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Effects of Unbalanced Approach Volumes on Roundabout Operations

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Abstract

Modern roundabouts are increasingly popular in the United States due to their advantages in improving safety and reducing delay at intersections. A roundabout is an intersection in which traffic enters the intersection and travels in a circular counterclockwise motion around a center island. In a roundabout, priority is given to vehicles traveling in the circular roadway, and incoming traffic at the roundabout approach must yield to the circulating traffic. If there is an unbalance in approach volume, the approaches with higher input volumes may dominate the circulating flow preventing vehicles the other approaches to enter the roundabout. This may consequently cause excessive delay at certain approaches and affects the overall performance of the roundabout. There are insufficient studies where the effects of unbalanced approach volumes at a roundabout are analyzed.

This research analyzed the average control delay and level of service of a typical four-leg, two-lane modern roundabout with different combinations of approach volume for three different unbalanced scenarios. The microscopic traffic simulation software, VISSIM, was used to simulate the three unbalanced scenarios under different approach volume combinations that ranged from 400 pc/h to 1600 pc/h. The roundabout model's parameters were calibrated using data collected from a roundabout in Olathe, Kansas that has the similar geometric attributes as the roundabout analyzed. The measures used to analyze the roundabout operational performance were average control delay and level of service. The results are presented in three charts for the three different unbalanced scenarios under different volume combinations. These charts serve as a reference guide for engineers to determine if a roundabout is feasible for implementation at an intersection under a given traffic demand.

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Chapter 1: Introduction

Modern roundabouts have become increasingly popular in the United States due to their innovative design and benefits on traffic operations. A roundabout is a circular intersection in which traffic drives around a circulatory roadway and yields at the entering approach. The 2008 edition of *Manual on Uniform Traffic Control Devices* (MUTCD) defines roundabouts as “a circular intersection with yield control at entry, which permits a vehicle on the circulatory roadway to proceed, and with deflection of the approaching vehicle counter-clockwise around a central island” (Robinson, et al., 2000). Roundabouts are being built next to and even replacing traditional signalized intersections. Even though roundabouts have been around in other countries, some transportation engineers in the United States have recently advocated their application in their jurisdictions. Roundabouts improve intersection operations by reducing stopping and queuing patterns thus increasing efficiency and safety, environmental benefits, reducing operating and maintenance cost (relative to the signalized intersections). Studies have shown a reduction in greenhouse gas emissions from a range of 17 to 65 percent and fuel consumption by 28 percent while also reducing vehicle related fatalities by 90 percent, injuries by 75 percent and all crashes by 35 percent when a signalized intersection was replaced by a roundabout (McCombs, et al., 2010). Overall, roundabouts are an efficient and effective form of intersections. Due to their increasing popularity it is important to investigate different traffic demand scenarios that may affect their overall performance and operations. A better understanding on the capacity and other limitations of roundabout operations help traffic engineering in selecting the best design for the intersections.

The Federal Highway Administration (FHWA) has created a Transportation Research Board (TRB) Task Force on Roundabouts. The committee comprises of several members that

specialize in different aspects of transportation engineering and are part of the public and private sectors. The Task Force focuses on researching all factors of roundabouts and meet annually to discuss these issues. This committee's objectives include:

- Serving as a forum for discussions about roundabout research, projects, and policy for all interested stakeholders.
- Indentifying research needs and developing research problem statements to meet the needs.
- Facilitating the exchange of knowledge by various media, meetings, and conferences. (TRB, 2010)

The FHWA recognized the importance of the networking of data through this Task Force, which facilitates the design process for engineers of roundabouts. This allows for all stakeholders to have a common understanding on the implementation of roundabouts in the United States. The creation of the Task Force demonstrates the importance of roundabouts in transportation-facility design.

1.1. Background

Traffic circles, rotaries, and modern roundabouts are subsets of circular intersections; each of them with different characteristics. Modern roundabouts can be considered as an evolution of the rotaries and traffic circles. The common characteristic of circular intersections includes that traffic travel in one direction around a central island. Famous circular intersections include the L'arc de Triomphe, Paris, France, a 550 ft diameter rotary with twelve major approaches; DuPont Circle, Washington, DC, a 500 ft rotary with ten major approaches; and the Columbus Circle, New York, NY, a traffic circle with six approaches and a 370 ft outer diameter

(Constructed in 1905 as the first circular intersection in America). The design characteristic of each circular intersection affects overall operating behavior of traffic, pedestrians and cyclists. Due to the considerable differences in dimensions and multiple approaches of traffic circles and rotaries, it is not surprising that misconceptions about modern roundabouts occur.

Traffic circles have two main differences from roundabouts: (i) traffic already in the circulation lanes yield to the entering traffic; and (ii) the geometric design of traffic circle is much greater than modern roundabouts. Rotaries on the other hand provide the right of way to the circulation flow in the rotary. In rotaries and traffic circles, the entering approaches are usually 90 degrees which allows for vehicles to enter at full-speed. The splitter islands are also common in the rotaries and provide a separation between the entering and exiting lanes. The splitter island also provides a physical protection to the pedestrians when using the crosswalk. In many cases rotaries are usually found in major intersections in older cities since they were mainly constructed during the first half of the 1900's and were later recently signalized to control the traffic. Although modern roundabouts have some similarities to traffic circles and rotaries, they also have standing differences which makes them more practical.

Modern roundabouts were first developed in the United Kingdom in 1966 as an alternative to improve the deficiencies in operation and safety associated with circular intersections. The new features included a smaller circular intersection, and channelized approaches (entering and exiting layout) that encourage speed reduction, and achieve slow circulating speeds. Like rotaries, modern roundabouts have priority control entrances, which indicate vehicles wishing to enter the roundabout to yield and provided right of way to those already in the roundabout. The flared entrance of a modern roundabout increases the number of lanes entering the roundabout, thus increasing the capacity at the entrance of a roundabout. The

diameters of modern roundabout are usually 90 ft to 180 ft compared to the diameter of about 360 ft of a rotary. The splitter island provides the separation between traffic in two directions and to slow down traffic before entering into the roundabout. **Figure 1.1** demonstrates the features of a modern roundabout for a two-lane roundabout (i.e., a roundabout with two lanes in the circulatory roadway).

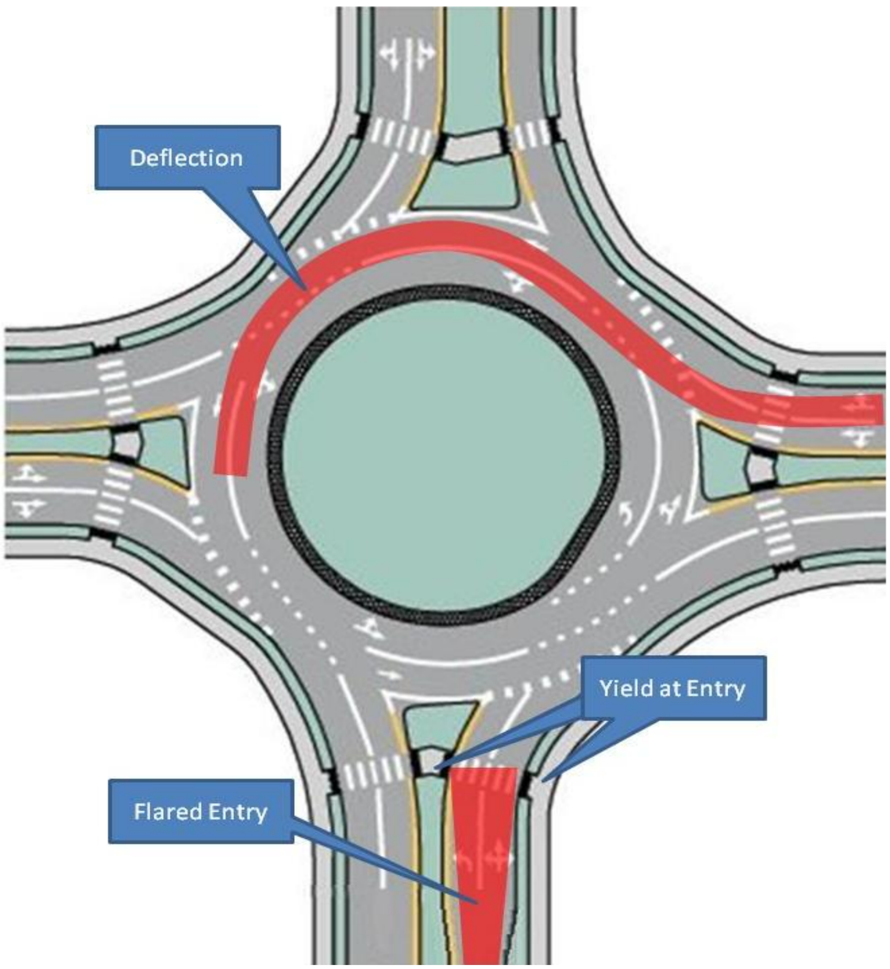

Figure 1.1: Modern Roundabout Features

1.2. Objective

Modern roundabouts have been commonly accepted in countries such as the United Kingdom, Germany and Australia. These countries have developed their national design guidelines to help with the design process of roundabouts. Modern roundabouts have been introduced in the United States in the 1990s and more than 300 roundabouts have been constructed since then (NCHRP, 2007). The most comprehensive reference guides used by engineers are the National Cooperative Highway Research Project (NCHRP) Report 3-65, the *Roundabouts: An Informational Guide* (Robinson, et al., 2000), NCHRP Report 572 *Roundabouts in the United States* (NCHRP, 2007) and the NCHRP Project 3-92 *Production of the 2010 Highway Capacity Manual* (HCM, 2010). The report either documents or analyzed an extensive roundabout data set collected in the U.S that has geometric, accident, speed, pedestrian/bicyclist and other operational data of up to 103 roundabouts. This data has helped to develop guidelines in the Highway Capacity Manual (HCM). The HCM, which is a publication of the Transportation Research Board (TRB), has recently been revised and has a chapter that is dedicated to the concepts, guidelines and formulation of the capacity and level of service of roundabouts (HCM, 2010). The draft of the new 2010 Edition of HCM (also known as HCM 2010) also has a supplementary tool, in the form of a Microsoft Excel spreadsheet, for the calculation of approach delays of a roundabout. For the rest of this thesis, modern roundabouts are simply referred to as roundabouts.

The new HCM2010 has provided many guidelines on roundabout design, compared to the 2000 version. However, many of their design aspects have not been studied extensively let alone incorporated into standard highway design guidelines. The objective of the research is to provide insight into the operations of roundabouts that are encountering unbalanced flow.

Balanced flow at a roundabout occurs when the approach volumes are approximately the same, while unbalanced flow occurs when one or more approach volumes are significantly higher than other approaches. The capacity and Level of Service (LOS) of a roundabout depends not only on the circulation flow but also the approach volume that contributes to the circulating flow. If there are unbalanced approach volumes in a roundabout, it ultimately will affect vehicles entering the roundabout due to the priority rule.

As of today, there is no sufficient information on the effects of unbalanced traffic volume on roundabout operations. The objective of this research is to analyze the operation of a two-lane roundabout under unbalanced approach volume conditions through simulation so as to understand the effects on delay and LOS. Moreover, the simulation results are used to develop delay and LOS charts for a two-lane roundabout under different approach volume conditions, which could be used as a reference guide for traffic and transportation engineers to quickly assess the feasibility of implementing roundabouts at intersections under certain traffic demands.

1.3. Research Scope

The complexity of two-lane roundabouts influences the analysis and the affects of unbalanced approach volumes. The research analyzes a four-leg two-lane roundabout for three different unbalanced approach volume scenarios (hereafter referred to as unbalanced volume scenarios or simply unbalanced scenarios) under various approach volume combinations (hereafter referred to as volume combinations). The design parameters of the roundabout follow the standard features for a two-lane roundabout used in HCM2010. The approach combinations ranged from 400 passenger cars per hour (pc/h) to 1600 pc/h, and were conducted in increments of 100 pc/hr. Due to the relatively small number of sites to make field observations and to

collect data, this research therefore considered analytical and simulation tools to perform analysis of roundabout operations. The analytical procedure was performed using the latest HCM2010 delay calculation procedures. Due to time constraints and software accessibility, one traffic simulation software was used to simulate different volume combinations for the three unbalanced scenarios. Software selection will be discussed in a later chapter of this document.

1.4. Thesis Organization

The research project entails several steps to adequately execute the analysis so as to meet the objective. The first step of the project was to conduct a literature review. Chapter 2 of this thesis summarizes the current guidelines provided by creditable agencies such the FHWA and TRB. This enabled the author to be informed of the latest roundabout capacity and LOS analysis procedures. Other documented study cases were researched which helped to refine the project tasks. A research methodology was conjured so as to have systematic steps to carry out the rest of the research. This research methodology is described Chapter 3 of this thesis. The next step of the research was to develop a four-leg, two-lane roundabout model using traffic simulation software that could realistically replicate roundabout operations. Chapter 4 describes the steps in the development of the roundabout simulation model. The model was created, calibrated and then used to simulate three different unbalanced scenarios under different volume combinations. Chapter 5 describes the roundabout design parameters and the three unbalanced scenarios in more detail. Chapter 6 presents and discusses the results obtained from the simulations in terms of delay and LOS. Chapter 7 compares the delay and LOS obtained from the simulations to the delay and LOS calculated using the HCM2010 procedure. This thesis ends with conclusions and recommendations in Chapter 8.

Chapter 2: Literature Review

This chapter provides literature review documenting the analysis of roundabout operations. Traffic engineers resort to guidelines provided by creditable agencies and simulation software for roundabout operations analysis and design. The chapter describes the steps that traffic engineers perform when analyzing roundabout operations using a mathematical approach provided by published guidelines. It will also describe how different simulation software is used for roundabout analysis and design. The literature review of both methods will be described in light of its application to this research study.

2.1. Roundabout Capacity and Level of Service

The HCM is commonly used to calculate the capacity of highways and intersections. The latest version of the NCHRP Project 3-92 *Production of the 2010 Highway Capacity Manual* has a chapter dedicated to roundabouts in which the capacity formulation is thoroughly explained. Chapter 21-Roundabouts, in the draft HCM2010 presents concepts and procedures for analyzing roundabouts developed based on the data collected from 31 sites in the U.S. in NCHRP Project 3-65 (NCHRP, 2005). The analysis methods described in this chapter is based on the recommendations found in the NCHRP Project 3-65.

The procedures to calculate the operational performance for roundabouts covers one-lane or two-lane roundabouts. The formulation for capacity is relatively simpler for a single lane roundabout than a multilane roundabout. For the purposes of this study, the multilane formulae were used since the project entails the analysis of a two-lane roundabout. **Figure 2.1** outlines the capacity calculation methodology as prescribed in HCM2010.

The operational performance of a roundabout approach may be evaluated using the Average Control Delay (ACD) per vehicle, which may ultimately be converted to LOS. Some steps seen in Figure 2 do not apply to this research project, such as step 6 which involves pedestrians, and therefore only the steps used in the analysis within the scope of this research are described in further detail. The thesis only focuses on the unbalanced approach volumes and not the effects that pedestrians or bicycles could have on roundabout operations.

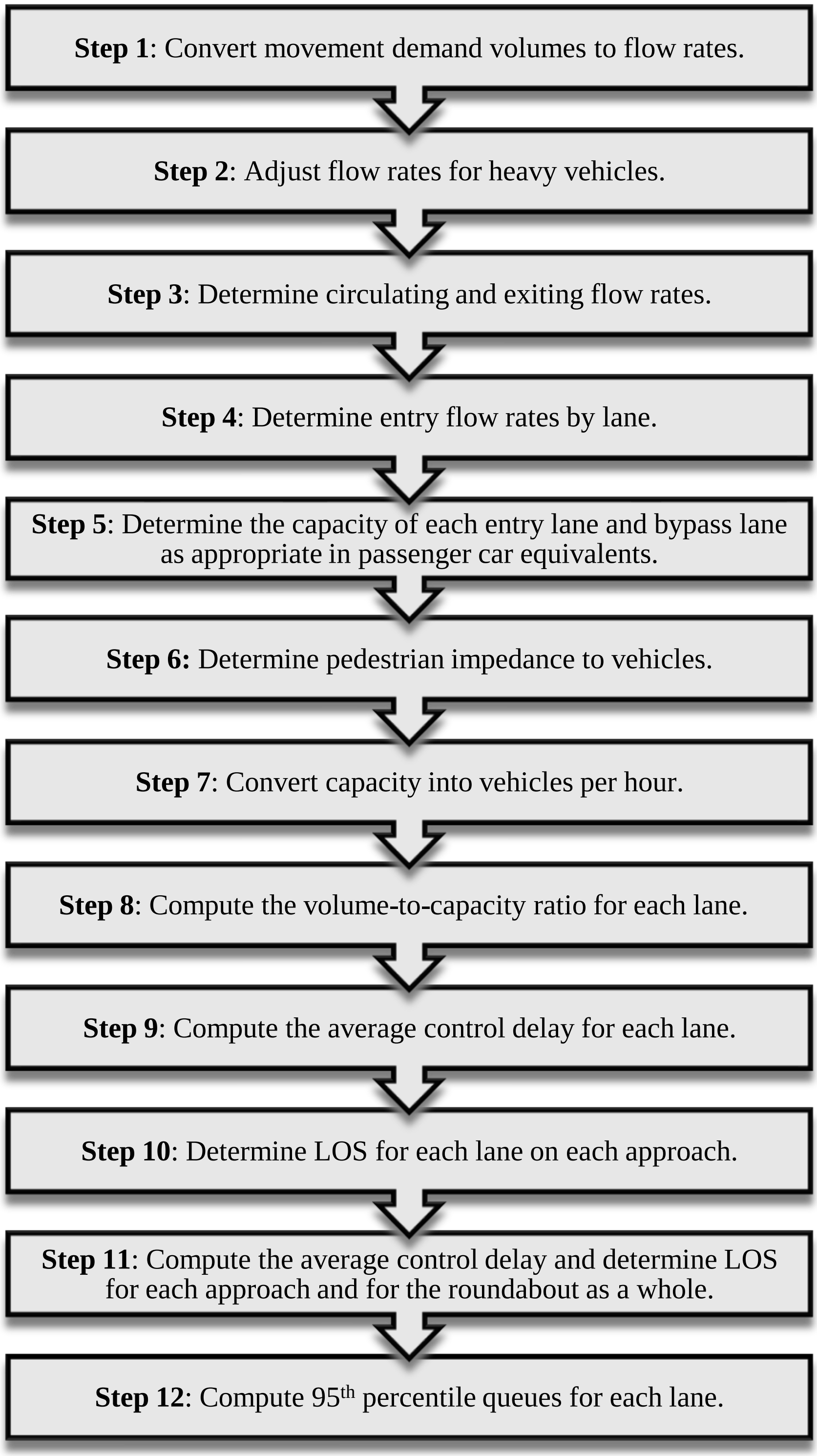

Figure 2.1: Roundabout Analysis Methodology (HCM, 2010)

The research project evaluates the roundabout performance using the ACD and LOS as each approach of the roundabout. **Table 2.1** demonstrates the mapping between the LOS based on ACD of a roundabout approach. The LOS for an approach with volume to capacity ratio greater than one is always F (since the capacity is exceeded).

Table 2.1: Level of Service based on Control Delay (HCM, 2010)

Control Delay (s/veh)	**LOS by Volume-to-Capacity Ratio**	
	v/c ≤ 1.0	**v/c ≥ 1.0**
0-10	A	F
>10-15	B	F
>15-25	C	F
>25-35	D	F
>35-50	E	F
>50	F	F

In order to compute the capacity of a roundabout approach using the formulae in HCM2010, several parameters must be known. The geometric configuration and the vehicle composition of the roundabout, such as the number of lanes and approach design, percent of heavy vehicles and volume distribution across the lanes for a multilane entry must be known. The volume of entering vehicles during the peak 15 minutes or during the peak hour with the Peak Hour Factor (PHF) is required as well. The length of the analysis period is also needed. For the purpose of this research, a typical two-lane four-leg roundabout, based on drawings provided in the latest edition of MUTCD (FHWA, 2009), will be used for an analysis period of one hour. The different volume combinations for the three unbalanced scenarios were inputted in the formulae.

Several steps need to be taken to compute the ACD of an approach of the roundabout (as shown in **Figure 2.1).** The important steps are discussed in this review. Step 1 in the capacity analysis is to calculate the flow rates (volume) for each movement in the roundabout. This can be achieved by using the demand volume in vehicles per hour and dividing it by the PHF. The HCM2010 has defined 0.92 as the default value for the PHF based on the NCHRP Report 599: *Default Values for Highway Capacity and Level of Service Analysis* (NCHRP, 2008). Heavy vehicles are converted into passenger car equivalent. The following formula demonstrates the conversion equations used in the analysis. The passenger car equivalent factor, E_T, for a heavy vehicle is 2. *Equation [2.2]* demonstrates the formula used to determine the heavy vehicle adjustment factor.

[2.1]

[2.2]

where

is demand flow rate for movement *i*, passenger cars per hour (pc/h);

is the demand volume for movement *i*, vehicles per hour (veh/h);

is the heavy vehicle adjustment factor;

is the proportion of demand volume that consist of heavy vehicles; and

is the passenger car equivalent for heavy vehicles.

