL PROGRAM  A=100 B=-0.008.
COMPUTE  PRED_=A*EXP(B*C_Total).
NLR E_Total
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  /PRED PRED_
  /CRITERIA ITER 500 SSCONVERGENCE 1E-10 PCON 1E-10.
```

Nonlinear Regression Analysis

Iteration History[b]

Iteration Number[a]	Residual Sum of Squares	Parameter	
		A	B
1.0	839398.875	100.000	-.008
1.1	1082529.284	123.448	.001
1.2	118365.391	130.632	-.005
2.0	118365.391	130.632	-.005
2.1	37940.873	141.791	-.004
3.0	37940.873	141.791	-.004
3.1	37065.661	142.568	-.004
4.0	37065.661	142.568	-.004
4.1	37065.539	142.617	-.004
5.0	37065.539	142.617	-.004
5.1	37065.539	142.617	-.004

Derivatives are calculated numerically.

a. Major iteration number is displayed to the left of the decimal, and minor iteration number is to the right of the decimal.

b. Run stopped after 11 model evaluations and 5 derivative evaluations because the relative reduction between successive residual sums of squares is at most SSCON = 1.00E-010.

Parameter Estimates

Parameter	Estimate	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
A	142.617	3.073	136.571	148.663
B	-.004	.000	-.004	-.003

Minitab outputs

Linear Model Output

Table D-1: Linear Models Output

Description	Linear Model		
	Equation	R^2	(Adj.) R^2
For Entry Approach	E-Total = 131.254 - 0.339204 C-Total	57.68 %	57.55 %