Step 3 in the capacity calculation methodology consists of determining circulation and exiting flow rates in the roundabout for each approach. According to HCM2010, the circulation flow is defined “as the flow conflicting with the entry flow, or the total flow of all lanes passing

in front of the splitter island next to the subject entry”**.** Once the volumes have been converted into demand flow rates (in passenger cars per hour) for all movements, the circulation flow that is in conflict with an entry flow can be calculated. **Figure 2.2** demonstrates the conflicting flow volume for the northbound (NB) movement. The same concept may be applied to calculate the conflicting flows for southbound (SB), eastbound (EB) and westbound (WB) movements. The following equation can be used to calculate the conflicting flow for the northbound approach.

[2.3]

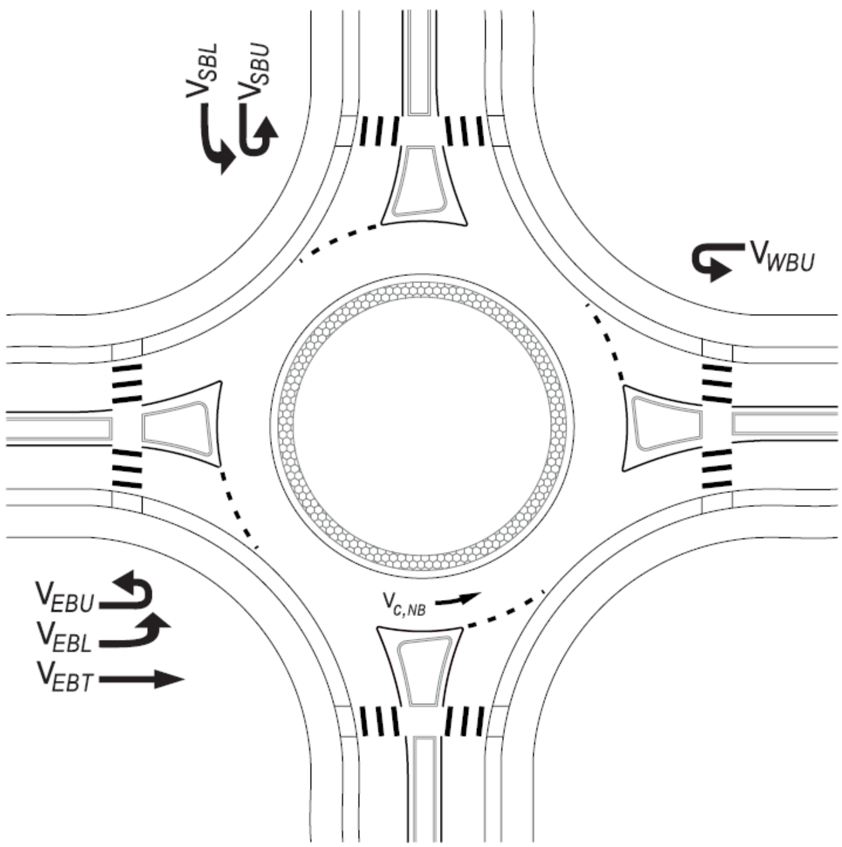

Figure 2.2: Diagram of Circulating Flow Calculation (HCM, 2010)

HCM2010 provides a guideline to determine the entry flow rates by lane of each approach. The calculation of capacity varies accordingly to the design parameters of the roundabout. For the purposes of this research, the equation for a roundabout with two entering and two circulating lanes are reviewed. The HCM2010 provides capacity equations for the right and left lanes of a two-lane approach. The equations shown below were used to calculate the capacity. *Equation [2.4]* is used for the right lane capacity of the roundabout approach whereas *Equation [2.5]* is used to calculate the capacity of the left lane or an approach. If the conflicting flow for either equation is set to zero, the capacity for each lane is 1130 pc/h.

[2.4]

[2.5]

where

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

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

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

According to HCM2010, the ACD of a roundabout is used to evaluate the performance of a roundabout approach. According to Quiroga & Bullock (1999), the ACD is defined as "the total delay due to the installation of vehicular control such as traffic signals, stop signs or even a roundabout, which includes deceleration delay, stopped delay and acceleration delay" (p. 271). The volume to capacity ratio for each lane needs to be computed first to calculate the ACD for each lane. *Equation [2.6]* is the formula used to determine the volume to capacity ratio that is later used in the ACD formula, *Equation [2.7]*, as suggested in Step 9.

[2.6]

[2.7]

where

d	is the average control delay (s/veh);
x	is the volume-to-capacity ratio of the subject lane;
c	is the capacity of subject lane (veh/h); and
T	is the time period, h (T = 1 for a 1-hour analysis, T = 0.25 for a 15-minute analysis).

Once the ACD has been determined, the LOS of each lane may be obtained using Table 2. HCM2010 further suggests (in Step 11) computing the ACD and LOS for each approach and for the roundabout as a whole. The ACD for an approach can be calculated using a weighted average of the ACD for each lane on the approach, which is the lane specific ACD weighted by the volume in each lane (including the bypass lane, if any). Moreover, the ACD for the intersection as a whole can be calculated as well. The ACD of a roundabout is basically the ACD of the approaches weighted by the approach volumes. *Equation [2.8]* and *[2.9]* are used to determine the control delay at each approach of the roundabout and for the intersection as a whole, respectively.

[2.8]

[2.9]

where

$d_{intersection}$ is the control delay for the entire intersection (s/veh);

d_i	is the control delay for approach i (s/veh); and
v_i	is the flow rate for approach i (veh/h).

2.2. Application of Simulation Software

Traffic and transportation engineers highly depend on simulation software to analyze traffic operations and to test different facility designs. The importance of simulation in traffic analysis is reflected by the development of an analysis tool box by the FHWA (FHWA, 2004). The FHWA roundabout guidelines provided a list of available software that helps to analyze functionality of roundabouts. In this research, a comparison of the best available software was conducted to in order to use the best available software for roundabout simulation. There are two categories of software that simulate roundabouts: macroscopic and microscopic. Macroscopic software uses aggregated input information, such as vehicular and pedestrian volumes, to model intersections as isolated locations. The calculations are based on equations developed based on macroscopic traffic flow theory, or empirical equations fitted to field data. Microscopic software simulates the movements of individual vehicles or pedestrians, thus permitting the analysis at a more detailed level. Based on past studies on roundabout operations, there are three frequently used simulation software, namely RODEL, SIDRA and VISSIM. The following sections describe the functions of each of the software and their possible application in this project.

2.2.1. RODEL

RODEL is empirical base capacity computer software developed specifically for roundabout analysis. It is based on the observations of roundabouts in the United Kingdom with distinct geometric compositions to derive linear regression equations from entry capacity and circulating flow (Johnson, 2010). The observations were conducted by the Transportation Research Laboratory (TRL) in the United Kingdom (Crown, 2008). Such observations allowed for the correlation between geometric characteristics of a roundabout approach and the capacity of the roundabout. Geometric characteristics include diameter, entry width, and flare length. The software was created as an interactive design tool that allows for the user to adjust the geometric characteristics of the roundabout to obtain the desired capacity. However, it only analyzes the approach capacity of the roundabout based on geometric characteristics and it does not evaluate an entire network. **Figure 2.3** is a screen shot of Version 2 of RODEL.

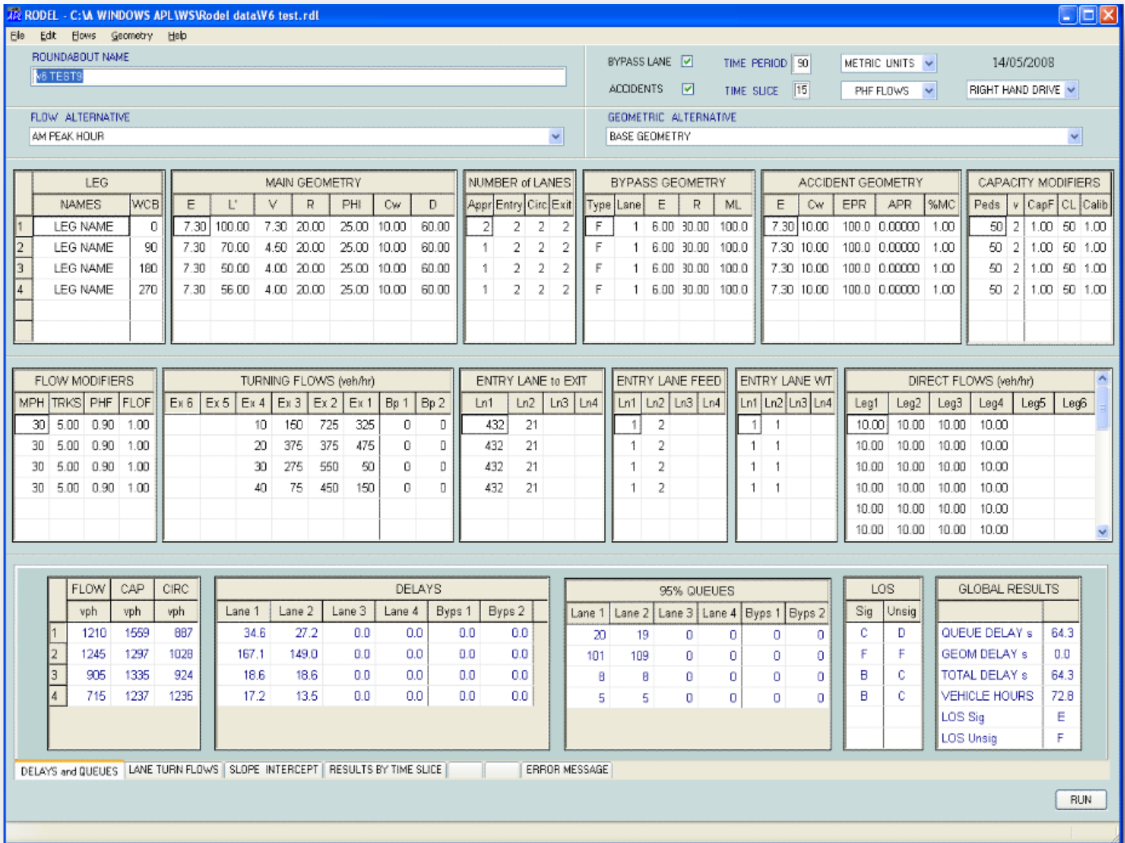

Figure 2.3: Screen shot of RODEL (Crown, 2008)

2.2.2. SIDRA

SIDRA is macroscopic simulation software that analyzes roundabouts using Australian methodologies similar to the approach used in the U.S. HCM2010. The software used gap acceptance to determine the capacity of each approach and the entire roundabout. It also allows the user to evaluate the LOS. The Version 4.0 of SIDRA incorporates roundabout capacity models that compare the original model, which is based on the Australian methodologies, to the NCHRP 572 Roundabout model (SIDRA, 2010). Due to the lack of case studies that use the latest version, Version 3.0 of SIDRA is demonstrated in **Figure 2.4**.

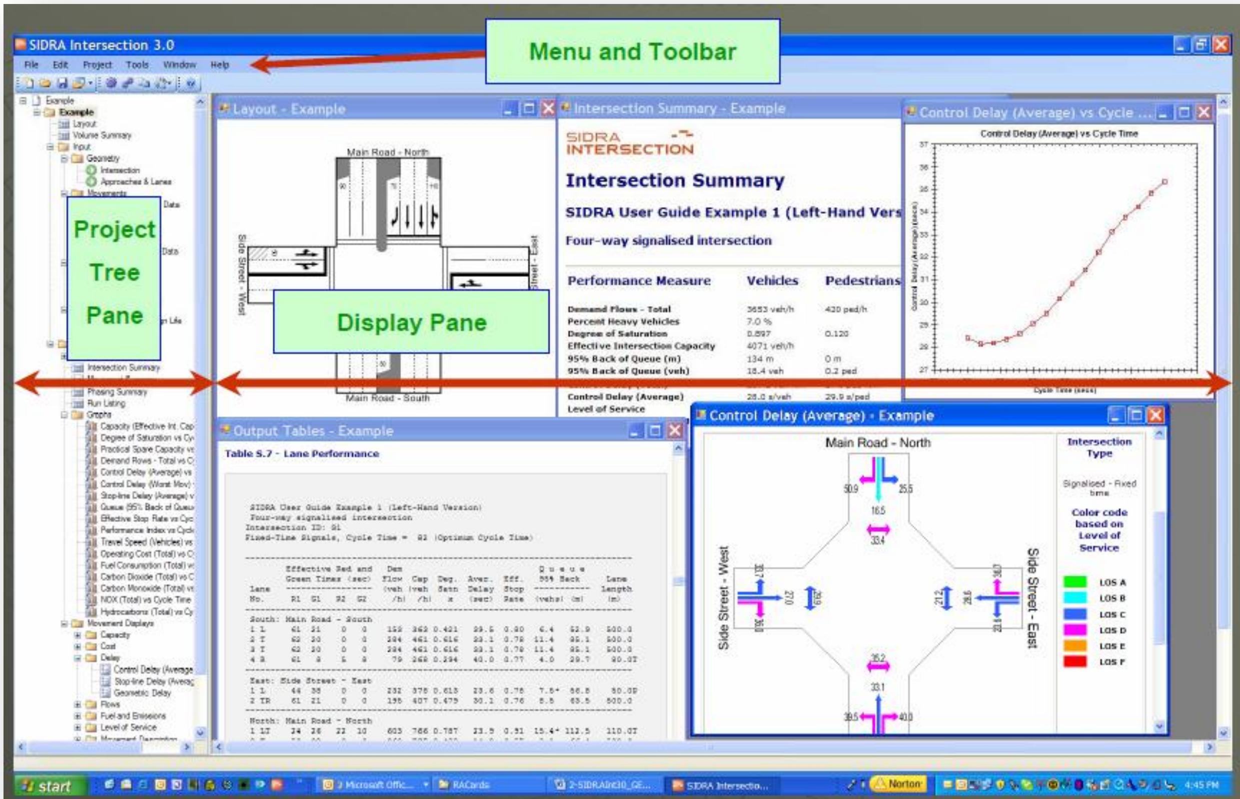

Figure 2.4: Screenshot of SIDRA (SIDRA, 2010)

2.2.3. VISSIM

VISSIM is microscopic simulation software that simulates individual driver behavior and characteristics to provide output measures of effectiveness of an entire simulated network. VISSIM is a time stepping traffic software used to model the movements of several vehicle-user types, including pedestrians, in a network. VISSIM uses a link-connector to represent the network that provides more modeling flexibility and higher amounts of details in designing road facilities. Vehicles in a network model simulate vehicle driving conditions such as lane changing, car-following, acceleration/deceleration, gap acceptance, to name a few. Parameters such as reduced speed areas, conflict areas, vehicle composition, 3D modeling, vehicle lane

usage and turning decisions are some that can be modeled using VISSIM. More detailed information may be found in the VISSIM 5.20 User Manual (PTV, 2009).

The Version 5.20 of VISSIM has the latest features (called conflict areas) that improve modeling of gap acceptance behavior for vehicles entering intersections, in this case a roundabout. Transportation researchers and practitioners often use VISSIM due to the software's features that help model a network with so much detail. **Figure 2.5** demonstrates a screenshot a roundabout model in VISSIM.

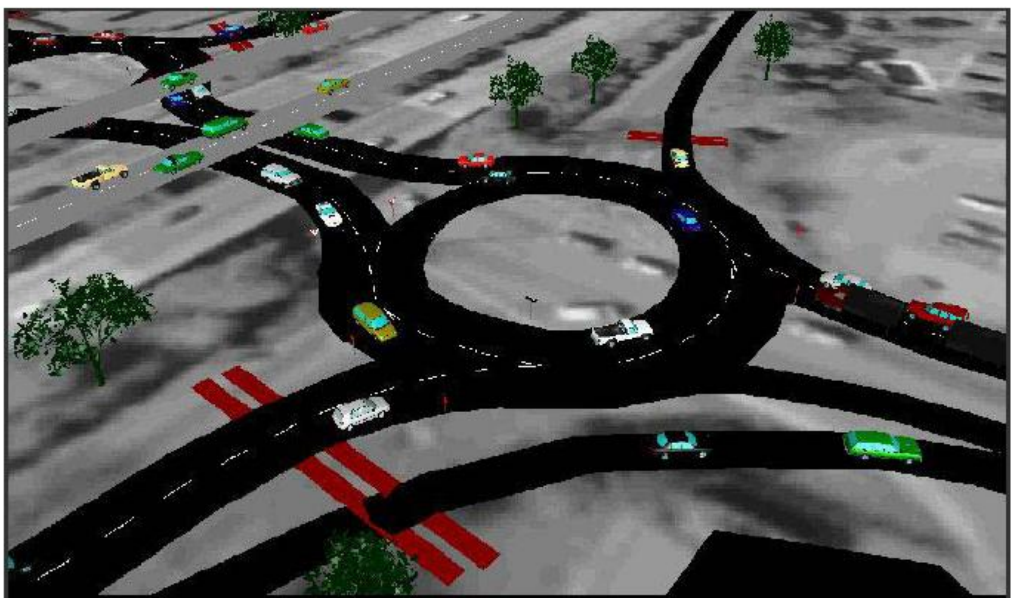

Figure 2.5: Screenshot of VISSIM in 3-D View

There are several publications where VISSIM is used to model roundabouts for either research or engineering design. VISSIM, being microscopic in nature, allows for different critical gaps by different vehicles. Due to the available features in VISSIM to capture driving

behavior and its ability to analyze roundabout operations, the author opted to perform the roundabout analysis using this software.

Chapter 3: Research Methodology

The research entails several steps to adequately perform experiments and analyze the roundabout performance with unbalanced traffic volume. The first step was to create a model in VISSIM 5.20 that would replicate existing traffic operations at a roundabout in the U.S. This allowed for the calibration of software parameters to be used in the model. Data collection of an existing roundabout was necessary to create a roundabout model for the calibration process. After the important model parameters have been calibrated, validation was performed to ensure that the model replicated the roundabout operations. Once the model passed the validation test, the calibrated and validated parameters were used to create three unbalanced volume scenarios and were analyzed under different volume combinations. The ACD obtained from the VISSIM simulation were compared to the ACD obtained from the HCM2010 procedure. Lastly, the conclusions and recommendations observed from the results are discussed. **Figure 3.1** demonstrates the flow chart of the research methodology.

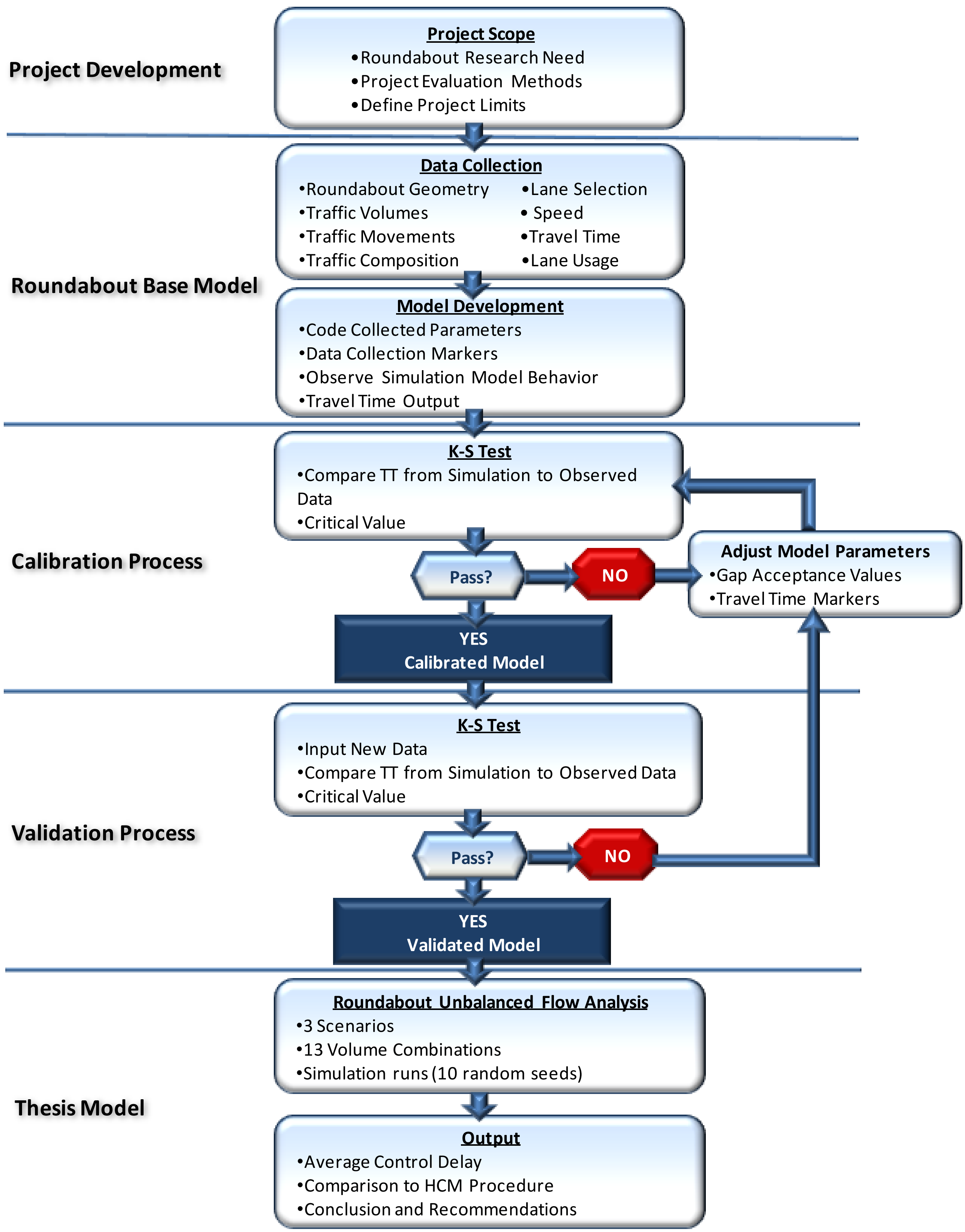

Figure 3.1: Research Methodology

Chapter 4: Model Development

The emphasis of this chapter is the development, calibration and validation of a model using the VISSIM microscopic traffic simulation software. From the software analysis, VISSIM 5.20 has the necessary design features that allow for the development of a model that simulates roundabout operations. The chapter includes steps performed in creating a roundabout model in VISSIM 5.20. It is then followed by the steps involved in calibrating and validating the important model parameters. The project will then use the calibrated and validated parameters for running the subsequent simulations to generate the results for roundabout performance analysis.