	General Regression Analysis: E-Total versus C-Total Regression Equation E-Total = 131.254 - 0.339204 C-Total Coefficients Term Coef SE Coef T P Constant 131.254 2.02761 64.7334 0.000 C-Total -0.339 0.01647 -20.5894 0.000 Summary of Model S = 11.0331 R-Sq = 57.68% R-Sq(adj) = 57.55% PRESS = 38351.7 R-Sq(pred) = 57.13%		

Description	Linear Model		
	Equation	R^2	(Adj.) R^2
Entry Lane 1	E-Lane 1 = 44.725 - 0.114989 C-Total	31.22 %	30.99 %
	General Regression Analysis: E-Lane 1 versus C-Total Regression Equation E-Lane 1 = 44.725 - 0.114989 C-Total Coefficients Term Coef SE Coef T P Constant 44.7250 1.19126 37.5443 0.000 C-Total -0.1150 0.00968 -11.8801 0.000 Summary of Model S = 6.48216 R-Sq = 31.22% R-Sq(adj) = 30.99% PRESS = 13250.1 R-Sq(pred) = 30.26%		
Entry Lane 2	E-Lane 2 = 48.9249 - 0.129737 C-Total	37.49 %	37.29 %
	General Regression Analysis: E-Lane 2 versus C-Total Regression Equation E-Lane 2 = 48.9249 - 0.129737 C-Total Coefficients Term Coef SE Coef T P Constant 48.9249 1.16903 41.8510 0.000 C-Total -0.1297 0.00950 -13.6586 0.000 Summary of Model S = 6.36118 R-Sq = 37.49% R-Sq(adj) = 37.29% PRESS = 12747.0 R-Sq(pred) = 36.69%		

Description	Linear Model		
	Equation	R^2	(Adj.) R^2
Entry Lane 3	E-Lane 3 = 37.6041 - 0.0944779 C-Total	20.23 %	19.97 %