4.1. Site Selection

The NCHRP Project 3-65 has the most comprehensive roundabout data set collected in the U.S. (NCHRP, 2005). The data set includes roundabout geometric, accidents, speed, pedestrian/bicyclist and other operational data of 103 roundabouts throughout the nation, in which video recordings of the 31 sites are available. This data set was used to develop Chapter 21 of HCM 2010 and is readily available. The video recordings were created using an omni-directional (dome) camera positioned in the central island of the roundabout. The video footage covers the roundabout's circulatory roadway and the approach entrances in a single screen. The project entails a four-leg, two-lane approach roundabout and therefore the selection of a roundabout with similar characteristics was made amongst the 31 sites in this data set. The roundabout located at Sheridan St and Rogers Rd in Olathe, Kansas was selected for the model development due to the similar geometric characteristics as the project requirement. In addition, it has the best available recording for a two-lane roundabout. The NCHRP Project 3-65 provided

the video recordings of the site in DVD format. The recordings were made on July 25, 2003 and through a preliminary volume count it was concluded that the highest volumes occurred from 10:30 a.m. to 11:30 a.m. CDT (morning peak hour) and from 3:30 p.m. to 4:30 p.m. CDT (the afternoon peak hour). **Figure 4.1** shows the screenshot of the video recording, where the upper left-hand corner is the north approach.

Figure 4.1: Screenshot of the two-lane roundabout in Olathe, Kansas

4.2. Data Collection

The video recordings allowed data to be collected for the model setup that included volume counts, traffic composition, travel time, turning movements and lane use. The traffic volumes for the morning and afternoon peak hours at the intersection were collected foremost. Vehicle composition was manually counted to determine the percentage of heavy vehicles, passenger cars and motorcycles. It was determined that heavy vehicles account for 1.7% and 2.5% of the vehicle population for the morning and afternoon peak hours, respectively. There was only one motorcycle observed in the video recording and therefore was ignored as the number was insignificant.

The turning movement counts were obtained for each approach of the roundabout for both the morning and afternoon peak hours. **Table 4.1** demonstrates the traffic counts for all movements and heavy traffic percentage at each approach of the roundabout.

Table 4.1: Roundabout Traffic Volume and Composition

AM Peak						
Approach	**Vehicular Movement (veh/h)**				**Heavy Traffic (veh/h)**	
	Right	**Through**	**Left**	**Total**	**Total**	**Percentage**
Southbound	90	97	7	194	0	0
Eastbound	165	196	43	404	13	0.50
Westbound	13	213	64	290	2	4.48
Northbound	48	130	149	327	6	4.83
Total	316	636	263	1215	21	1.73

PM Peak						
Approach	**Vehicular Movement (veh/h)**				**Heavy Traffic (veh/hr)**	
	Right	**Through**	**Left**	**Total**	**Total**	**Percentage**
Southbound	141	137	13	291	0	0
Eastbound	228	321	69	618	23	0.65
Westbound	10	202	43	255	4	9.02
Northbound	72	113	171	356	11	3.09
Total	451	773	296	1520	38	2.50

The travel time data was also obtained from the video recordings. It was observed that the roundabout was operating at the traffic demand it was designed for and therefore there was no evidence of substantial queue or delay. Therefore, the calibration and validation process compared the travel time output from the VISSIM model to that of the video recordings. The travel time was recorded from the instant the rear bumper of the vehicle entered the video screen until the same bumper left the video screen. Travel time distributions for the through movements where used for the calibration and validation process. **Table 4.2** summarizes the travel time statistics observed for through traffic movements during both peaks hours.

Table 4.2: Travel Time Summary

AM Peak				
Movement	**No. Observed**	**Travel time (sec)**		
		Min	**Max**	**Average**
NBT	61	5.6	15.5	8.8
SBT	43	6.6	15.9	10.2
EBT	47	5.7	14.3	8.5
WBT	49	6.6	28.8	12.7
PM Peak				
Movement	**No. Observed**	**Travel time (sec)**		
		Min	**Max**	**Average**
NBT	54	5.41	29.13	11.64
SBT	69	7.54	34.75	14.01
EBT	135	5.91	23.62	9.46
WBT	108	8.28	33.19	14.08

Turning movement and lane use were also noted during the data collection. This data was obtained in order to code drivers' lane selection behavior in the roundabout model. To observe the driver behavior at each approach, the video was played back at a slower speed several times and observed by at least two persons. The term lane use refers to (i) the distribution of left-turn, through and right-turn vehicles among the two lanes in an approach; and (ii) the lane (among the two circulatory lanes) vehicles used to negotiate the roundabout to make the turns; and (iii) the distribution of vehicles among the two exit lanes of an approach. **Table 4.3** demonstrates the lane changing data collected for the respective peak hours. **Table 4.4** shows the lane use data collected for the roundabout, arranged by the entry and exit lane combinations. This information was necessary in order to set up the vehicular routes in the VISSIM model. The data was represented through vehicular routes which will be explained in further detail under Model

Coding section of this chapter. The lane use data demonstrates that, overall, 51% of the vehicles used the left lane and 49% used the right lane to enter the roundabout.

Table 4.3: Lane Use Data Listed by Entry-Exit Lane Combination

AM Peak				
Exit Lane	**Left**	**Right**	**Right**	**Left**
Entry Lane	**Left**	**Left**	**Right**	**Right**
Southbound	50%	0%	50%	0%
Eastbound	64%	29%	7%	0%
Westbound	74%	21%	5%	0%
Northbound	65%	17%	19%	0%
Average	**63%**	**17%**	**20%**	**0%**
PM Peak				
Exit Lane	**Left**	**Right**	**Right**	**Left**
Entry Lane	**Left**	**Left**	**Right**	**Right**
Southbound	0%	0%	100%	0%
Eastbound	14%	5%	81%	0%
Westbound	57%	8%	33%	2%
Northbound	4%	4%	88%	4%
Average	**19%**	**4%**	**75%**	**1%**

Table 4.4: Lane Use Data Listed by Entry Lane

Lane Use Behavior	Entry Lane	
	Left Lane	Right Lane
Stay in same lane	41%	48%
Merge into other lane	10%	1%
Total	**51%**	**49%**

It is fundamentally important to represent lane changing and lane use behavior in order to simulate the events realistically in the roundabout model. The data collected demonstrates that drivers followed the pavement marking and signage provided. For right and left-turn movements, vehicles that entered the roundabout using the right lane of an approach usually traveled in the outer circulatory lane and exited to the right of an approach. The same behavior was observed for vehicles in the left lane. That is, vehicles that entered the roundabout from the left lane of an approach usually traveled in the inner circulatory lane and exited to the left lane of an approach. The data demonstrates a high percentage of the vehicles staying in the same lane (refer to Table 4.4). The lane changing percentages in the circulatory roadway were at relatively lower values than the percentages of the vehicles staying in the same lanes. For the morning peak hour, 17% of the vehicles changed lanes in the circulatory roadway, while in the afternoon peak hour only 5% changed lanes in the circulatory roadway.

4.3. Model Coding

The roundabout model was coded in VISSIM 5.20 following the procedure described in the user's manual. Digital images of the roundabout in Olathe, Kansas were obtained from

Google Earth and used to render the geometric dimensions of the roundabout. **Figure 4.2** and **Figure 4.3** demonstrates how the aerial image was used to create the roundabout circulating roadway. The first step was to start with one link and shape it into circle as seen in Figure 4.2. Then links and connectors that join the approach link to the circulatory link were added. **Figure 4.4** depicts the final links and connectors, where the connectors are in pink and links are in blue. Each link consists of two lanes but each connector consists of only one lane.

Figure 4.2: Initial Roundabout Model

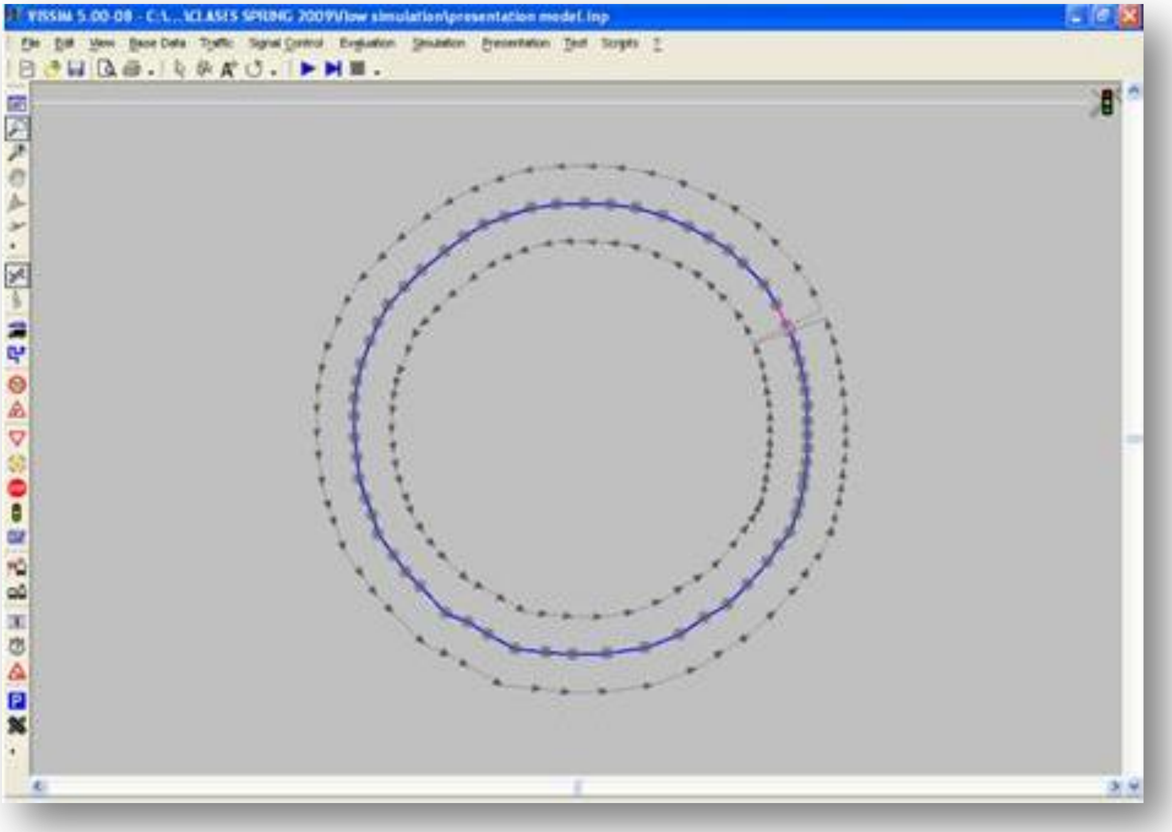

Figure 4.3: Initial Roundabout Model

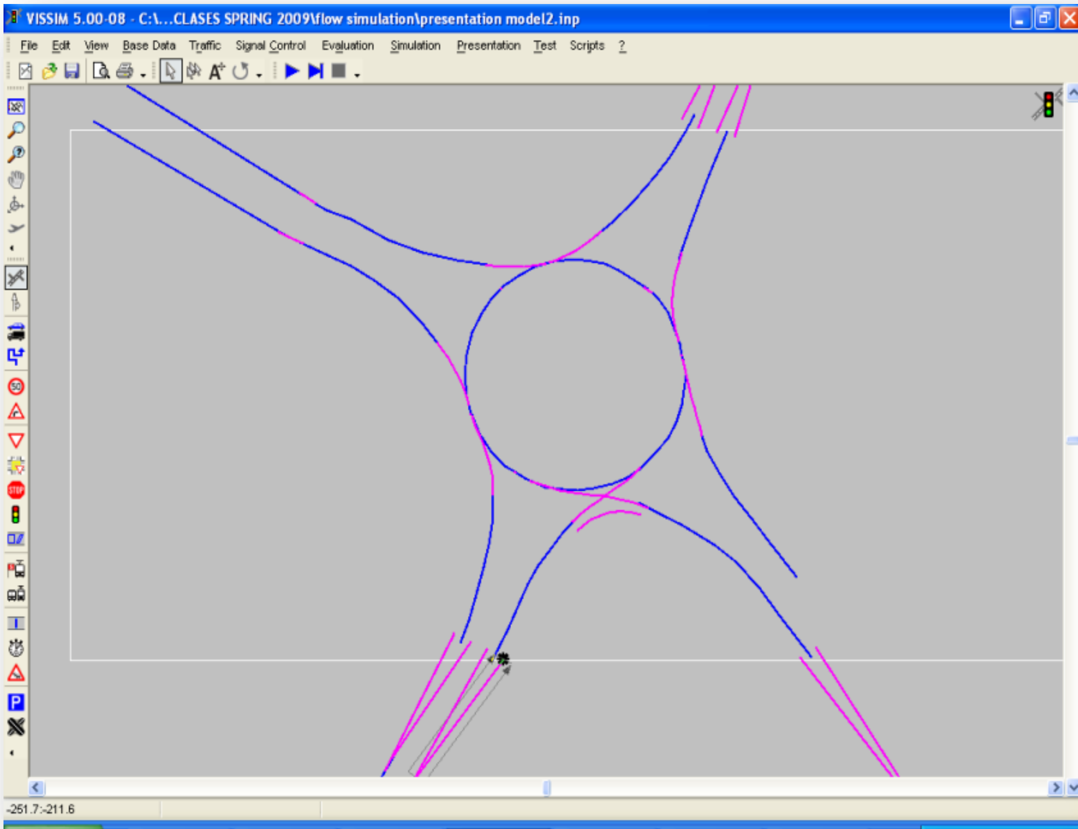

Figure 4.4: Links and Connectors for a Roundabout in VISSIM

The data collected for the morning peak hour was coded into the roundabout model. The routing decisions, vehicle volumes and compositions, lane usage and turning percentages were inputted as obtained from the data collection. **Figure 4.5** is an example of how the routing decision was coded for the right turn movement. The screen box is where the traffic volumes were inputted into the routes.

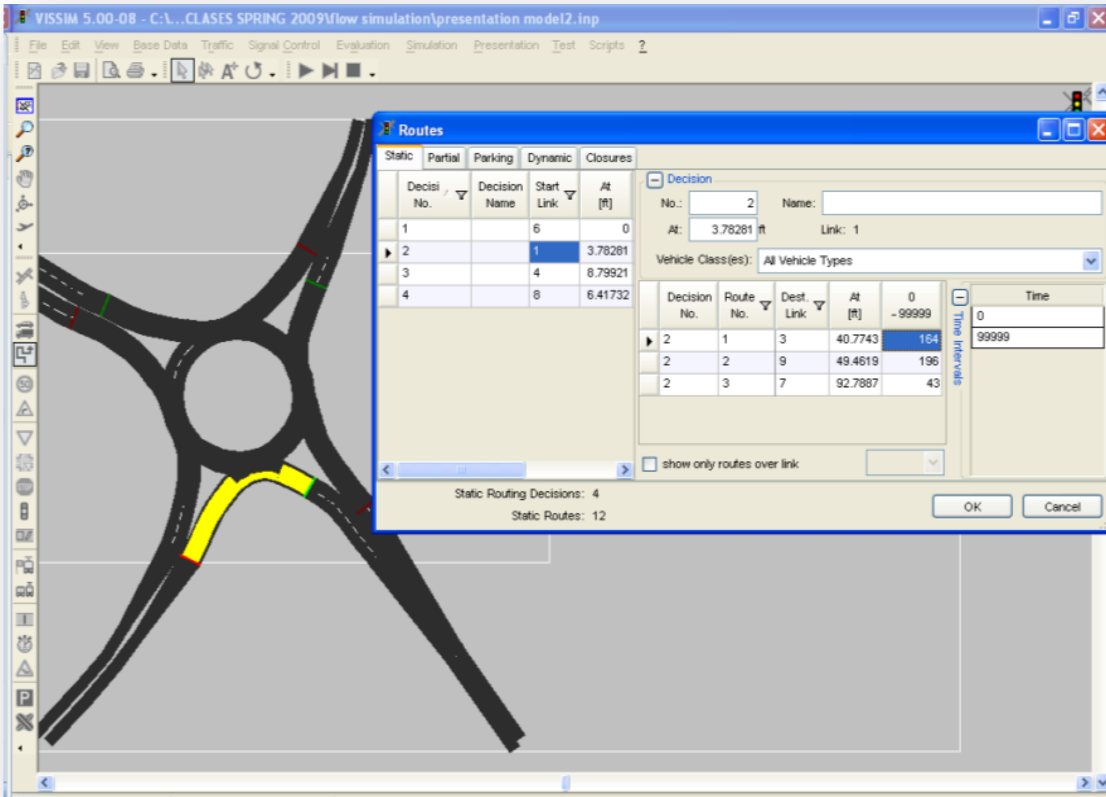

Figure 4.5: Routing Decisions for a Roundabout Model in VISSIM

Travel time sections were inputted for each through movement of each approach of the roundabout. This enabled the comparison of travel times observed in the video recording to that provided by the VISSIM model. It was important to replicate travel time sections as close as possible to the manner the travel time were measured from the video recordings. Therefore, the travel time sections were closely measured to match the locations where the vehicles' entered the screen and the rear bumper was visible. **Figure 4.6** demonstrates the travel time sections as coded in VISSIM with the red marker as the beginning of the travel time section and the green marker as the end of the section. Conflict areas are a feature of VISSIM 5.20, where two links or connectors in a network overlap and the user selects which conflicting link has the right of way

(PTV, 2009). In the case of the roundabout, the circulating roadway has the right of way, i.e., the entering flow yield to the circulating flow. The conflict areas are shown in Figure 4.6 and are depicted as the yellow polygons. The conflict areas model gap acceptance behavior of vehicles as they enter the roundabout. Modifications may be made to the conflict area parameters that allow the different of gap acceptances of vehicles.