	General Regression Analysis: E-Lane 3 versus C-Total Regression Equation E-Lane 3 = 37.6041 - 0.0944779 C-Total Coefficients Term Coef SE Coef T P Constant 37.6041 1.30924 28.7220 0.000 C-Total -0.0945 0.01064 -8.8813 0.000 Summary of Model S = 7.12416 R-Sq = 20.23% R-Sq(adj) = 19.97% PRESS = 16006.7 R-Sq(pred) = 19.11%		

Quadratic Model Output

Table D-2: Quadratic Models Output

Description	Quadratic Model		
	Equation	R^2	(Adj.) R^2
For Entry Approach	E-Total = 145.15 - 0.58 C-Total + 0.0009 (C-Total)^2	0.59	0.58
	General Regression Analysis: E-Total versus C-Total, (C-Total)^2 Regression Equation E-Total = 145.153 - 0.58117 C-Total + 0.000953142 (C-Total)^2 Coefficients Term Coef SE Coef T P Constant 145.153 5.20926 27.8644 0.000 C-Total -0.581 0.08528 -6.8150 0.000 (C-Total)^2 0.001 0.00033 2.8906 0.004 Summary of Model S = 10.9049 R-Sq = 58.79% R-Sq(adj) = 58.53% PRESS = 37446.6 R-Sq(pred) = 58.14%		

<table>
<tr><td rowspan="2">Description</td><td colspan="3">Quadratic Model</td></tr>
<tr><td>Equation</td><td>R^2</td><td>(Adj.) R^2</td></tr>
<tr><td rowspan="2">Entry Lane 1</td><td>E-Lane 1 = 51.82 - 0.24 C-Total + 0.001 (C-Total)^2</td><td>0.33</td><td>0.31</td></tr>
<tr><td colspan="3">General Regression Analysis: E-Lane 1 versus C-Total, (C-Total)^2
Regression Equation
E-Lane 1 = 51.8224 - 0.238548 C-Total + 0.000486718 (C-Total)^2
Coefficients
Term Coef SE Coef T P
Constant 51.8224 3.07061 16.8769 0.000
C-Total -0.2385 0.05027 -4.7456 0.000
(C-Total)^2 0.0005 0.00019 2.5041 0.013
Summary of Model
S = 6.42792 R-Sq = 32.58% R-Sq(adj) = 32.14%
PRESS = 13092.5 R-Sq(pred) = 31.09%</td></tr>
<tr><td rowspan="2">Entry Lane 2</td><td>E-Lane 2 = 50.66 - 0.16 C-Total + 0.00012 (C-Total)^2</td><td>0.38</td><td>0.36</td></tr>
<tr><td colspan="3">General Regression Analysis: E-Lane 2 versus C-Total, (C-Total)^2
Regression Equation
E-Lane 2 = 50.6576 - 0.159901 C-Total + 0.000118824 (C-Total)^2
Coefficients
Term Coef SE Coef T P
Constant 50.6576 3.04176 16.6541 0.000
C-Total -0.1599 0.04980 -3.2112 0.001
(C-Total)^2 0.0001 0.00019 0.6171 0.538
Summary of Model
S = 6.36752 R-Sq = 37.57% R-Sq(adj) = 37.17%
PRESS = 12802.9 R-Sq(pred) = 36.41%</td></tr>
</table>

Description	Quadratic Model		
	Equation	R^2	(Adj.) R^2
Entry Lane 3	E-Lane 3 = 42.67 - 0.18 C-Total + 0.0004 (C-Total)^2	0.21	0.19
	General Regression Analysis: E-Lane 3 versus C-Total, (C-Total)^2 Regression Equation E-Lane 3 = 42.6728 - 0.18272 C-Total + 0.0003476 (C-Total)^2 Coefficients Term Coef SE Coef T P Constant 42.6728 3.39439 12.5716 0.000 C-Total -0.1827 0.05557 -3.2882 0.001 (C-Total)^2 0.0003 0.00021 1.6178 0.107 Summary of Model S = 7.10571 R-Sq = 20.90% R-Sq(adj) = 20.39% PRESS = 15956.1 R-Sq(pred) = 19.36%		