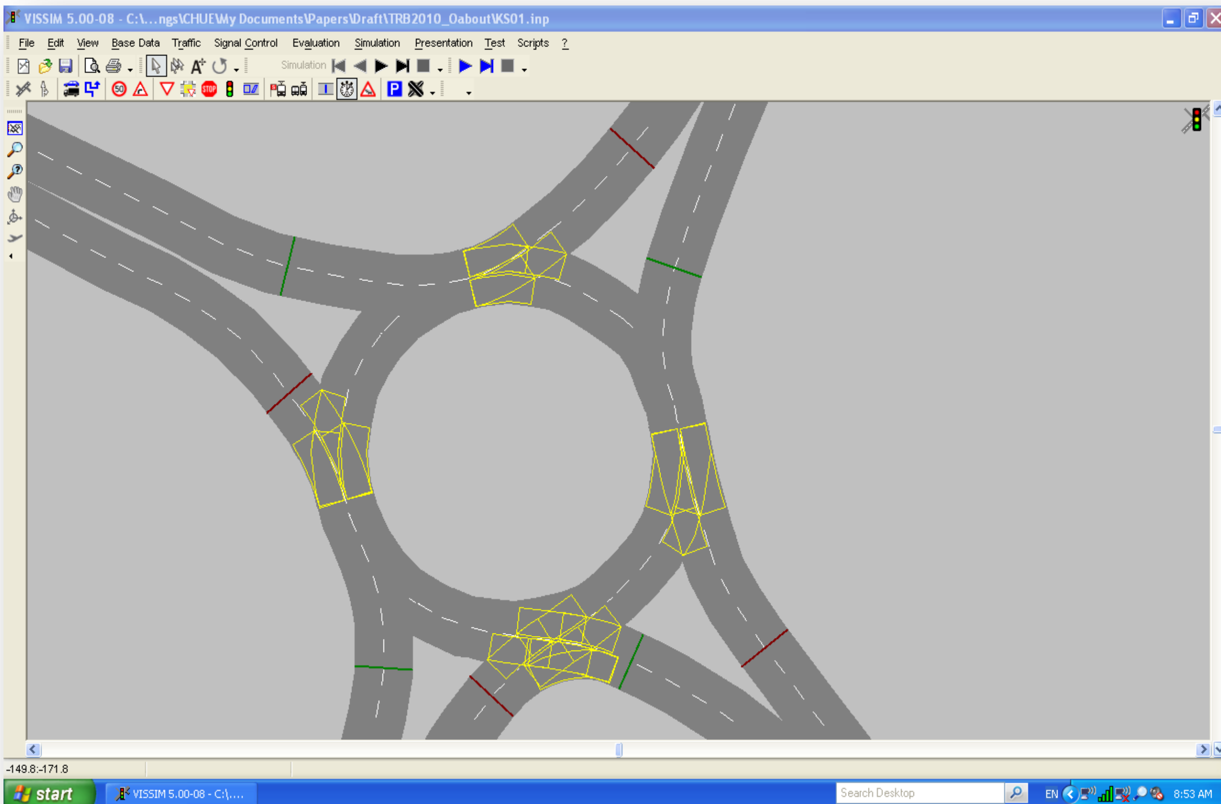

Figure 4.6: Coded Roundabout Parameters in VISSIM

The speeds that vehicles traveled in the roundabout varied due to geometric design of the intersection. Vehicles traveling along the circulatory roadway had lower traveling speeds

compared to the speeds of the vehicles approaching the intersection. Therefore, the network was coded by having reduced speed areas in the circulatory roadway. Since the traveling speeds of the vehicles in the video recording were easily measureable, the speed distribution was calculated in an indirect manner. From the observed travel time, the space-mean speed was plotted for each approach's through movement and circulatory roadway. It was noted that the space-mean speed follow a normal distribution having approximately same mean values. The speed limit for the overall network ranged from 15.5mph to 18.6 mph and the reduced speed areas had a lower speed limit range of 12.4 mph to 15.5 mph. VISSIM automatically accounts for acceleration and deceleration as the vehicles approach and leave the intersection. **Figure 4.7** demonstrates the reduced speed areas for the roundabout model depicted in the orange polygons.

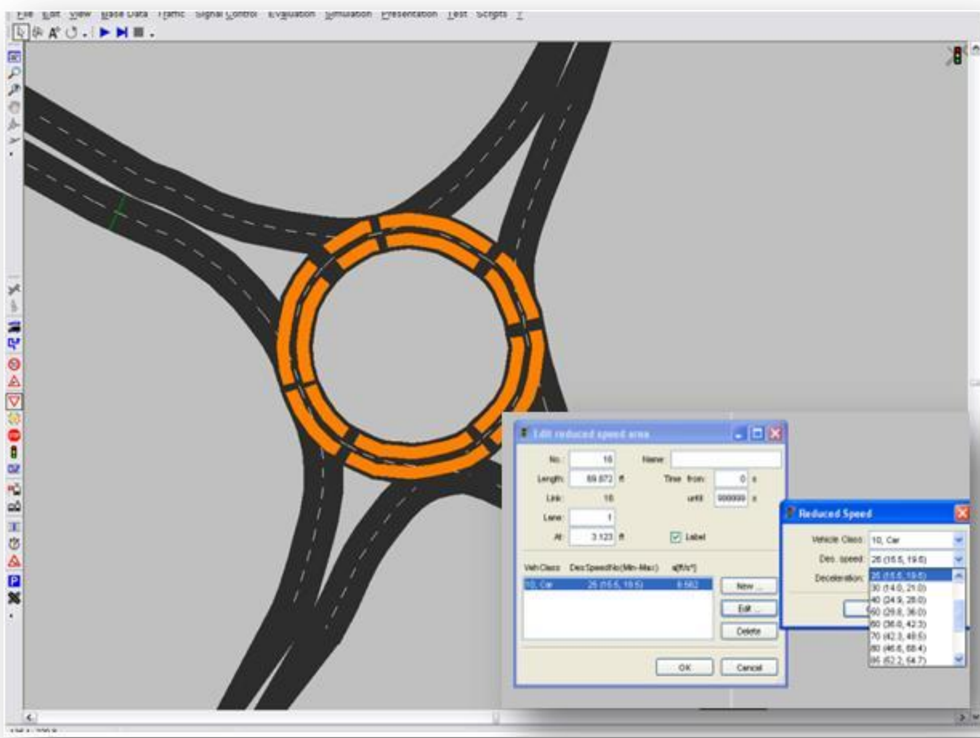

Figure 4.7: Reduced Speed Areas for a Roundabout in VISSIM

The simulation time was set to one hour at 10 time steps per simulation second. The model did not allow users to have a warm up period in a simulation run prior to data collection. Since the network only included one roundabout intersection, the vehicles started to fill up the network seconds after the simulation had initiated. Once the roundabout model was coded, the calibration process was initiated.

4.4. Kolmogorov-Smirnov Test

The calibration and validation of the roundabout model was an iterative process where the roundabout parameters were modified until the observed travel time distributions from the video recording were similar to that of the simulation results. The Kolmogorov-Smirnov (K-S) test, which compares the experimental (or observed) cumulative probability distribution with an assumed theoretical cumulative probability distribution, was used to determine the goodness of fit of the VISSIM's travel time outputs (Ang, et al., 2007). The K-S test is a widely used goodness-of-fit test that quantifies the maximum discrepancy, D_n, of the cumulative distribution functions between the sample and theoretical probabilities. **Figure 4.8** demonstrates the K-S test graphically, where D_n, experimental cumulative probability function ($S_n(x)$) and the assumed theoretical cumulative probability function ($F_x(x)$) are shown. In plotting S_n(x), is where the experimental data is rearranged in increasing order of *x* and *Equation [4.1]* is used to develop the experimental cumulative probability function.

–

[4.1]

where

is the experimental cumulative probability;

n is the sample size;

k is the interval of observation; and

x_n is the observed values of the ordered set of data.

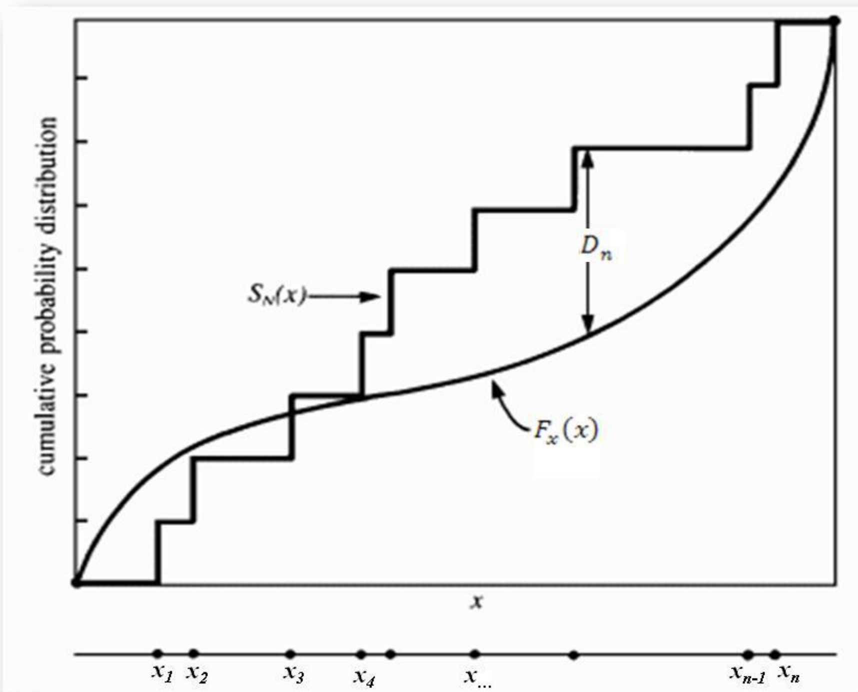

Figure 4.8: K-S Test Features

The formula for the K-S test is denoted in *Equation [4.2]*. The procedure is to test the null hypothesis that the theoretical cumulative distribution function is equivalent to the observed cumulative distribution. If such discrepancy is greater than the normally expected for a given sample size, *n*, the theoretical distribution is not representative of the sample population and is therefore rejected. However, if the maximum discrepancy is less than the critical value (a

prescribed significance level accordingly to the sample size *n*), the theoretical distribution is not rejected. **Table 4.5** demonstrates the critical values for the K-S Test under different significance levels and sample sizes. If the sample size is greater than 50, there are formulas to calculate the critical values as seen in the table.

[4.2]

Table 4.5: Test Critical Values of K-S Test with Significance Level α

Sample Size	**Significance Level**			
	α = 0.20	**α = 0.10**	**α = 0.05**	**α = 0.01**
5	0.45	0.51	0.56	0.67
10	0.32	0.37	0.41	0.49
15	0.27	0.30	0.34	0.40
20	0.23	0.26	0.29	0.36
25	0.21	0.24	0.27	0.32
30	0.19	0.22	0.24	0.29
35	0.18	0.20	0.23	0.27
40	0.17	0.19	0.21	0.25
45	0.16	0.18	0.20	0.24
50	0.15	0.17	0.19	0.23
>50	——	——	——	——

4.5. Parameter Calibration

After setting up the roundabout model, the following procedure was used to calibrate the model's parameters. One of the standard modeling procedures involves calibrating and validating simulation models to replicate existing conditions. Performance measures, such as travel time, delay and queue, are preferred for the calibration and validation process (FHWA, 2003).

However, due to lack of data on delay and queue, the roundabout model was calibrated and validated with travel time data.

According to the model set up, conflict area parameters influenced the simulation results (gap acceptance and hence the travel time). Therefore, they were modified to obtain similar travel times as observed in the video recording of the existing roundabout conditions. The four conflict area parameters that may be altered in VISSIM to influence travel time are visibility, front gap, rear gap and safety distance factor. The visibility is the maximum distance from where the approaching vehicle can see vehicles on the circulating link of the roundabout (PTV, 2009). As there is no visual obstruction in the area where the roundabout of interest is located, the default parameter of 100 m (328 ft) was used.

Several simulation runs were performed to determine the relative sensibility of the other three conflict area parameters to the vehicle’s travel time in a preliminary experiment. During this preliminary experiment, one parameter’s value was increased and decreased while the rest of the parameters remained at their default values. The safety distance factor had the most significant effect onto travel time while the front and rear gaps had relatively smaller effects. According the VISSIM 5.20 User’s Manual, the safety distance factor is the value that is multiplied with the normal desired safety distance of a vehicle on the main road to determine the minimum headway that a vehicle from the minor road must provide at the moment when it is completely inside the merging conflict area (PTV, 2009). Front and rear gap parameters were also altered. The front gap refers to the minimum gap between the rear end of the vehicle in the circulating roadway and the front end of the vehicle at the roundabout approach. The rear gap is the minimum gap between the rear end of the vehicle at the roundabout approach and the front end of the vehicle in the circulating roadway. Both the front gap and rear gap are in second and

have a default value of 0.5 seconds while the default safety distance factor is 1.5 and is unit less. The front and rear gaps are only for crossing conflict, in other words when the outer lane of the circulating roadway merges into the inner lane; therefore they do not have as a great impact on travel time as the safety distance factor.

4.2.1. Calibration Results

The calibration process was performed iteratively until the travel time parameters passed the K-S test. Recall that the travel time was collected for through movements from each approach. The sample size *n* of each movement was necessary to determine the critical value (refer to Table 4.5) **Table 4.6** shows the necessary critical values and the maximum discrepancy, D_n, for the calibration process.

Table 4.6: Calibration Critical Values for Roundabout Approaches

Approach	Number of Observations	Critical Value	D_n
Southbound	69	0.16	0.16
Eastbound	135	0.12	0.11
Westbound	108	0.13	0.13
Northbound	54	0.19	0.18

As described in the procedure of K-S test, it was necessary to arrange the travel time data in increasing order and determine the frequency in which the travel time occurred. This was performed for each movement individually. The maximum discrepancy between the cumulative distribution constructed from the VISSIM output data and the cumulative distribution constructed from the video recording data were then compared to that of the critical value.

Each approach was analyzed separately and modifications to the gap acceptance parameters were performed until the K-S test did not reject the null hypothesis (that the two distributions are equivalent). **Figure 4.9** is an example of the calibration travel time results for the westbound approach, where travel time distributions for the data collected in the video recording, before and after calibration are shown. The graphs for the other three approaches are shown in the Appendix A of the thesis.

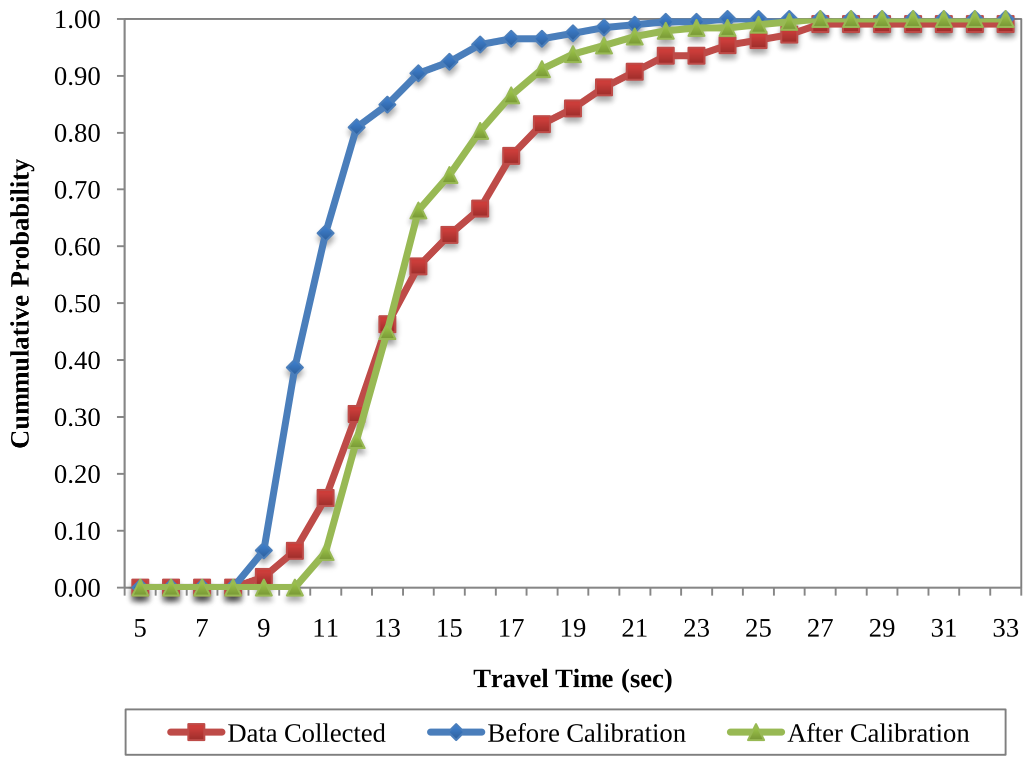

Figure 4.9: Calibration Results for Westbound Approach

4.6. Parameter Validation

Once the calibrated model passed the K-S test it was necessary to validate the selected conflict are parameters. In this validation, a new simulation scenario was coded with the calibrated parameter values and the simulation results should replicate the observed travel time distributions. The volume data set collected for the morning peak hour for the same roundabout was coded into the calibrated model and simulated to ensure that the travel time results passed the K-S test. The number of travel time observations *n* varied for each approach and therefore the critical value for each approach varied and is depicted in **Table 4.7**. Similar to the calibration, the travel time data collected from the simulation model and the video recording was arranged in increasing order and used to construct the cumulative probability distribution. The cumulative distributions obtained from the two methods were then compared to obtain the maximum discrepancy. The maximum discrepancy for each approach was then compared to the critical value seen in Table 8.

Table 4.7: Validation Critical Values for Roundabout Approach

Approach	Number of Observations	Critical Value	D_n
Southbound	43	0.21	0.21
Eastbound	47	0.19	0.19
Westbound	49	0.19	0.19
Northbound	61	0.17	0.09

Similar to calibration, each movement was analyzed separately when conducting the K-S test. **Figure 4.10** is an example of the validation travel time results for the westbound approach,

where travel time for the data collected in the video recording and VISSIM output with the calibrated parameters are shown. The graphs for the other three approaches may be seen in Appendix A of the thesis.

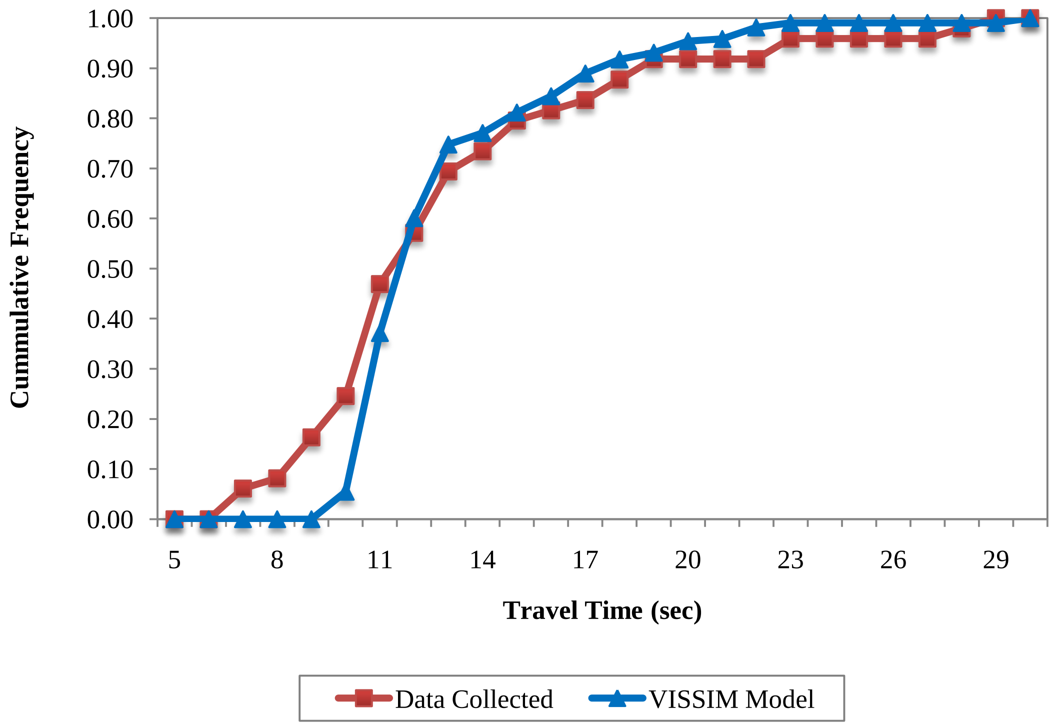

Figure 4.10: Validation Results for Westbound Approach

Chapter 5: Simulation Scenarios

The research analyzed ACD and LOS for three unbalanced scenarios under different volume combinations for a typical four-leg, two-lane roundabout. This chapter describes the scenarios in further detail such as roundabout geometry as well as input parameters for the simulated scenarios. Each scenario highlights the effect of unbalanced volumes in one or two approaches.

5.1. Roundabout Scenarios

The roundabout models were coded in VISSIM 5.20. All four approaches of the roundabout have two lanes, including the circulatory roadway. There is no right-turn bypass lane. The inscribed diameter of the roundabout was designed to be 165 ft, which clearly is between the 150 ft to 180 ft range of a modern roundabout. The lanes approaching the roundabout were set to be 600 ft, which permits a maximum queue of 24 vehicles.

The roundabout was coded to have several routing decisions. **Figure 5.1** demonstrates the routing decisions as coded in VISSIM 5.20 for the NB approach. The vehicles entering the roundabout using the left entry lane of each approach were coded to travel in the inner circulatory lane and were allowed to make left-turn and through movements. Vehicles entering the roundabout using the right entry lane were coded to make right-turn movements and use the outer circulatory lane for through movements. This prevented lane changing behavior in the circulatory roadway and replicated driving behavior as observed in the video recordings of the roundabout in Olathe, Kansas.

For each approach the turning volumes (through, left-turn and right-turn volumes) were divided into percentages. The volume was distributed accordingly to 35% for through, 35% for left-turn and 30% for right-turn movements. These percentages were obtained from the NCHRP 572 Appendix J, which represents the average values found in the two-lane roundabouts (NCHRP, 2007). The left-turn vehicles were all assigned to the left entry lane of an approach, while the right-turn vehicles were assigned to the right entry lane of an approach. For the through movement the percentage was split into a 40% to 60%, a mid-range ratio. Therefore the input volume for each approach was split into 49% for the right lane and 51% for the left lane. Reference may be made to Figure 5.1.