Cubic Model Output

Table D-3: Cubic Models Output

Description	Cubic Model		
	Equation	R^2	(Adj.) R^2
For Entry Approach	E-Total = 122.4 - 0.014 C-Total - 0.003 C-Total^2 + 0.000010 C-Total^3	0.59	0.58
	General Regression Analysis: E-Total versus C-Total, (C-Total)^2, (C-Total)^3 Regression Equation E-Total = 122.419 - 0.0140407 C-Total - 0.00334359 (C-Total)^2 + 1.00119e-005(C-Total)^3 Coefficients Term Coef SE Coef T P Constant 122.419 12.6738 9.65924 0.000 C-Total -0.014 0.3007 -0.04669 0.963 (C-Total)^2 -0.003 0.0022 -1.51278 0.131 (C-Total)^3 0.000 0.0000 1.96582 0.050 Summary of Model S = 10.8549 R-Sq = 59.30% R-Sq(adj) = 58.91% PRESS = 37464.9 R-Sq(pred) = 58.12%		

<table>
<tr><th rowspan="2">Description</th><th colspan="3">Cubic Model</th></tr>
<tr><th>Equation</th><th>R^2</th><th>(Adj.) R^2</th></tr>
<tr><td rowspan="2">Entry Lane 1</td><td>E-Lane 1 = 63.79 - 0.54 C-Total + 0.003 C-Total^2 - 0.00001 C-Total^3</td><td>0.33</td><td>0.31</td></tr>
<tr><td colspan="3">General Regression Analysis: E-Lane 1 versus C-Total, (C-Total)^2, (C-Total)^3
Regression Equation