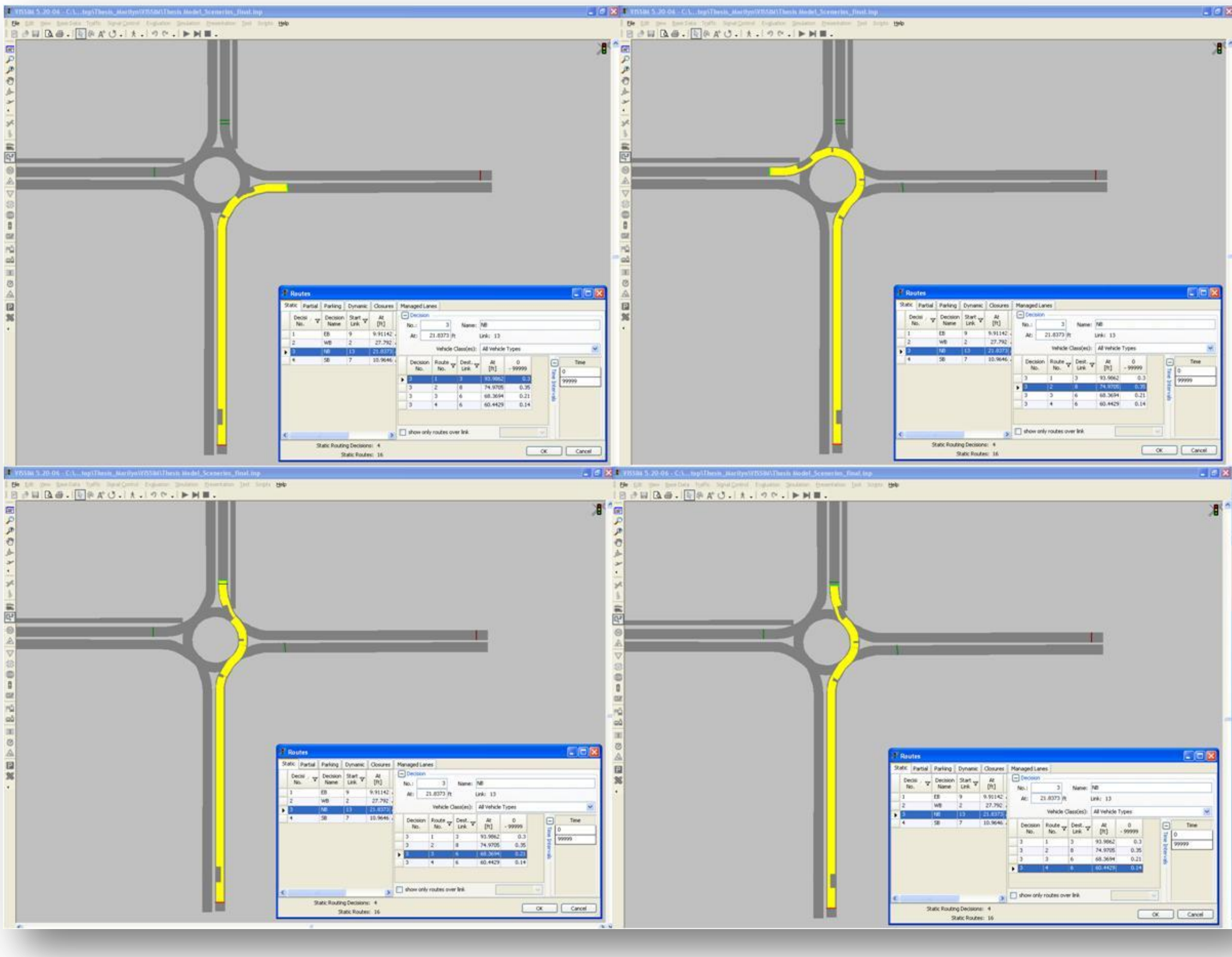

Figure 5.1: Routing Decisions for the Roundabout Model in VISSIM

The speed range of the roundabout was set to be between 15.5mph to 18.6 mph for the network and between 12.4 mph to 15.5 mph in the reduced speed limit areas. The vehicle composition of the roundabout was 100% passenger cars so that the results could be compared to the results calculated using the HCM2010 procedure. **Figure 5.2** demonstrates the roundabout model as coded in VISSIM 5.20. The green polygons depict the reduced speed areas and the dialog boxes demonstrate the vehicle composition and corresponding speed limit. The

roundabout model included markers at each approach which captured the control delay experienced by the vehicles in the model.

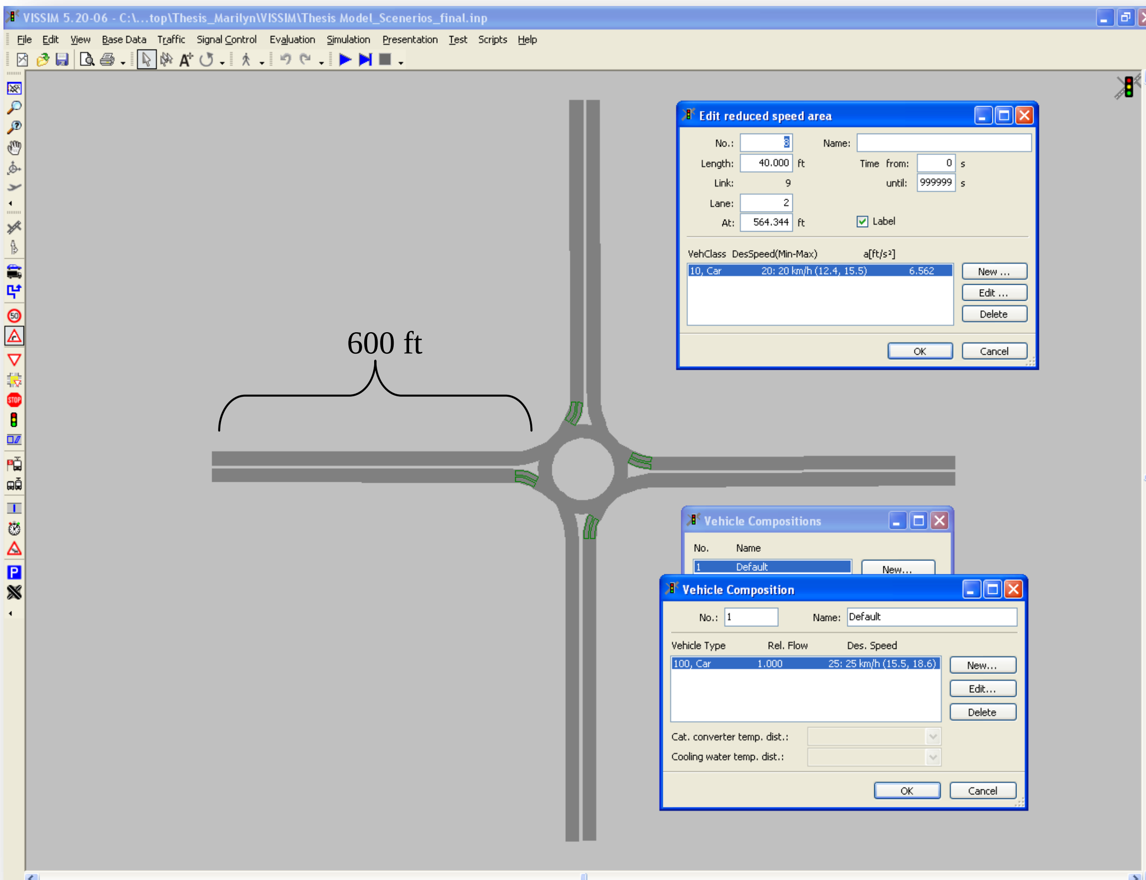

Figure 5.2: Vehicle Composition and Reduced Speed Areas Coded in VISSIM

The roundabout operational performance was analyzed in terms of ACD and LOS. Control delay at a roundabout includes the initial deceleration delay, queue move-up time and stopped delay and acceleration delay caused by the traffic control devices and right of way rules established (NCHRP, 2007). In VISSIM, two travel time detectors can provide the ACD encountered by the vehicles in the system as they passed the upstream and downstream detectors. The ACD may then be converted to LOS by using the Table 2.1 in the thesis as provided by

HCM. One pair of detectors was coded for each movement at each approach. **Figure 5.3** demonstrates the detectors to capture vehicles entering the roundabout from the WB approach that makes left-turn, through and right-turn movements. The detectors for the other approaches are also visible in the figure. The detectors were placed at 600 ft from the roundabouts entry lanes. The red marker detects vehicles as they enter the network and the green marker detects the same vehicles when they leave the network.

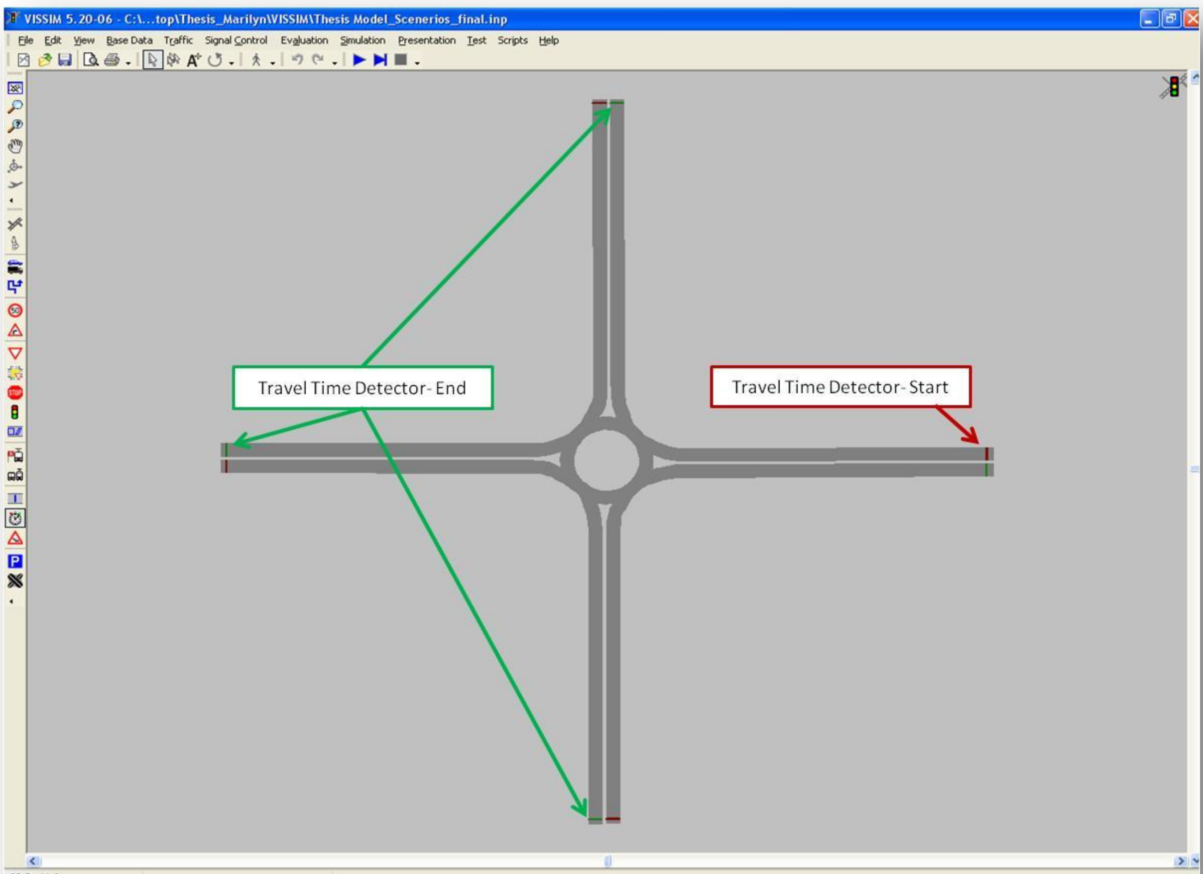

Figure 5.3: Travel Time detectors for the Roundabout Model in VISSIM

The three unbalanced scenarios were designed to reflect the relatively high or low input volumes on one or two approaches of the roundabout. In all the three unbalanced scenarios, the approach volumes are represented by hourly traffic volume of either volume 1, V_1, or volume 2, V_2. The volumes for V_1 and V_2 are in passenger cars per hour. Scenario A is designed to have V_1 for the NB approach, while the other approaches have volume of V_2. **Figure 5.4** demonstrates the approach volumes for Scenario A. The lane markings follow the standard markings for a roundabout as suggested in the MUTCD. The markings are for visualization purposes only and do not have an effect on vehicular behavior in the VISSIM simulations. Scenario B is where V_1 pertains to the NB and SB approaches, while EB and WB approaches have volume of V_2. **Figure 5.5** demonstrates the approach volumes for Scenario B. Scenario C is where the NB and WB approaches have volume V_1 and SB and EB approaches have volume V_2. **Figure 5.6** shows the approach volumes for Scenario C.

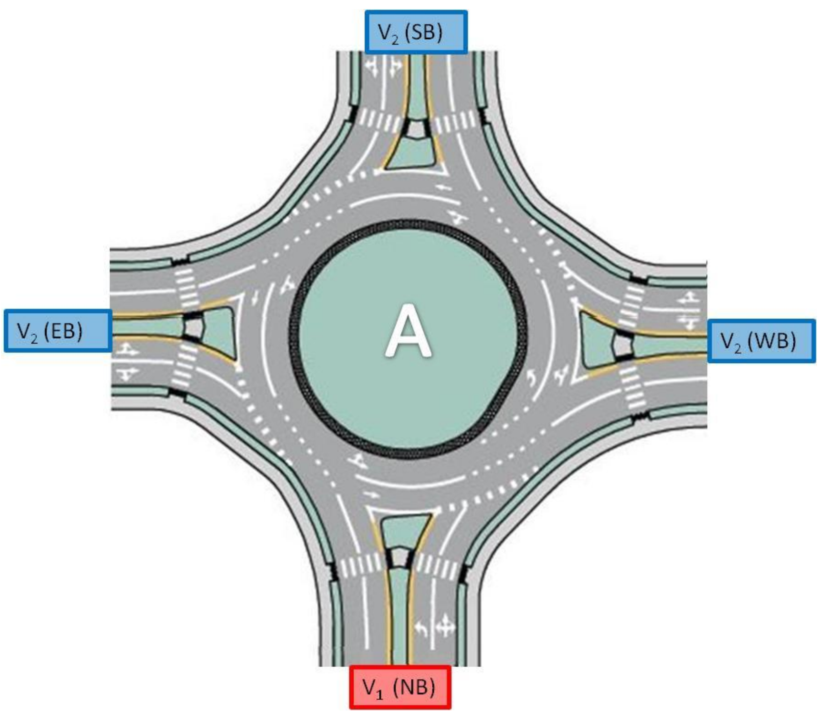

Figure 5.4: Unbalanced Approach Volume for Scenario A

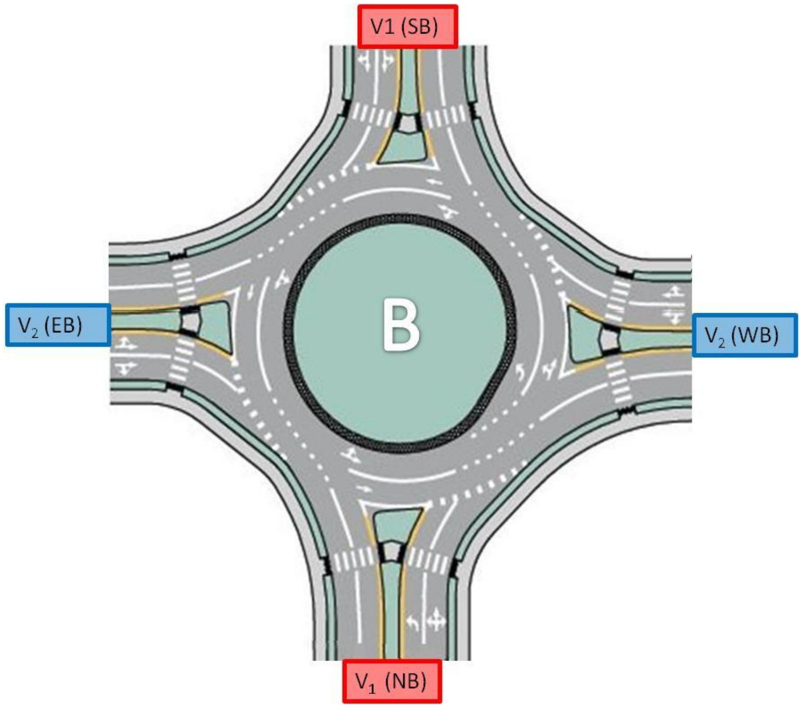

Figure 5.5: Unbalanced Approach Volume for Scenario B

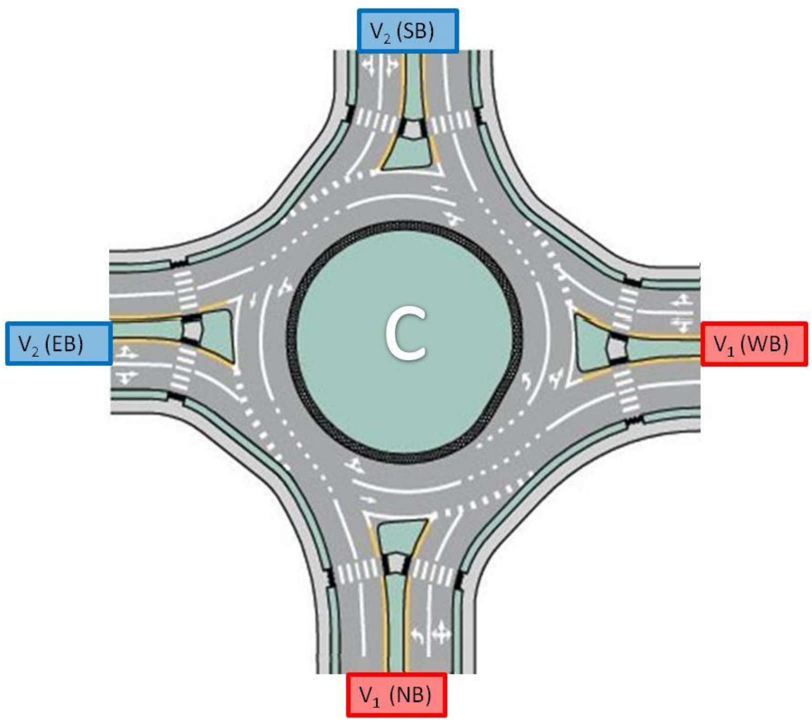

Figure 5.6: Unbalanced Approach Volume for Scenario C

5.2. Input Parameters

The conflict area parameters were the same as the calibrated and validated with the roundabout model from Olathe, Kansas. The input parameters for the gap acceptance features were 0.5 sec for the front gap, 1.5 sec for rear gap and 0.9 for the safety distance factor. The default value of 328 ft was used for visibility.

For each unbalanced scenario, the analysis included running simulations under various values for V_1 and V_2. The volumes ranged from 400 pc/h to 1600 pc/h, at increments of 100 pc/h. With the three unbalanced scenarios, each with 13 possible V_1 values and 13 possible V_2 values, the total number of volume combinations was 507. For each volume combination, the simulations were repeated for 10 times, each with a random number seed. Therefore a total of 5070 VISSIM simulation runs were performed for the analysis. The simulation was conducted for one hour at a time step of 0.1 second. **Table 5.1** demonstrates an example of one of the simulation cases where each approaches' ACD obtained from the 10 simulation replicates were averaged. The full results are presented in Chapter 6.

Table 5.1: Average Control Delay of a Simulation Case (Scenario A,V1 and V2=400)

		V_1=400pc/h										
		Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10	Average
V_2=400 pc/h	NB	1.7	2.1	2.2	2.3	2.4	2.3	2.3	2.0	2.1	2.0	2.1
	WB	1.6	1.7	2.0	1.9	1.9	2.3	1.6	2.1	1.8	1.8	1.9
	SB	2.2	2.0	2.3	2.0	1.4	2.0	2.2	2.2	1.7	1.7	2.0
	EB	2.0	2.0	1.9	1.8	1.5	2.2	1.8	2.1	2.0	1.5	1.9
	Average	1.9	2.0	2.1	2.0	1.8	2.2	2.0	2.1	1.9	1.8	2.0

Chapter 6: Simulation Results

In this chapter, the simulation results for the different unbalanced scenarios are first presented separately. The three unbalanced scenarios produced different effects on the roundabouts operations. The results are presented in chart format where the ACD and LOS are shown under different volume combinations of V_1 and V_2. Each column in the chart represents a V_1 value, while each horizontal block in the chart represents a V_2 value. Moreover, under each V_2 value the four approach delays are listed in separate rows. The details of the results for each scenario are explained in the following sections.

6.1. Scenario A- VISSIM Results

Scenario A is where the NB approach of the roundabout has input volume V_1 while the other three approaches (SB, EB and WB) have input volumes V_2, (see Figure 5.4). The results obtained from VISSIM are demonstrated in **Figure 6.1** where the ACD (seconds per passenger car) and LOS are portrayed in a color coded range. Each color corresponds to a LOS as specified by HCM2010 (see Table 2.1).

In the instances where V_1 is equal to V_2, the ACD is displayed in the diagonal blocks of the chart. As both volume input increases and V_1 is equal to V_2, the ACD increases and the LOS in the roundabout worsens. The ACD increases drastically and almost doubled when the input values were increased from 800 pc/h to 900pc/h and then again to 1000 pc/h. The LOS dropped from B to a D within the 200 pc/h span. This reflects that the once the capacity (approximately 1000 pc/h per approach, after taking into account the conflict flow) is reached the performance measures (ACD and LOS) becomes worse. The same observation occurs for the other two unbalanced scenarios as well.