E-Lane 1 = 63.7906 - 0.537116 C-Total + 0.00274875 (C-Total)^2 - 5.27082e-006(C-Total)^3
Coefficients
Term Coef SE Coef T P
Constant 63.7906 7.48003 8.52812 0.000
C-Total -0.5371 0.17749 -3.02623 0.003
(C-Total)^2 0.0027 0.00130 2.10717 0.036
(C-Total)^3 -0.0000 0.00000 -1.75350 0.081
Summary of Model
S = 6.40652 R-Sq = 33.24% R-Sq(adj) = 32.60%
PRESS = 13078.7 R-Sq(pred) = 31.16%</td></tr>
<tr><td rowspan="2">Entry Lane 2</td><td>E-Lane 2 = 36.39 + 0.2 C-Total - 0.003 C-Total^2 + 0.00001 C-Total^3</td><td>0.39</td><td>0.37</td></tr>
<tr><td colspan="3">General Regression Analysis: E-Lane 2 versus C-Total, (C-Total)^2, (C-Total)^3
Regression Equation
E-Lane 2 = 36.3865 + 0.196116 C-Total - 0.00257846 (C-Total)^2 + 6.28502e-006(C-Total)^3
Coefficients
Term Coef SE Coef T P
Constant 36.3865 7.39318 4.92163 0.000
C-Total 0.1961 0.17543 1.11794 0.264
(C-Total)^2 -0.0026 0.00129 -1.99986 0.046</td></tr>
</table>

<table>
<tr><th rowspan="2">Description</th><th colspan="3">Cubic Model</th></tr>
<tr><th>Equation</th><th>R^2</th><th>(Adj.) R^2</th></tr>
<tr><td></td><td colspan="3">(C-Total)^3 0.0000 0.00000 2.11547 0.035
Summary of Model
S = 6.33213 R-Sq = 38.46% R-Sq(adj) = 37.87%
PRESS = 12758.8 R-Sq(pred) = 36.63%</td></tr>
<tr><td rowspan="2">Entry Lane 3</td><td>E-Lane 3 = 22.24 + 0.33 C-Total - 0.004 C-Total^2 + 0.00001 C-Total^3</td><td>0.23</td><td>0.20</td></tr>
<tr><td colspan="3">General Regression Analysis: E-Lane 3 versus C-Total, (C-Total)^2, (C-Total)^3
Regression Equation
E-Lane 3 = 22.2421 + 0.326959 C-Total - 0.00351387 (C-Total)^2 + 8.99772e-006(C-Total)^3
Coefficients
Term Coef SE Coef T P
Constant 22.2421 8.21160 2.70862 0.007
C-Total 0.3270 0.19485 1.67804 0.094
(C-Total)^2 -0.0035 0.00143 -2.45373 0.015
(C-Total)^3 0.0000 0.00000 2.72670 0.007
Summary of Model
S = 7.03309 R-Sq = 22.76% R-Sq(adj) = 22.01%
PRESS = 15834.5 R-Sq(pred) = 19.98%</td></tr>
</table>

Exponential Model Output

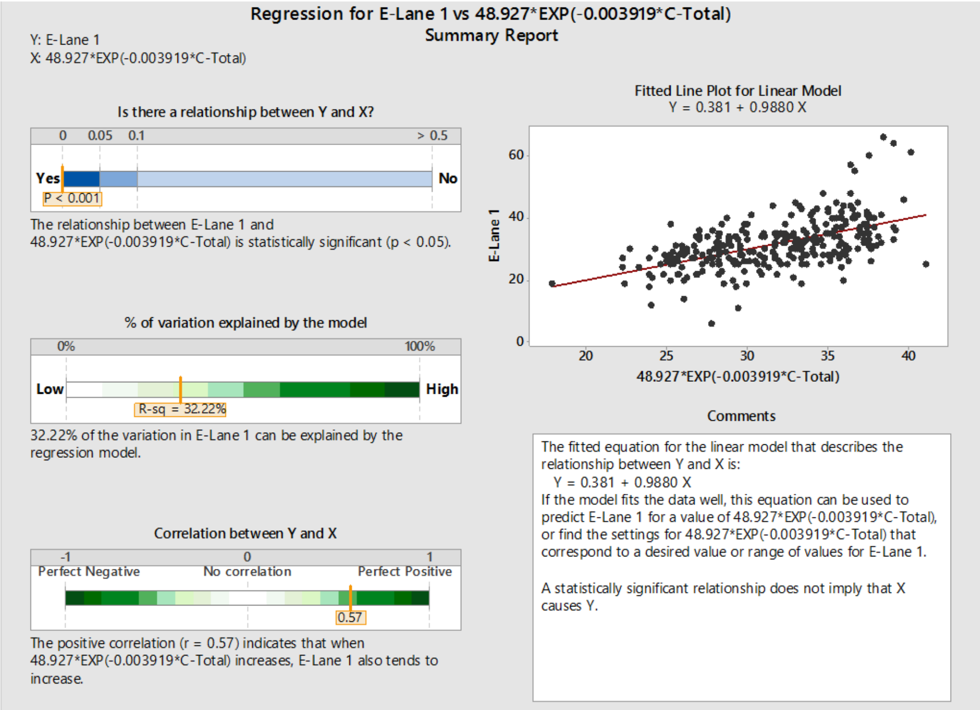


Figure D-7: E-Lane 1 (Assistant Summary Report)

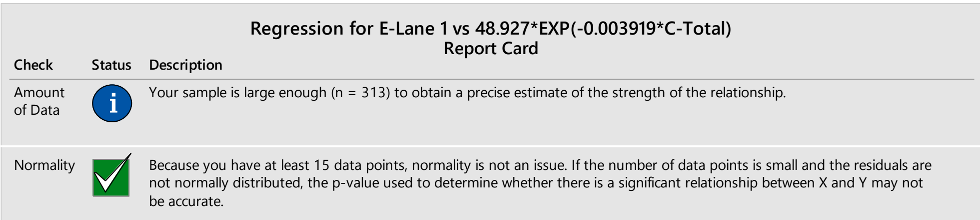
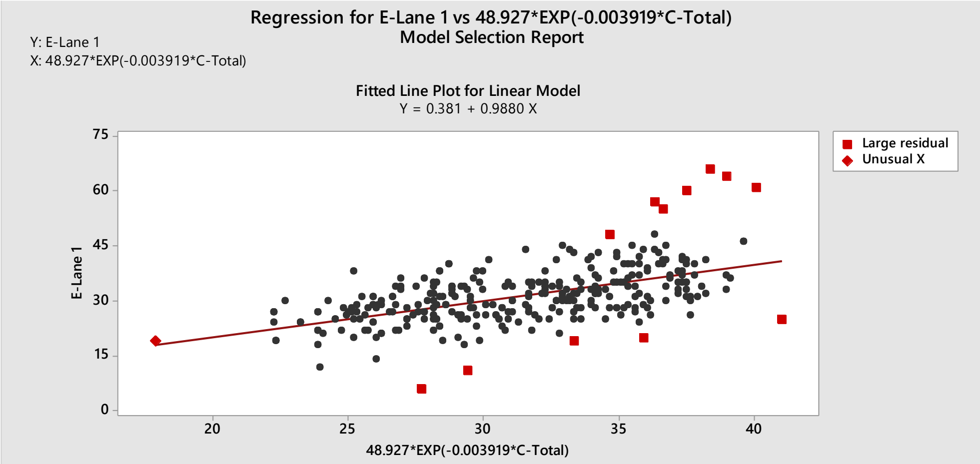


Figure D-8: E-Lane 1 (Assistant Report Card)



Statistics	Selected Model Linear	Alternative Model Quadratic
R-squared (adjusted)	32.00%	32.48%
P-value, model	<0.005*	<0.005*
P-value, linear term	<0.005*	0.431
P-value, quadratic term	—	0.074
Residual standard deviation	6.435	6.412

** Statistically significant (p < 0.05)*

Figure D-9: E-Lane 1 (Assistant Model Selection Report)

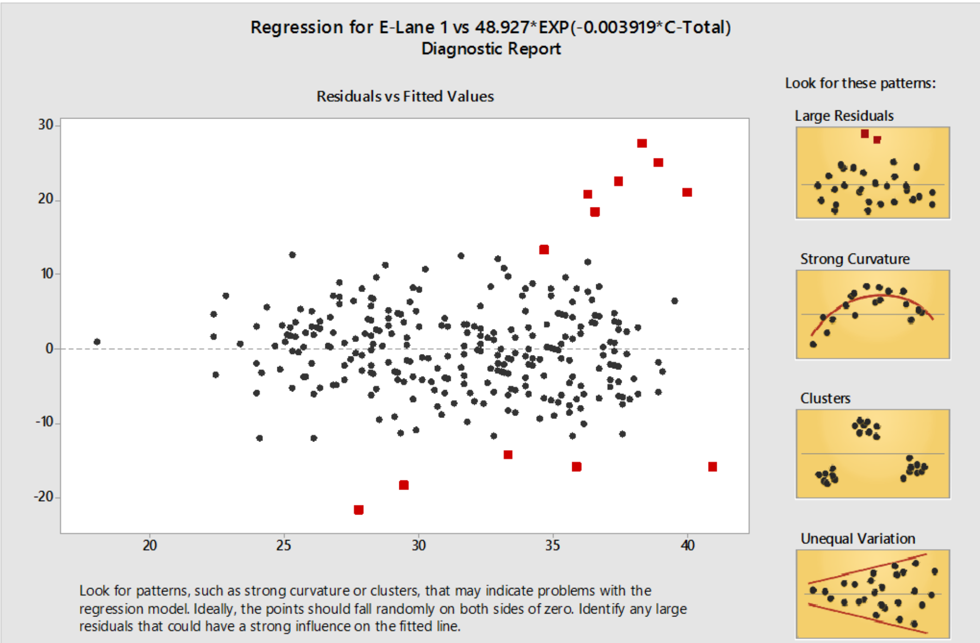


Figure D-10: E-Lane 1 (Diagnostic Report)

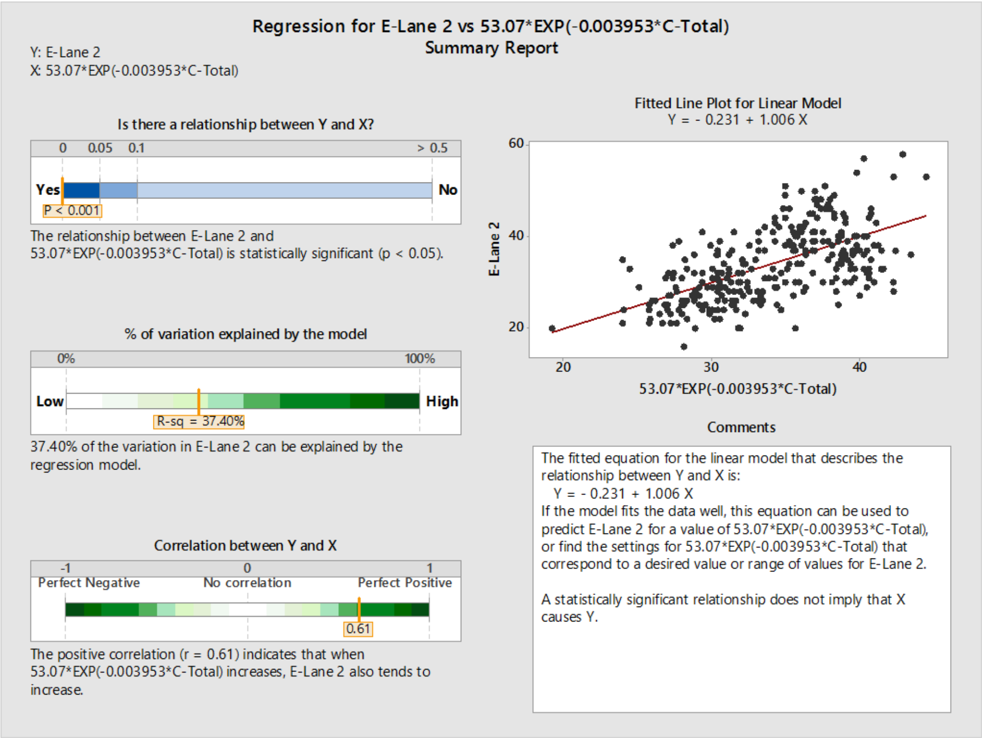