The chart exhibits several patterns under different volume combinations. The roundabout has minimal delay and best LOS (A and B) when the volume inputs for both V_1 and V_2 are less than or equal to 800 pc/h. The section bounded by $V_1 \geq 900$ pc/h and $V_2 \leq 900$ pc/h, where V_1 is greater than V_2, occupies the upper right region on the chart. This section shows a greater delay for the WB approach due to the relatively high volume of vehicles that enter the intersection from the NB approach and make the through and left-turn movements. This consequently reduces the gap available for vehicles to enter the roundabout from the WB approach. In other words, the circulating flow is dominated by the high volume of traffic from the NB approach, which prevents vehicles from the WB approach to enter the roundabout. Under the same V_1 conditions, however where V_2 is between 1000 pc/h and 1600 pc/h (lower right section of the chart) the overall roundabout performance deteriorates to LOS of E or F, which is unsatisfactory. This signifies that when one approach has a significantly higher volume than three other approaches, it affects the delay on the approach to the right.

For the combinations where V_1 is less than V_2, the effects are different than previously mentioned. The region where $V_1 \leq 1000$ pc/h and $V_2 \geq 1000$ pc/h (bottom left section of the chart) the NB approach has a lower volume input and therefore has a lower ACD than the other approaches. Since there are few vehicles entering the roundabout from the NB approach, vehicles from the WB approach have gaps to enter the roundabout. Consequently, this produces a lower delay and better LOS compared to that of the SB and EB approaches. The chart also demonstrates that for the most part, SB and EB have LOS F due to the increasingly high input volumes.

SCENARIO A VISSIM Ave. control delay (s/pc)			V1 (pc/h)												
			400	500	600	700	800	900	1000	1100	1200	1300	1400	1500	1600
V2 (pc/h)	400	NB	2.0	2.3	2.6	2.8	3.2	3.6	3.9	4.2	4.9	5.3	6.1	6.8	7.6
		WB		2.4	2.7	3.2	4.0	4.7	5.4	6.4	7.6	8.8	9.6	11.6	14.6
		SB		2.1	2.3	2.5	2.6	2.5	2.8	2.9	2.8	3.3	3.4	3.7	3.9
		EB		1.8	1.9	1.9	2.0	2.0	2.1	2.1	2.1	2.2	2.2	2.1	2.2
	500	NB	2.7	2.9	3.4	3.6	4.2	4.7	5.4	5.9	6.8	8.2	9.4	10.9	12.4
		WB	2.3		3.4	4.1	4.9	5.9	6.9	7.8	9.9	12.2	13.4	18.6	24.5
		SB	2.6		2.9	3.2	3.2	3.4	4.0	4.0	3.9	4.3	4.5	4.8	4.8
		EB	2.9		2.9	2.8	3.1	3.0	3.0	3.1	3.0	3.0	3.0	2.9	3.0
	600	NB	3.3	3.7	4.1	4.8	5.6	6.2	7.4	8.9	10.4	12.6	15.3	17.9	20.6
		WB	2.7	3.5		5.0	6.3	7.1	9.0	11.4	14.4	16.9	22.1	28.7	34.6
		SB	3.5	3.5		4.1	4.5	4.7	4.9	5.2	5.4	6.0	6.0	6.4	6.4
		EB	4.1	4.3		4.4	4.1	4.2	4.2	4.3	4.5	4.2	4.3	4.3	4.3
	700	NB	4.3	4.7	5.5	6.4	7.2	8.7	11.8	14.6	16.5	22.8	25.8	27.4	32.1
		WB	3.5	4.3	5.3		8.4	9.9	13.8	17.3	27.3	31.5	44.5	58.9	56.5
		SB	4.9	5.1	5.5		6.3	7.0	7.1	7.7	7.8	8.7	8.7	8.4	8.7
		EB	6.5	6.9	6.7		6.7	6.8	7.2	7.1	6.6	6.5	6.5	6.2	6.3
	800	NB	5.2	5.8	7.0	9.4	11.7	14.7	20.3	26.8	31.5	36.4	39.3	41.6	41.9
		WB	4.4	5.6	7.2	9.5		15.7	21.9	35.6	38.7	48.7	50.0	57.4	60.6
		SB	7.3	8.0	8.3	9.2		11.4	11.5	12.2	13.1	11.8	11.6	10.8	11.2
		EB	11.9	12.5	13.2	13.1		12.8	12.7	10.9	12.3	11.2	11.7	11.1	10.6
	900	NB	6.5	7.9	9.4	12.2	18.3	24.1	34.9	42.5	45.3	46.3	48.8	49.0	49.3
		WB	5.6	7.2	9.5	12.9	18.1		36.0	42.7	48.9	55.2	56.5	61.8	66.9
		SB	9.5	10.8	12.7	13.7	16.7		18.1	18.0	17.1	17.3	16.5	14.5	15.6
		EB	29.3	30.0	24.4	26.6	26.3		25.2	25.0	23.7	22.8	22.1	21.0	19.3
	1000	NB	6.7	7.8	9.7	13.5	19.0	30.1	40.7	48.5	51.3	53.1	53.1	52.7	53.8
		WB	6.2	7.5	10.0	16.5	21.8	31.4		46.3	54.3	55.7	58.5	63.7	63.4
		SB	16.7	19.3	23.5	27.5	29.9	33.2		29.8	27.7	27.3	25.3	22.2	23.4
		EB	53.6	53.3	53.0	52.1	52.7	48.6		45.7	45.6	43.7	42.7	42.9	41.2
	1100	NB	6.7	8.2	10.4	12.9	22.6	30.2	43.4	49.6	53.5	56.5	54.7	54.7	53.7
		WB	6.1	7.7	11.3	18.3	25.7	39.0	47.0		53.4	54.2	58.1	60.4	61.3
		SB	30.3	34.3	39.2	42.1	44.9	47.4	45.4		38.7	37.1	36.7	36.6	34.6
		EB	66.4	64.4	62.8	60.6	59.8	57.7	55.6		56.3	55.8	56.2	55.2	57.0
	1200	NB	7.4	9.0	11.0	12.5	21.9	31.8	42.9	48.3	53.9	55.6	54.8	55.1	55.6
		WB	6.8	9.7	14.1	21.4	30.7	41.4	46.7	51.1		55.4	58.5	61.2	61.4
		SB	45.5	47.7	50.9	53.0	54.6	52.8	53.6	52.2		48.6	49.0	43.9	44.0
		EB	69.1	68.5	66.2	65.6	62.8	60.9	59.7	59.9		60.2	59.5	59.9	58.0
	1300	NB	7.2	8.5	9.9	12.7	19.0	31.1	45.5	50.2	54.8	56.4	56.0	55.2	56.1
		WB	7.8	11.1	15.6	26.1	35.4	44.1	48.9	52.3	54.0		57.2	59.9	62.1
		SB	51.8	54.4	57.0	59.6	58.5	57.8	56.3	53.9	53.6		50.5	50.8	49.1
		EB	70.7	68.0	67.8	64.0	63.5	61.3	60.6	60.3	60.2		60.5	61.4	60.7
	1400	NB	7.1	7.9	10.7	13.5	21.7	32.0	44.6	49.9	54.4	56.0	57.5	56.2	56.2
		WB	9.2	13.0	20.9	27.2	40.5	45.1	49.1	51.6	54.9	55.2		60.4	60.4
		SB	59.0	59.8	61.9	62.1	61.4	60.2	58.8	56.9	56.3	53.9		53.5	53.0
		EB	70.1	71.1	67.9	67.2	64.0	62.5	62.4	62.7	62.0	62.8		60.6	61.1
	1500	NB	6.7	8.2	9.7	13.7	21.5	35.2	43.6	51.5	54.5	56.1	55.4	58.3	56.0
		WB	10.8	17.4	23.4	32.7	40.8	45.8	49.2	51.4	53.5	55.7	56.8		60.0
		SB	63.5	64.6	64.4	65.6	63.4	61.9	60.7	59.6	59.1	57.8	56.5		54.2
		EB	70.4	69.5	68.5	65.1	63.8	62.7	62.1	61.9	61.1	61.1	63.0		63.5
	1600	NB	6.4	7.6	10.7	13.6	22.5	30.1	45.4	52.2	54.7	55.5	56.9	55.9	58.6
		WB	13.7	20.0	26.3	36.0	42.7	45.9	50.7	52.0	53.9	56.7	58.2	58.6	
		SB	68.1	69.1	68.8	66.5	65.4	64.0	61.5	61.2	58.5	58.0	56.7	57.0	
		EB	71.5	69.1	67.7	63.7	62.6	63.4	62.4	61.0	61.7	62.3	61.1	62.2	

NB	V1
WB	V2
SB	V2
EB	V2

LOS	A	B	C	D	E	F	
	<=10	>10-15	>15-25	>25-35	>35-50	>50	(sec/veh)

Figure 6.1: Scenario A- VISSIM Results

6.2. Scenario B -VISSIM Results

Scenario B is where the NB and SB approaches of the roundabout have input volume V_1 while the EB and WB approaches have input volume V_2, (see Figure 5.5). The results obtained from VISSIM are demonstrated in **Figure 6.2**.

Scenario B demonstrated some similar observations as seen in Scenario A. At the top left corner, where V_1 and V_2 are less than 800 pc/h, the ACD and LOS are in excellent ranges. The low input volumes, balanced or unbalanced between the approaches, have no negative effect on roundabout performance. At the bottom right corner of the chart (V_1 and $V_2 \geq$ 1000 pcph) the capacity appears to have exceeded and therefore the results show unsatisfactory conditions with LOS E or F.

There are differences in other sections of the chart to that observed in Scenario A. The top right section where V_1 is greater than V_2 ($V_1 \geq 1000$ pc/h and $V_2 \leq 700$ pc/h) the NB and SB approaches, which have volumes of V_1, have a notably higher ACD than the other approaches. However, when V_2 is increased from 700 pc/h to about 1000 pc/h the ACD for the WB and EB approaches (with V_2) increases and is higher than the other approaches. This is due to the higher number of vehicles trying to enter the roundabout through the EB and WB approaches. The NB and SB approaches are dominating the circulatory flow in the roundabout and therefore vehicles from the EB and WB approaches are not able to enter. In the case where V_2 is greater than V_1, the WB and EB approaches experience the worst delay. This again is due to the high number of vehicles entering the roundabout through these approaches.

SCENARIO B VISSIM Ave. control delay (s/pc)		V1 (pc/h) 400	500	600	700	800	900	1000	1100	1200	1300	1400	1500	1600
V2 (pc/h) 400	NB	2.0	2.5	2.9	3.5	4.5	5.8	6.6	7.8	12.7	15.7	22.0	25.7	30.1
	WB		2.5	3.0	3.4	4.2	4.6	5.5	6.4	7.6	8.5	9.2	10.2	11.4
	SB		2.2	2.7	3.2	4.0	4.6	5.8	7.7	10.3	13.6	17.4	23.0	25.6
	EB		2.5	2.9	3.7	4.2	5.1	5.9	6.9	8.3	9.8	11.0	12.8	14.2
500	NB	2.6	2.9	3.5	4.4	5.2	6.6	8.9	12.6	17.7	24.9	30.5	32.6	36.1
	WB	2.4		3.3	3.9	4.8	5.7	6.7	8.4	9.1	10.9	12.7	14.2	13.9
	SB	2.3		3.1	3.9	4.8	5.9	7.5	10.3	13.0	17.3	23.5	27.2	28.9
	EB	2.4		3.6	4.3	5.0	6.0	7.7	8.8	9.8	11.3	15.5	18.5	18.9
600	NB	2.9	3.5	4.1	5.0	6.2	8.8	12.6	18.3	25.3	33.0	37.4	40.1	40.6
	WB	2.9	3.4		5.2	6.7	7.4	9.0	11.2	13.5	14.8	17.4	15.7	19.6
	SB	2.7	3.2		4.8	6.1	7.6	10.3	13.8	17.9	24.1	28.2	30.6	34.7
	EB	3.0	3.6		5.1	6.5	8.0	9.4	12.7	16.1	19.1	23.9	29.8	32.5
700	NB	3.5	4.4	4.7	6.4	6.4	11.7	17.4	26.4	34.4	40.0	42.6	45.1	42.6
	WB	3.4	4.2	5.1		8.8	10.7	13.9	15.5	19.0	20.2	24.2	27.6	29.7
	SB	3.1	3.8	4.6		7.3	9.9	13.2	21.2	25.9	30.3	34.0	36.9	40.1
	EB	3.4	4.3	5.1		9.4	10.7	13.8	18.8	25.7	34.3	38.1	45.5	53.2
800	NB	4.1	5.2	6.2	8.1	11.7	17.1	11.7	37.5	41.6	45.4	45.3	46.1	45.5
	WB	4.5	6.1	7.3	10.1		15.9	21.1	24.5	32.6	33.3	39.7	46.1	55.3
	SB	3.8	4.7	5.3	6.7		12.9	18.8	28.6	33.2	36.8	39.7	41.6	41.9
	EB	4.4	5.2	7.5	9.1		17.2	23.4	29.4	42.0	54.9	56.9	60.3	64.0
900	NB	4.8	6.2	7.2	9.4	14.5	24.1	37.2	42.6	48.0	47.0	47.2	46.9	46.6
	WB	5.9	7.7	9.4	14.2	19.1		33.9	36.9	41.6	47.2	51.5	54.0	58.6
	SB	4.6	5.2	6.9	9.4	11.7		23.2	32.1	36.4	40.9	43.3	44.5	44.5
	EB	5.3	7.0	10.2	13.8	18.2		37.2	46.0	51.4	60.1	61.2	67.4	72.4
1000	NB	5.7	7.4	9.3	12.2	19.3	30.0	40.7	48.3	48.6	49.7	49.8	49.2	49.0
	WB	7.4	10.4	13.7	19.3	28.2	36.3		46.0	47.5	51.3	55.8	55.9	61.1
	SB	5.4	6.4	8.5	11.3	17.0	26.8		37.0	42.0	44.4	46.6	46.5	46.7
	EB	6.8	10.4	13.4	19.8	31.1	39.5		52.1	58.2	62.1	62.9	69.4	68.1
1100	NB	6.6	8.7	11.5	16.4	23.6	33.6	45.4	49.6	51.8	53.2	51.5	50.5	51.2
	WB	10.8	15.0	20.7	29.3	36.6	41.2	46.7		53.2	53.3	56.9	59.3	61.3
	SB	6.1	7.3	10.4	12.6	19.0	30.9	38.4		46.4	46.8	49.5	48.9	48.5
	EB	9.7	12.9	19.5	27.4	39.6	47.4	51.0		58.8	64.0	65.0	66.6	67.2
1200	NB	8.5	11.5	14.1	21.5	31.4	40.4	47.7	52.9	53.9	54.2	52.5	52.4	52.0
	WB	14.0	19.2	27.3	34.6	41.0	46.2	50.0	51.6		56.1	58.9	60.6	63.4
	SB	6.4	8.6	11.7	16.6	24.1	34.9	41.8	46.2		50.0	50.7	51.7	50.5
	EB	12.9	19.5	25.9	37.9	46.8	50.6	54.8	56.5		62.1	63.6	64.4	66.0
1300	NB	8.9	12.6	14.5	26.0	35.2	43.1	52.4	55.0	56.3	56.4	55.5	53.9	53.7
	WB	18.7	24.7	30.9	41.4	43.9	47.4	48.9	51.4	53.8		57.8	59.8	61.0
	SB	8.5	9.9	12.8	18.8	30.1	40.4	47.5	51.4	52.0		52.9	52.7	52.5
	EB	18.9	24.6	32.4	38.8	48.2	51.0	54.4	57.4	58.8		62.5	64.7	65.5
1400	NB	10.8	12.9	21.2	25.3	43.4	52.7	54.9	56.4	57.2	57.0	57.5	55.0	55.0
	WB	24.1	31.3	37.3	40.2	45.9	47.6	49.4	53.1	53.7	56.6		60.0	61.6
	SB	9.1	11.2	14.2	23.3	34.8	44.7	51.9	54.5	54.8	54.2		54.6	53.9
	EB	24.5	30.7	37.3	44.2	47.1	51.7	54.3	56.2	58.1	59.5		62.7	63.8
1500	NB	11.6	15.9	22.4	33.1	40.0	51.9	57.3	59.6	58.0	56.8	56.0	58.3	55.2
	WB	29.0	33.7	38.3	42.7	45.3	48.0	51.1	52.8	53.6	55.5	57.3		60.9
	SB	10.6	13.3	15.8	25.8	34.8	47.9	51.7	53.4	55.8	56.2	56.1		54.8
	EB	28.4	33.6	38.6	44.7	49.1	51.6	53.5	56.0	57.6	59.6	61.3		62.9
1600	NB	13.5	16.4	19.1	29.7	45.6	54.0	58.2	59.2	58.5	57.4	55.9	56.0	58.6
	WB	31.6	35.4	40.5	42.9	47.0	47.6	50.6	52.1	53.9	55.8	57.5	59.5	
	SB	11.8	15.2	18.5	32.4	37.5	51.9	54.4	55.8	58.0	57.1	56.2	54.6	
	EB	31.2	36.1	41.4	45.8	48.8	51.3	53.6	55.5	57.6	59.3	61.3	63.1	

NB	V1
WB	V2
SB	V1
EB	V2

LOS	A	B	C	D	E	F	
	<=10	>10-15	>15-25	>25-35	>35-50	>50	(sec/veh)

Figure 6.2: Scenario B- VISSIM Results

6.3. Scenario C- VISSIM Results

Scenario C is where the NB and WB approaches of the roundabout have input volume V_1 while the SB and EB approaches have input volume V_2, (see Figure 5.6). The results obtained from VISSIM are demonstrated in **Figure 6.3**.

Scenario C demonstrates similar patterns or operational characteristics as seen in the previous unbalanced scenarios. At the top left corner where V_1 and V_2 are less than 800 pc/h, the ACD and LOS are in excellent ranges. The low input volumes, with balanced or unbalanced volume between the approaches, produce low ACD and satisfactory LOS. The ACD and LOS at the bottom right corner of the chart (V_1 and $V_2 \geq$ 1000 pc/h when the capacity is exceeded) show unsatisfactory conditions.

Scenario C produces different results for the other sections of the chart compared to the previous two unbalanced scenarios. The top right section, where V_1 is greater than V_2 ($V_1 \geq$1000 pc/h and $V_2 \leq$900 pc/h), the WB approach experiences the highest delay and worst LOS. This is due to the excessive amounts of vehicles entering from the NB approach. Vehicles from the NB approach have gaps to enter the roundabout since the volume from the EB approach is relatively lower. Therefore the vehicles from the NB approach dominate the circulating flow in the roundabout, causing queues to form in the WB approach. The lower section on the left of the chart presents the condition where V_2 is greater than V_1. Under this condition, the EB approach resulted in higher ACD due to the lack of gaps in the circulating flow for vehicles in this approach to enter the roundabout. The high SB traffic volumes also caused this approach to experience high delays. The high volume of vehicles entering from the EB approach causes the NB approach (with V_1 volumes) to also have high delays when V_1 increases. These observations may be seen in **Figure 6.3**.

SCENARIO C VISSIM Ave. control delay (s/pc)			V1 (pc/h)												
			400	500	600	700	800	900	1000	1100	1200	1300	1400	1500	1600
V2 (pc/h)	400	NB	2.0	2.5	2.6	2.9	3.2	3.5	4.0	4.6	5.0	5.6	6.0	6.7	7.8
		WB		2.8	3.7	4.9	7.5	12.4	21.8	38.2	50.3	57.4	62.0	65.2	69.5
		SB		2.3	3.0	3.7	4.9	5.8	7.5	8.5	10.4	9.0	10.0	11.3	10.3
		EB		2.2	2.4	2.5	2.7	2.8	3.1	3.0	3.1	2.8	2.7	2.6	2.5
	500	NB	2.6	2.9	3.3	3.8	4.1	4.8	5.5	6.0	6.5	8.1	8.5	11.4	12.9
		WB	2.2		4.0	5.2	8.2	13.6	24.8	40.2	54.0	60.7	63.9	68.2	71.7
		SB	2.1		3.3	4.1	5.4	7.0	9.1	11.2	11.6	12.5	15.8	14.2	12.9
		EB	2.7		3.0	3.5	3.6	3.8	3.9	3.9	3.8	3.6	3.3	3.4	3.4
	600	NB	3.2	3.6	4.1	4.7	5.8	6.6	7.4	8.8	11.4	12.5	15.5	18.1	20.8
		WB	2.2	3.4		5.8	9.1	16.5	32.4	48.0	58.0	62.3	65.4	67.9	71.1
		SB	2.4	3.0		4.8	6.3	7.8	11.5	12.1	15.1	14.1	16.9	16.3	14.4
		EB	3.7	4.0		4.5	5.0	5.1	5.7	5.4	5.5	5.1	4.8	4.8	4.5
	700	NB	4.1	4.7	5.2	6.4	7.7	9.7	11.1	14.3	16.2	22.2	25.4	29.1	31.8
		WB	2.5	3.3	4.7		10.4	19.9	35.9	49.9	60.1	62.7	66.2	69.5	72.2
		SB	2.7	3.4	4.4		7.9	11.2	14.6	17.5	18.8	21.5	21.1	19.0	22.8
		EB	5.1	5.6	5.9		7.6	7.5	8.3	7.9	7.3	6.8	6.7	6.2	6.6
	800	NB	5.2	6.2	6.4	8.8	11.7	15.3	19.9	24.3	31.0	36.0	37.4	39.9	41.9
		WB	2.8	3.4	5.0	7.1		22.1	43.9	55.0	61.6	64.4	64.4	67.0	69.2
		SB	3.0	3.9	5.2	6.9		15.1	20.6	24.6	22.7	25.1	30.3	29.5	25.0
		EB	7.9	8.5	9.7	10.7		13.7	14.7	12.4	11.3	11.0	11.4	10.1	11.0
	900	NB	7.0	8.1	9.1	12.0	16.6	24.1	29.2	42.3	43.3	47.9	48.1	47.9	48.2
		WB	2.8	3.9	5.4	7.4	13.6		43.2	53.6	59.7	62.0	63.0	65.9	66.5
		SB	3.4	4.3	5.7	8.0	12.0		26.9	29.2	30.5	31.5	34.5	31.6	31.5
		EB	12.6	13.3	15.4	19.6	25.1		27.2	24.9	24.9	23.7	20.3	18.9	19.4
	1000	NB	7.6	10.4	12.3	17.7	25.7	30.6	40.7	50.4	52.9	53.2	52.9	53.0	52.2
		WB	3.0	4.1	5.4	7.6	13.2	25.1		53.2	57.6	59.8	61.4	63.0	65.6
		SB	3.9	4.8	6.9	9.9	15.2	23.4		38.0	38.5	39.9	42.9	42.5	39.8
		EB	24.8	27.6	35.6	39.5	45.4	48.5		41.6	40.4	41.4	38.6	37.0	37.0
	1100	NB	8.8	12.1	14.0	19.5	26.6	34.9	43.0	49.6	54.3	54.2	54.5	55.0	55.3
		WB	2.8	4.0	5.2	7.1	11.3	21.3	39.3		55.6	57.0	60.9	61.9	63.3
		SB	4.5	5.5	8.0	12.1		29.1	41.5		45.8	49.2	48.5	49.1	47.3
		EB	37.0	45.3	52.0	53.1	57.9	59.7	58.7		55.0	52.4	49.3	49.8	49.1
	1200	NB	11.0	12.6	15.4	20.9	30.5	38.8	44.5	52.9	53.9	54.8	55.1	54.5	56.5
		WB	3.0	3.7	5.2	6.7	12.0	19.0	33.5	48.7		57.0	58.4	61.2	62.3
		SB	4.9	6.4	9.9	14.5	23.7	34.6	45.1	47.5		50.5	52.8	52.7	49.5
		EB	53.4	57.6	60.3	63.0	64.9	65.3	63.0	61.0		57.1	57.3	55.1	55.6
	1300	NB	9.9	13.1	16.9	21.8	34.5	39.3	44.3	51.7	53.5	56.4	56.3	56.1	56.5
		WB	2.8	3.6	4.8	6.2	9.5	17.2	32.5	46.4	52.4		59.0	59.0	61.2
		SB	5.3	7.2	11.9	17.3	29.5	39.2	47.6	50.6	52.3		52.4	55.2	52.1
		EB	61.6	63.8	65.8	67.0	67.1	67.1	65.4	62.4	61.1		59.0	58.0	59.4
	1400	NB	10.2	13.5	18.8	19.1	32.9	38.1	47.2	51.0	53.2	54.9	57.5	55.5	55.8
		WB	2.6	3.3	4.7	6.0	10.6	16.2	32.1	46.6	51.4	55.7		59.3	61.4
		SB	5.9	8.7	12.8	22.9	34.6	42.2	49.4	52.2	52.8	53.8		55.4	54.1
		EB	66.2	68.4	70.4	71.4	69.0	68.2	66.2	64.1	65.3	63.4		61.2	61.3
	1500	NB	10.5	12.8	18.0	26.5	32.8	39.3	44.8	50.3	55.6	55.0	55.5	58.3	55.7
		WB	2.6	3.3	4.3	6.4	10.0	17.2	30.4	41.5	50.8	54.7	57.0		61.2
		SB	6.9	10.6	16.6	26.0	36.9	42.7	49.9	52.3	54.0	54.2	54.4		54.9
		EB	71.1	73.5	73.7	74.7	71.6	69.8	67.8	66.9	64.8	64.8	63.8		62.4
	1600	NB	10.8	14.5	16.1	22.2	28.3	37.5	41.7	51.0	53.3	54.7	55.4	56.1	58.6
		WB	2.6	3.3	4.1	5.9	9.1	17.7	28.0	42.9	52.1	55.3	56.8	59.1	
		SB	8.2	12.4	19.8	28.9	37.6	44.2	50.0	53.1	52.9	54.9	55.4	55.8	
		EB	76.2	76.8	77.8	75.4	75.3	71.5	69.8	67.5	66.9	64.4	63.3	62.7	

NB	V1
WB	V1
SB	V2
EB	V2

LOS	A	B	C	D	E	F	
	<=10	>10-15	>15-25	>25-35	>35-50	>50	(sec/veh)

Figure 6.3: Scenario C- VISSIM Results

Chapter 7: Comparison with HCM Procedure

The HCM2010 procedure to calculate the ACD for each approach of the roundabout was also performed so as to compare the mathematical solutions to that of the results obtained in Chapter 6. The same values inputted into the VISSIM model were used in the HCM2010 formulas (Equation [2.1] to [2.9]). The results for each of the three unbalanced scenarios are presented in the same chart format as previously seen in Chapter 6.

7.1. Average Control Delay

An observation for all the scenarios and volume combinations was that the ACD calculated with the HCM2010 procedure was higher than the ACD obtained from the VISSIM simulations. This means that the LOS of the roundabout approaches, if determined based on the HCM2010 procedure, is always the same or worse than the LOS that is based on simulation. Since the HCM2010 is or will be commonly used for roundabout design, it is practical for design engineers to overestimate delay which underestimate the capacity of the roundabout. This can be used as a design safety factor so that roundabout performance will operate at better conditions than designed for. A possible reason for the higher ACD calculated according to the HCM2010 procedure is that, the conflicting flow for an approach is taken as the sum of the volumes of all the movements that pass the entrance of a roundabout. The summation process does not take into account the capacity of the circulatory roadways, or the capacity of the entry lanes at other approaches. Without checking these capacity constraints, the conflicting flow in entry lane capacity equations [2.4 and 2.5] may be overestimated, causing the entry lane capacity to be under estimated. This increases the ACD according to [2.7]. Moreover, the ACD calculated using the HCM2010 procedure is the same for a stop-controlled intersection with the

modification in the second term that accounts for the yielding on entry rule for roundabouts (in Equation [2.7]). The original control delay formula automatically assumes that every vehicle comes to a complete stop before entering the roundabout, which may not always be the case if there is low volume circulating flow.

The results from the VISSIM simulation and the HCM2010 procedure were not expected to be identical since they were obtained through different methods. The HCM2010 calculations are a macroscopic, mathematical approach that may not take into account detailed vehicular behavior that is represented in the microscopic simulation. Moreover, the travel time sections of which the simulation method used to calculate the ACD may not be comparable to the ACD obtained using the HCM2010 procedure. It is difficult to determine if the travel time sections entered in the roundabout model were placed at the adequate position where it may capture the ACD similar to that as defined in the HCM2010 procedure. Since the approaches in the VISSIM model are 600 ft each, any queue that exceeds this length would cause the ACD to be under estimated by the VISSIM model. VISSIM calculates the ACD by subtracting the actual travel time from the ideal travel time. Delay includes the time lost due to deceleration, acceleration, yield (possibly stop) at the roundabout entrance and exit, and acceleration to the normal speed. The ideal travel time is where there is no queue that would cause delay and vehicles are traveling at the desired speeds under no traffic control.

Under heavily congested conditions, the queue exceeded the length of the link in the roundabout model in VISSIM. This caused underestimation of the ACD. However, the LOS will still be F since the ACD has exceeded 50 s/veh. Note that the unit of ACD is expressed in terms of s/veh to be consistent with HCM2010, although the unit of seconds per passenger car (s/pc) is more precise. Congested conditions also affect the results calculated using the HCM2010

procedure. According to Chapter 21 of HCM2010, “If demand exceeds capacity during a 15 min period, the delay results calculated by the procedure may not be accurate due to the likely presence of a queue at the start of the time period.” (HCM, 2010).

The following sections will describe the observations made from the results calculated using the HCM2010 procedure for each of the three unbalanced scenarios. Comparisons are made with the charts developed from the VISSIM simulation results.

7.2. Scenario A- HCM2010 Results

Scenario A is where the NB approach of the roundabout has input volume V_1 while the other three approaches (SB, EB and WB) have input volumes V_2. **Figure 7.1** demonstrates the results for ACD and LOS calculated for Scenario A using the HCM2010 procedure.

The results obtained from the HCM2010 procedure differ from the results obtained through the simulation. For the conditions where V_1 and V_2 are less than 800 pc/h (top left section of the charts) the ACD calculated with the HCM2010 procedure is significantly higher, resulting in LOS A to C, whereas the simulation results (Figure 6.1) show more cells covered by LOS A. The highest ACD in the simulation results is 13.2 sec/veh but it is 19.5 sec/veh according to the HCM2010 procedure. Regardless of the procedure used to calculate the ACD, the same LOS F is observed when both V_1 and V_2 exceed 1100pc/h (the bottom right section of the charts) as long as the ACD has exceeded 50s/veh.

The HCM2010 results show that the NB approach has the highest ACD and worst LOS for the section where V_1 is greater than V_2 (the top right section of the chart). The HCM2010 procedure accounts for the amount of volume coming from the NB approach and therefore has

the highest ACD. The chart also demonstrates that SB and EB have LOS F due to the increasingly high input volumes.

SCENARIO A HCM			V1 (pc/h)												
Ave. control delay (s/pc			400	500	600	700	800	900	1000	1100	1200	1300	1400	1500	1600
V2 (pc/h)	400	NB	6.9	7.7	8.5	9.5	10.7	12.0	13.6	15.7	18.3	21.9	26.9	34.3	44.9
		WB		7.3	7.8	8.4	9.0	9.6	10.3	11.1	11.9	12.9	13.9	15.1	16.4
		SB		7.1	7.3	7.6	7.8	8.1	8.4	8.7	9.0	9.3	9.6	9.9	10.3
		EB		6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9
	500	NB	7.6	8.5	9.5	10.8	12.2	13.9	16.1	19.0	23.0	28.7	37.1	49.4	65.9
		WB	7.9		9.1	9.8	10.6	11.4	12.4	13.4	14.6	15.9	17.5	19.2	21.2
		SB	8.2		8.8	9.1	9.5	9.8	10.2	10.6	11.0	11.4	11.9	12.4	12.9
		EB	8.5		8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5
	600	NB	8.4	9.5	10.7	12.2	14.1	16.4	19.5	23.8	30.0	39.4	53.2	71.7	94.3
		WB	9.2	9.9		11.6	12.7	13.8	15.1	16.6	18.4	20.4	22.9	25.8	29.3
		SB	9.9	10.3		11.2	11.6	12.1	12.7	13.2	13.8	14.4	15.1	15.8	16.6
		EB	10.7	10.7		10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7
	700	NB	9.3	10.6	12.1	14.0	16.4	19.6	24.1	30.8	40.9	56.0	76.3	101.2	129.2
		WB	10.8	11.7	12.8		15.4	17.1	19.1	21.4	24.3	27.7	32.0	37.4	44.2
		SB	12.2	12.8	13.4		14.7	15.4	16.2	17.1	18.1	19.1	20.2	21.4	22.8
		EB	14.0	14.0	14.0		14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0
	800	NB	10.3	11.9	13.8	16.2	19.5	24.1	30.9	41.5	57.5	79.4	106.4	136.8	169.4
		WB	12.8	14.1	15.6	17.4		22.1	25.3	29.3	34.4	40.9	49.2	59.7	72.6
		SB	15.6	16.4	17.4	18.4		20.7	22.1	23.6	25.3	27.2	29.3	31.7	34.4
		EB	19.5	19.5	19.5	19.5		19.5	19.5	19.5	19.5	19.5	19.5	19.5	19.5
	900	NB	11.5	13.4	15.8	19.1	23.6	30.4	41.1	57.6	80.8	109.6	142.5	177.7	214.3
		WB	15.5	17.4	19.6	22.4	25.9		36.2	43.7	53.3	65.4	80.2	97.8	118.0
		SB	21.0	22.4	24.1	25.9	28.0		33.1	36.2	39.7	43.7	48.2	53.3	59.1
		EB	30.4	30.4	30.4	30.4	30.4		30.4	30.4	30.4	30.4	30.4	30.4	30.4
	1000	NB	12.9	15.2	18.4	22.8	29.3	39.7	56.2	80.1	110.6	145.8	183.8	223.3	263.8
		WB	19.5	22.4	26.1	30.9	37.2	45.5		69.6	85.8	104.8	126.5	150.8	177.3
		SB	30.9	33.9	37.2	41.1	45.5	50.5		62.5	69.6	77.3	85.8	95.0	104.8
		EB	56.2	56.2	56.2	56.2	56.2	56.2		56.2	56.2	56.2	56.2	56.2	56.2
	1100	NB	14.5	17.5	21.6	27.7	37.4	53.3	77.3	109.1	146.5	187.2	229.7	273.4	317.7
		WB	25.8	30.8	37.4	46.2	57.6	71.9	89.1		131.8	157.0	184.4	213.9	245.6
		SB	51.6	57.6	64.4	71.9	80.1	89.1	98.7		120.1	131.8	144.1	157.0	170.4
		EB	109.1	109.1	109.1	109.1	109.1	109.1	109.1		109.1	109.1	109.1	109.1	109.1
	1200	NB	16.4	20.2	25.8	34.6	49.2	72.5	104.8	144.1	187.5	233.3	280.3	328.1	376.4
		WB	36.8	45.8	57.5	72.2	90.0	110.6	133.9	159.6		217.6	249.6	283.8	320.0
		SB	90.0	100.0	110.6	122.0	133.9	146.5	159.6	173.3		202.3	217.6	233.3	249.6
		EB	187.5	187.5	187.5	187.5	187.5	187.5	187.5	187.5		187.5	187.5	187.5	187.5
	1300	NB	18.6	23.6	31.3	44.2	65.8	97.8	138.3	184.4	233.3	283.9	335.4	387.5	440.0
		WB	56.0	70.8	88.8	109.6	133.1	159.1	187.2	217.4	249.6		320.3	358.7	399.4
		SB	145.8	159.1	172.8	187.2	202.0	217.4	233.3	249.6	266.5		301.8	320.3	339.2
		EB	283.9	283.9	283.9	283.9	283.9	283.9	283.9	283.9	283.9		283.9	283.9	283.9
	1400	NB	21.4	28.0	38.9	57.8	88.1	129.1	177.3	229.5	283.8	339.2	395.4	452.0	508.9
		WB	85.6	106.4	129.8	155.7	183.8	213.9	246.1	280.3	316.5	354.9		438.1	483.2
		SB	213.9	229.7	246.1	262.9	280.3	298.2	316.5	335.4	354.9	374.9		416.5	438.1
		EB	395.4	395.4	395.4	395.4	395.4	395.4	395.4	395.4	395.4	395.4		395.4	395.4
	1500	NB	24.7	33.7	49.4	76.4	116.4	166.0	221.2	279.3	338.9	399.4	460.4	521.8	583.4
		WB	124.3	149.9	177.7	207.6	239.5	273.4	309.4	347.4	387.5	429.9	474.6		571.4
		SB	291.1	309.4	328.1	347.4	367.2	387.5	408.5	429.9	452.0	474.6	497.9		546.3
		EB	521.8	521.8	521.8	521.8	521.8	521.8	521.8	521.8	521.8	521.8	521.8		521.8
	1600	NB	28.9	41.4	63.8	100.6	150.3	208.0	269.9	333.8	398.8	464.6	530.8	597.3	664.0
		WB	169.4	198.9	230.3	263.8	299.2	336.8	376.4	418.2	462.4	508.9	557.9	609.6	
		SB	376.4	397.0	418.2	440.0	462.4	485.3	508.9	533.1	557.9	583.4	609.6	636.4	
		EB	664.0	664.0	664.0	664.0	664.0	664.0	664.0	664.0	664.0	664.0	664.0	664.0	

NB	V1
WB	V2
SB	V2
EB	V2

LOS	A	B	C	D	E	F	
	<=10	>10-15	>15-25	>25-35	>35-50	>50	(s/pc)

Figure 7.1: Scenario A- HCM2010 Results

7.3. Scenario B- HCM2010 Results

Scenario B is where the NB and SB approaches of the roundabout have input volume V_1 while the EB and WB approaches have input volume V_2. The results obtained from VISSIM are demonstrated in Figure 6.2 while the results obtained from the HCM2010 procedure is shown in **Figure 7.2**.

The results for Scenario B obtained by the HCM2010 procedure produce similar patterns as that obtained from VISSIM simulations. At the top left corner, where V_1 and V_2 are less than 800 pc/h, the ACD and LOS are in acceptable ranges. The VISSIM results have two volume combinations that resulted in LOS B, whereas the HCM2010 results have a higher ACD and LOS of C was obtained. At the bottom right section of the chart (V_1 and $V_2 \geq$ 1000 pc/h) the approach capacity is exceeded and therefore the results show unsatisfactory conditions with LOS of F.

The top right section where V_1 is greater than V_2 ($V_1 \geq$1000 pc/h and $V_2 \leq$800 pc/h) the NB and SB approaches, which have input volume V_1 , have a notably higher ACD than the other approaches as seen with in the VISSIM results.