Figure D-11: E-Lane 2 (Assistant Summary Report)

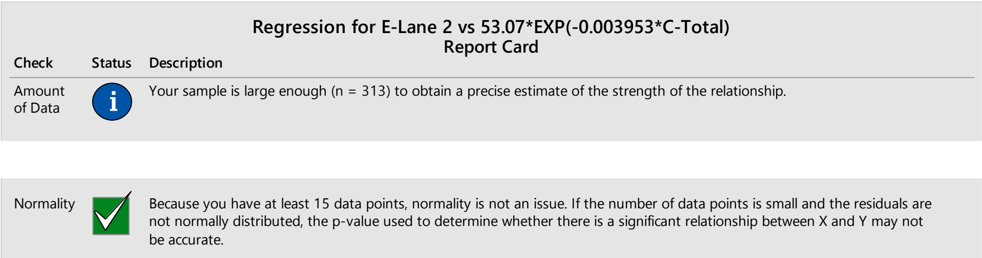
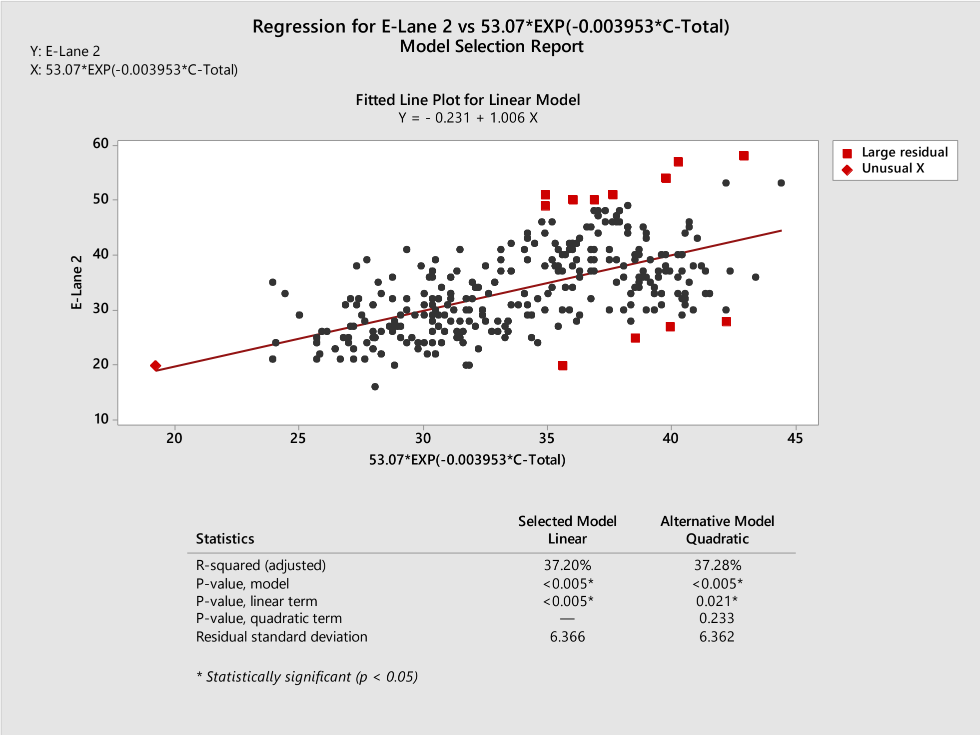


Figure D-12: E-Lane 2 (Assistant Report Card)



Statistics	Selected Model Linear	Alternative Model Quadratic
R-squared (adjusted)	37.20%	37.28%
P-value, model	<0.005*	<0.005*
P-value, linear term	<0.005*	0.021*
P-value, quadratic term	—	0.233
Residual standard deviation	6.366	6.362

** Statistically significant (p < 0.05)*

Figure D-13: E-Lane 2 (Assistant Model Selection Report)

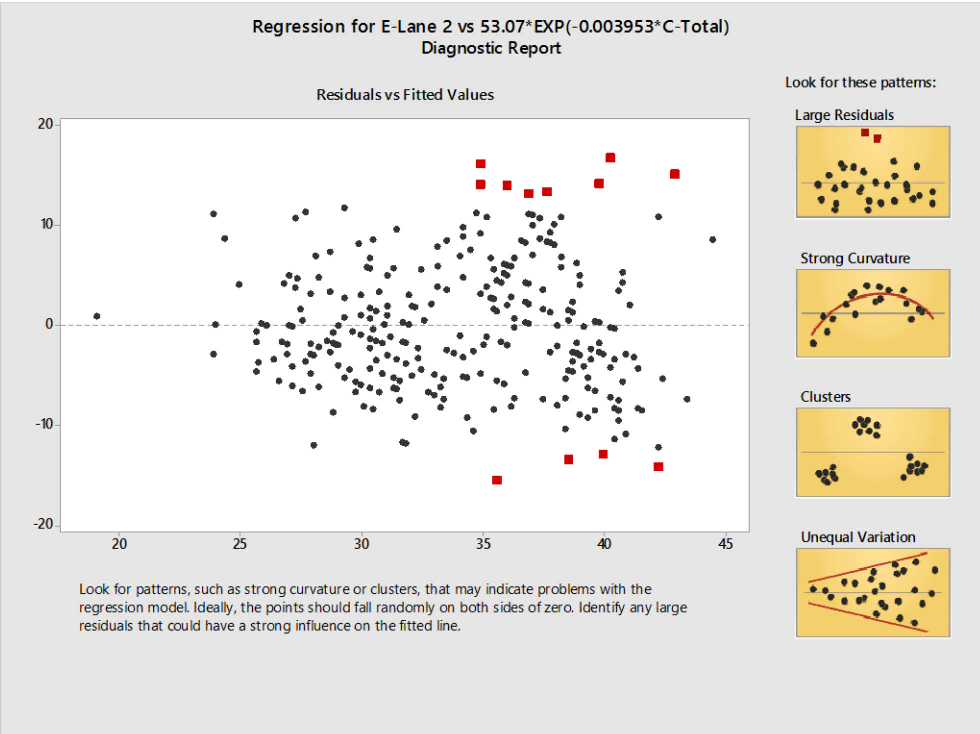


Figure D-14: E-Lane 2 (Diagnostic Report)

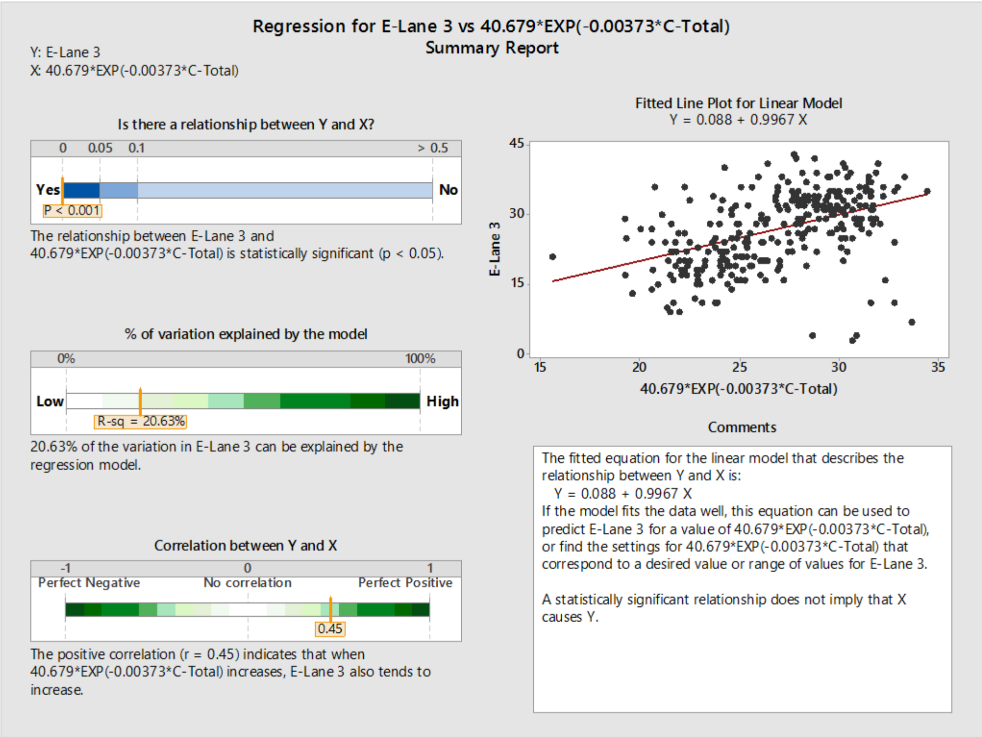


Figure D-15: E-Lane 3 (Assistant Summary Report)

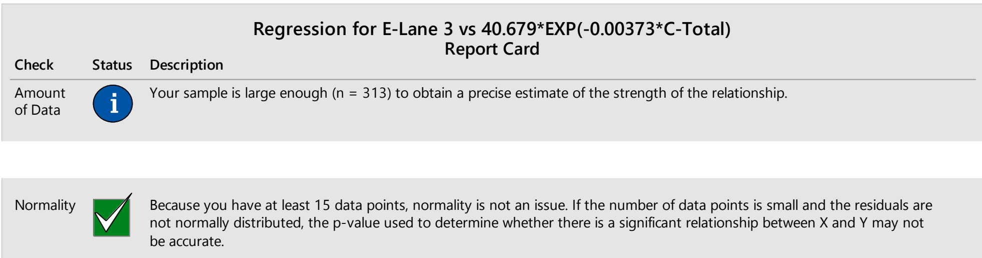
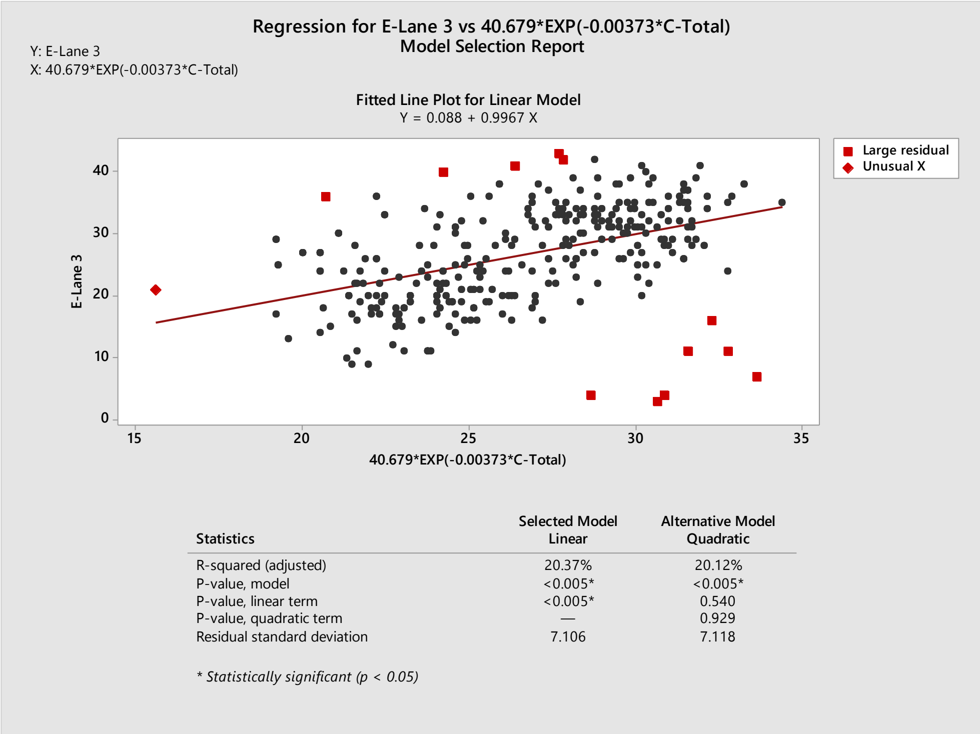


Figure D-16: E-Lane 3 (Assistant Report Card)



Statistics	Selected Model Linear	Alternative Model Quadratic
R-squared (adjusted)	20.37%	20.12%
P-value, model	<0.005*	<0.005*
P-value, linear term	<0.005*	0.540
P-value, quadratic term	—	0.929
Residual standard deviation	7.106	7.118

* *Statistically significant (p < 0.05)*

Figure D-17: E-Lane 3 (Assistant Model Selection Report)

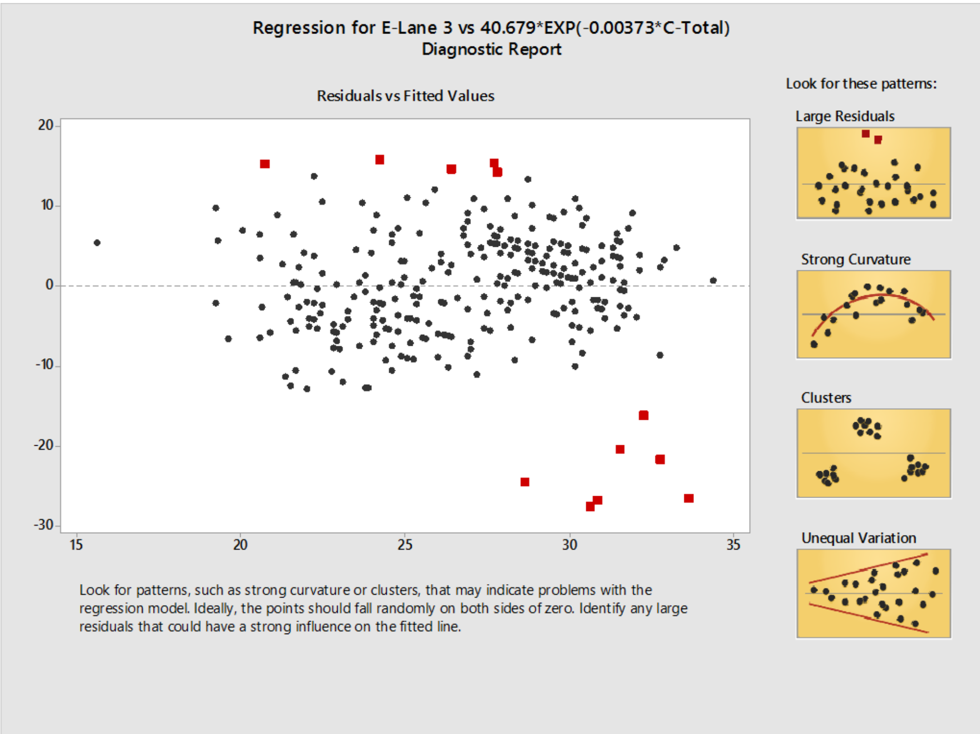


Figure D-18: E-Lane 3 (Diagnostic Report)

Anderson-Darling Normality Figures