SCENARIO B	HCM		V_1 (pc/h)												
Ave. control delay (s/pc			400	500	600	700	800	900	1000	1100	1200	1300	1400	1500	1600
V2 (pc/h)	400	NB	6.9	7.9	9.2	10.8	12.8	15.5	19.5	25.8	36.8	56.0	85.6	124.3	169.4
		WB		7.3	7.8	8.4	9.0	9.6	10.3	11.1	11.9	12.9	13.9	15.1	16.4
		SB		7.9	9.2	10.8	12.8	15.5	19.5	25.8	36.8	56.0	85.6	124.3	169.4
		EB		7.3	7.8	8.4	9.0	9.6	10.3	11.1	11.9	12.9	13.9	15.1	16.4
	500	NB	7.3	8.5	9.9	11.7	14.1	17.4	22.4	30.8	45.8	70.8	106.4	149.9	198.9
		WB	7.9		9.1	9.8	10.6	11.4	12.4	13.4	14.6	15.9	17.5	19.2	21.2
		SB	7.3		9.9	11.7	14.1	17.4	22.4	30.8	45.8	70.8	106.4	149.9	198.9
		EB	7.9		9.1	9.8	10.6	11.4	12.4	13.4	14.6	15.9	17.5	19.2	21.2
	600	NB	7.8	9.1	10.7	12.8	15.6	19.6	26.1	37.4	57.5	88.8	129.8	177.7	230.3
		WB	9.2	9.9		11.6	12.7	13.8	15.1	16.6	18.4	20.4	22.9	25.8	29.3
		SB	7.8	9.1		12.8	15.6	19.6	26.1	37.4	57.5	88.8	129.8	177.7	230.3
		EB	9.2	9.9		11.6	12.7	13.8	15.1	16.6	18.4	20.4	22.9	25.8	29.3
	700	NB	8.4	9.8	11.6	14.0	17.4	22.4	30.9	46.2	72.2	109.6	155.7	207.6	263.8
		WB	10.8	11.7	12.8		15.4	17.1	19.1	21.4	24.3	27.7	32.0	37.4	44.2
		SB	8.4	9.8	11.6		17.4	22.4	30.9	46.2	72.2	109.6	155.7	207.6	263.8
		EB	10.8	11.7	12.8		15.4	17.1	19.1	21.4	24.3	27.7	32.0	37.4	44.2
	800	NB	9.0	10.6	12.7	15.4	19.5	25.9	37.2	57.6	90.0	133.1	183.8	239.5	299.2
		WB	12.8	14.1	15.6	17.4		22.1	25.3	29.3	34.4	40.9	49.2	59.7	72.6
		SB	9.0	10.6	12.7	15.4		25.9	37.2	57.6	90.0	133.1	183.8	239.5	299.2
		EB	12.8	14.1	15.6	17.4		22.1	25.3	29.3	34.4	40.9	49.2	59.7	72.6
	900	NB	9.6	11.4	13.8	17.1	22.1	30.4	45.5	71.9	110.6	159.1	213.9	273.4	336.8
		WB	15.5	17.4	19.6	22.4	26.9		36.2	43.7	53.3	65.4	80.2	97.8	118.0
		SB	9.6	11.4	13.8	17.1	22.1		45.5	71.9	110.6	159.1	213.9	273,4	336.8
		EB	15.5	17.4	19.6	22.4	25.9		36.2	43.7	53.3	65.4	80.2	97.8	118.0
	1000	NB	10.3	12.4	15.1	19.1	25.3	36.2	56.2	89.1	133.9	187.2	246.1	309.4	376.4
		WB	19.5	22.4	26.1	30.9	37.2	45.5		69.6	85.8	104.8	126.5	150.8	177.3
		SB	10.3	12.4	15.1	19.1	25.3	36.2		89.1	133.9	187.2	246.1	309.4	376.4
		EB	19.5	22.4	26.1	30.9	37.2	45.5		69.6	85.8	104.8	126.5	150.8	177.3
	1100	NB	11.1	13.4	16.6	21.4	29.3	43.7	69.6	109.1	159.6	217.4	280.3	347.4	418.2
		WB	25.8	30.8	37.4	46.2	57.6	71.9	89.1		131.8	157.0	184.4	213.9	245.6
		SB	11.1	13.4	16.6	21.4	29.3	43.7	69.6		159.6	217.4	280.3	347.4	418.2
		EB	25.8	30.8	37.4	46.2	57.6	71.9	89.1		131.8	157.0	184.4	213.9	245.6
	1200	NB	11.9	14.6	18.4	24.3	34.4	53.3	85.8	131.8	187.5	249.6	316.5	387.5	462.4
		WB	36.8	45.8	57.5	72.2	90.0	110.6	133.9	159.6		217.6	249.6	283.8	320.0
		SB	11.9	14.6	18.4	24.3	34.4	53.3	85.8	131.8		249.6	316.5	387.5	462.4
		EB	36.8	45.8	57.5	72.2	90.0	110.6	133.9	159.6		217.6	249.6	283.8	320.0
	1300	NB	12.9	15.9	20.4	27.7	40.9	65.4	104.8	157.0	217.6	283.9	354.9	429.9	508.9
		WB	56.0	70.8	88.8	109.6	133.1	159.1	187.2	217.4	249.6		320.3	358.7	399.4
		SB	12.9	15.9	20.4	27.7	40.9	65.4	104.8	157.0	217.6		354.9	429.9	508.9
		EB	56.0	70.8	88.8	109.6	133.1	159.1	187.2	217.4	249.6		320.3	358.7	399.4
	1400	NB	13.9	17.5	22.9	32.0	49.2	80.2	126.5	184.4	249.6	320.3	395.4	474.6	557.9
		WB	85.6	106.4	129.8	155.7	183.8	213.9	246.1	280.3	316.5	354.9		438.1	483.2
		SB	13.9	17.5	22.9	32.0	49.2	80.2	126.5	184.4	249.6	320.3		474.6	557.9
		EB	85.6	106.4	129.8	155.7	183.8	213.9	246.1	280.3	316.5	354.9		438.1	483.2
	1500	NB	15.1	19.2	25.8	37.4	59.7	97.8	150.8	213.9	283.8	358.7	438.1	521.8	609.6
		WB	124.3	149.9	177.7	207.6	239.5	273.4	309.4	347.4	387.5	429.9	474.6		571.4
		SB	15.1	19.2	25.8	37.4	59.7	97.8	150.8	213.9	283.8	358.7	438.1		609.6
		EB	124.3	149.9	177.7	207.6	239.5	273.4	309.4	347.4	387.5	429.9	474.6		571.4
	1600	NB	16.4	21.2	29.3	44.2	72.6	118.0	177.3	245.6	320.0	399.4	483.2	571.4	664.0
		WB	169.4	198.9	230.3	263.8	299.2	336.8	376.4	418.2	462.4	508.9	557.9	609.6	
		SB	16.4	21.2	29.3	44.2	72.6	118.0	177.3	245.6	320.0	399.4	483.2	571.4	
		EB	169.4	198.9	230.3	263.8	299.2	336.8	376.4	418.2	462.4	508.9	557.9	609.6	

NB	V1
WB	V2
SB	V1
EB	V2

LOS	A	B	C	D	E	F	
	<=10	>10-15	>15-25	>25-35	>35-50	>50	(s/pc)

Figure 7.2: Scenario B- HCM2010 Results

7.4. Scenario C- HCM2010 Results

Scenario C is where the NB and WB approaches of the roundabout have input volume V_1 while the SB and EB approaches have input volume V_2. The results obtained from the VISSIM simulations are demonstrated in Figure 6.3 while the results obtained from the HCM210 are shown in **Figure 7.3**.

Both Figures 6.3 and 7.3 exhibit the same patterns in the color codes that represent the LOS, with the exception that the ACD are significantly higher in Figure 7.3. For the low demand condition when both $V_1$and V_2 are less than 800 pc/h (the top left section of the chart), the LOS of the roundabout approaches range from A to C in Figure 7.3 whereas in Figure 6.3 all except two cell have LOS A. The highest ACD obtained from VISSIM simulations in this region is 11.7 sec/veh while the highest ACD obtained using the HCM2010 procedure is 19.5 sec/veh. In the case where both V_1 and V_2 are greater than 1000 pc/h, LOS of F was obtained from the HCM2010 procedure. On the other hand, the VISSIM simulation results show LOS of E and F.

When V_1 is greater than V_2 (the top right section of the chart), the ACD obtained from the simulations and HCM2010 procedure both resulted in higher ACD for the WB approach and lowest ACD for the EB approach.

SCENARIO C HCM Ave. control delay (s/pc)		V1 (pc/h) 400	500	600	700	800	900	1000	1100	1200	1300	1400	1500	1600
V2 (pc/h) 400	NB	6.9	7.7	8.5	9.5	10.7	12.0	13.6	15.7	18.3	21.9	26.9	34.3	44.9
	WB		8.2	9.9	12.2	15.6	21.0	30.9	51.6	90.0	145.8	213.9	291.1	376.4
	SB		7.6	8.4	9.3	10.3	11.5	12.9	14.5	16.4	18.6	21.4	24.7	28.9
	EB		7.1	7.3	7.6	7.8	8.1	8.4	8.7	9.0	9.3	9.6	9.9	10.3
500	NB	7.6	8.5	9.5	10.8	12.2	13.9	16.1	19.0	23.0	28.7	37.1	49.4	65.9
	WB	7.1		10.3	12.8	16.4	22.4	33.9	57.6	100.0	159.1	229.7	309.4	397.0
	SB	7.7		9.5	10.6	11.9	13.4	15.2	17.5	20.2	23.6	28.0	33.7	41.4
	EB	8.2		8.8	9.1	9.5	9.8	10.2	10.6	11.0	11.4	11.9	12.4	12.9
600	NB	8.4	9.5	10.7	12.2	14.1	16.4	19.5	23.8	30.0	39.4	53.2	71.7	94.3
	WB	7.3	8.8		13.4	17.4	24.1	37.2	64.4	110.6	172.8	246.1	328.1	418.2
	SB	8.5	9.5		12.1	13.8	15.8	18.4	21.6	25.8	31.3	38.9	49.4	63.8
	EB	9.9	10.3		11.2	11.6	12.1	12.7	13.2	13.8	14.4	15.1	15.8	16.6
700	NB	9.3	10.6	12.1	14.0	16.4	19.6	24.1	30.8	40.9	56.0	76.3	101.2	129.2
	WB	7.6	9.1	11.2		18.4	25.9	41.1	71.9	122.0	187.2	262.9	347.4	440.0
	SB	9.5	10.8	12.2		16.2	19.1	22.8	27.7	34.6	44.2	57.8	76.4	100.6
	EB	12.2	12.8	13.4		14.7	15.4	16.2	17.1	18.1	19.1	20.2	21.4	22.8
800	NB	10.3	11.9	13.8	16.2	19.5	24.1	30.9	41.5	57.5	79.4	106.4	136.8	169.4
	WB	7.8	9.5	11.6	14.7		28.0	45.5	80.1	133.9	202.0	280.3	367.2	462.4
	SB	10.7	12.2	14.1	16.4		23.6	29.3	37.4	49.2	65.8	88.1	116.4	150.3
	EB	15.6	16.4	17.4	18.4		20.7	22.1	23.6	25.3	27.2	29.3	31.7	34.4
900	NB	11.5	13.4	15.8	19.1	23.6	30.4	41.1	57.6	80.8	109.6	142.5	177.7	214.3
	WB	8.1	9.8	12.1	15.4	20.7		50.5	89.1	146.5	217.4	298.2	387.5	485.3
	SB	12.0	13.9	16.4	19.6	24.1		39.7	53.3	72.5	97.8	129.1	166.0	208.0
	EB	21.0	22.4	24.1	25.9	28.0		33.1	36.2	39.7	43.7	48.2	53.3	59.1
1000	NB	12.9	15.2	18.4	22.8	29.3	39.7	56.2	80.1	110.6	145.8	183.8	223.3	263.8
	WB	8.4	10.2	12.7	16.2	22.1	33.1		98.7	159.6	233.3	316.5	408.5	508.9
	SB	13.6	16.1	19.5	24.1	30.9	41.1		77.3	104.8	138.3	177.3	221.2	269.9
	EB	30.9	33.9	37.2	41.1	45.5	50.5		62.5	69.6	77.3	85.8	95.0	104.8
1100	NB	14.5	17.5	21.6	27.7	37.4	53.3	77.3	109.1	146.5	187.2	229.7	273.4	317.7
	WB	8.7	10.6	13.2	17.1	23.6	36.2	62.5		173.3	249.6	335.4	429.9	533.1
	SB	15.7	19.0	23.8	30.8	41.5	57.6	80.1		144.1	184.4	229.5	279.3	333.8
	EB	51.6	57.6	64.4	71.9	80.1	89.1	98.7		120.1	131.8	144.1	157.0	170.4
1200	NB	16.4	20.2	25.8	34.6	49.2	72.5	104.8	144.1	187.5	233.3	280.3	328.1	376.4
	WB	9.0	11.0	13.8	18.1	25.3	39.7	69.6	120.1		266.5	354.9	452.0	557.9
	SB	18.3	23.0	30.0	40.9	57.5	80.8	110.6	146.5		233.3	283.8	338.9	398.8
	EB	90.0	100.0	110.6	122.0	133.9	146.5	159.6	173.3		202.3	217.6	233.3	249.6
1300	NB	18.6	23.6	31.3	44.2	65.8	97.8	138.3	184.4	233.3	283.9	335.4	387.5	440.0
	WB	9.3	11.4	14.4	19.1	27.2	43.7	77.3	131.8	202.3		374.9	474.6	583.4
	SB	21.9	28.7	39.4	56.0	79.4	109.6	145.8	187.2	233.3		339.2	399.4	464.6
	EB	145.8	159.1	172.8	187.2	202.0	217.4	233.3	249.6	266.5		301.8	320.3	339.2
1400	NB	21.4	28.0	38.9	57.8	88.1	129.1	177.3	229.5	283.8	339.2	395.4	452.0	508.9
	WB	9.6	11.9	15.1	20.2	29.3	48.2	85.8	144.1	217.6	301.8		497.9	609.6
	SB	26.9	37.1	53.2	76.3	106.4	142.5	183.8	229.7	280.3	335.4		460.4	530.8
	EB	213.9	229.7	246.1	262.9	280.3	298.2	316.5	335.4	354.9	374.9		416.5	438.1
1500	NB	24.7	33.7	49.4	76.4	116.4	166.0	221.2	279.3	338.9	399.4	460.4	521.8	583.4
	WB	9.9	12.4	15.8	21.4	31.7	53.3	95.0	157.0	233.3	320.3	416.5		636.4
	SB	34.3	49.4	71.7	101.2	136.8	177.7	223.3	273.4	328.1	387.5	452.0		597.3
	EB	291.1	309.4	328.1	347.4	367.2	387.5	408.5	429.9	452.0	474.6	497.9		546.3
1600	NB	28.9	41.4	63.8	100.6	150.3	208.0	269.9	333.8	398.8	464.6	530.8	597.3	664.0
	WB	10.3	12.9	16.6	22.8	34.4	59.1	104.8	170.4	249.6	339.2	438.1	546.3	
	SB	44.9	65.9	94.3	129.2	169.4	214.3	263.8	317.7	376.4	440.0	508.9	583.4	
	EB	376.4	397.0	418.2	440.0	462.4	485.3	508.9	533.1	557.9	583.4	609.6	636.4	

NB	V1
WB	V1
SB	V2
EB	V2

LOS	A	B	C	D	E	F	
	<=10	>10-15	>15-25	>25-35	>35-50	>50	(s/pc)

Figure 7.3: Scenario C- HCM2010 Results

Chapter 8: Conclusions and Recommendations

The thesis analyzes the effect of unbalanced approach volumes on the operations of a typical four-leg, two-lane roundabout. The results obtained from two practical methods, microscopic traffic simulation and the HCM2010 procedure, are compared. The study was conducted for three different unbalanced scenarios under the same range of different volume combinations.

8.1. Conclusions

The research study noted several observations for the three unbalanced scenarios under different volume combinations. The results obtained from the traffic simulation software, VISSIM, show that the ACD obtained from the HCM procedure are significantly higher compared to the results obtained from VISSIM. It may be concluded that HCM procedure parameters were developed in such a manner to include observations from 31 roundabouts and therefore overestimates delay so that the capacity of the roundabout is underestimated. This could result in conservative design of roundabouts which would consequently result in effective roundabout performance.

When the roundabout is operating under free flow or congested conditions, the unbalanced approach volumes have no significant affect on roundabout operations.

The research study observed the effects of the unbalanced flow under different input volume combinations for three scenarios. For the first scenario under which one approach corresponded to one set of input volumes (V_1) and the other three approaches to another (V_2), two conditions apply. Unbalanced flow occurs when one approach's input volume is higher than the

rest or when one approach input volume is lower than the other three. In the case where the one approach is higher ($V_1 > V_2$), the approach adjacent its right hand side is negatively affected and resulted in a higher ACD and poorer LOS than the rest of the approaches. Where the approach has a lower input volume the other three approaches, the approach with the lower volume has the lowest ACD and best LOS, followed by the approach on its right hand side. The approach on the left hand side of this low volume approach has the highest ACD and worst LOS.

The second unbalanced scenario is when the opposite approaches shared the same input volume while the two approaches in the cross street have a different input volume. In this scenario, the approaches that have higher input volume have higher ACD and poorer LOS. However, when the input volume of these two approaches are lower than the cross street volume, the low volume approaches have better ACD and LOS.

The third scenario is where two adjacent approaches share the same volume, while the two approaches in the opposite half of the roundabout share the different approach volume. The two approaches with the high volumes negatively affect the approaches downstream in the direction of travel (counter-clockwise). The downstream approach (in the counter-clockwise direction) that has the higher approach volume experiences the highest ACD and worst LOS.

The thesis included ACD calculations based on the HCM2010 procedure and produced design charts as performed with the simulation software results. The purpose of the charts was to compare the results of ACD and LOS using the two methods. The charts demonstrate that the results of ACD were higher from the HCM2010 procedure. As a result, the LOS given by the HCM2010 procedure is always worse than the simulated outcome. The difference is significant when the approach is operating in congested conditions. However, both methods predict the

same patterns in traffic operations in the roundabout under three unbalanced flow scenarios. The possible reasons for the difference in numerical results are discussed.

In the process of analyzing the results obtained from simulations and from the HCM2010 procedure, charts for the ACD and LOS of roundabout approaches, for the three unbalanced scenarios, with different volume combinations, have been developed. The charts provided in this thesis may be used by transportation engineers or planners as a quick reference to assess the effects of different volume combinations on a four-leg two-lane roundabout.

8.2. Recommendations for Further Research

Based on the results from the research study, the following recommendations should be considered for further study:

1. It is suggested that more data should be collected on roundabout operations, such as queue and delay, so that roundabout models could be calibrated with these parameters.
2. The charts provided in this research study should be used as a quick reference for traffic engineers and planners. The charts are tailored to a typical four-leg, two-lane roundabout with specific turning percentages and lane use. Additional charts could be developed with the same approaches (VISSIM simulation and HCM2010 procedure) for different geometry, turning percentages and lane use.
3. The HCM2010 appears to underestimate the roundabout entry capacity which leads to overestimation of ACD, relative to the simulation results. More in depth investigations are needed to understand the differences and the reasons

4. The roundabout model considered in this research did not include pedestrian crosswalk, bicycle lane and bus stop. The effect of these facilities on roundabout operations with unbalanced approach volume should be investigated in the future.
5. The ACD results obtained from this study should be compared to the ACD of an existing roundabout with the same features, including geometry, volume distributions and lane changing behavior. This will help determine which method, simulation software or analytical formulation, approximates more to real time data.

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Appendix A: Calibration and Validation Data

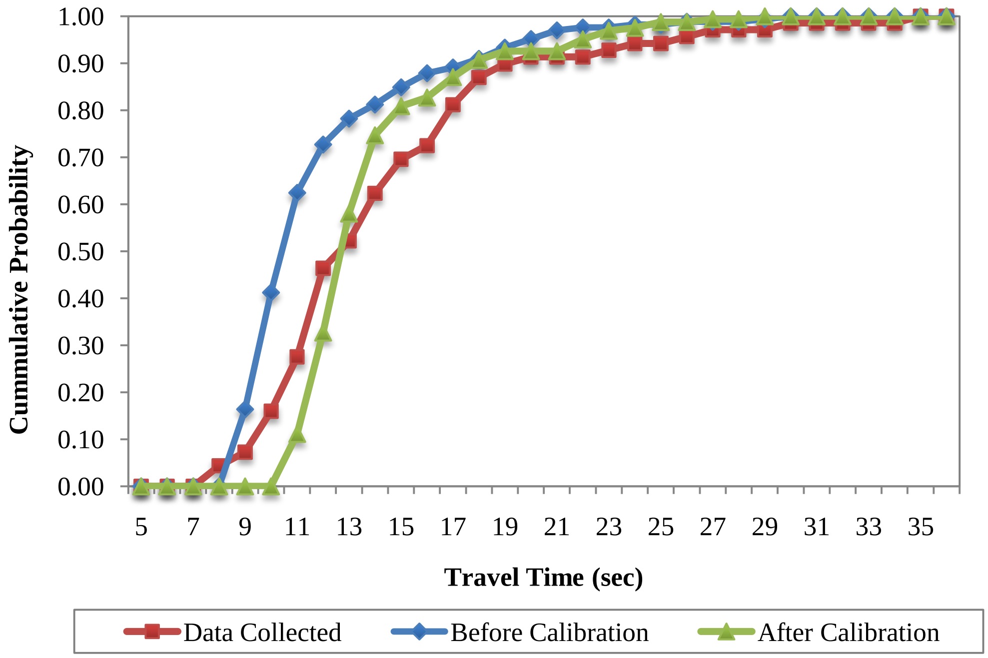

Figure A.1: Calibration Results for Southbound Approach

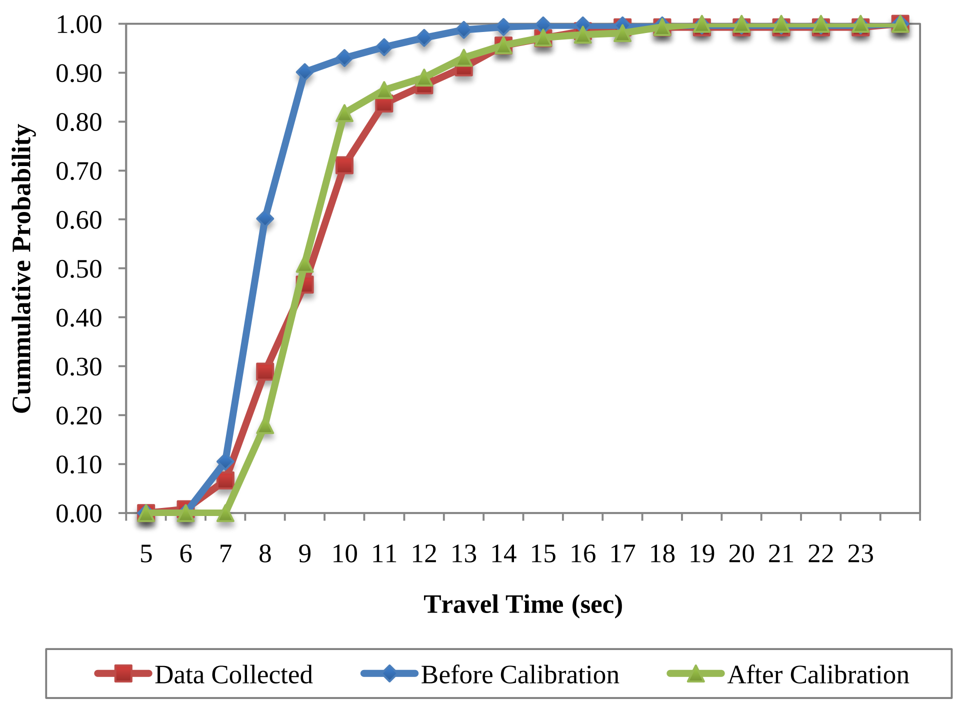

Figure A. 2: Calibration Results for Eastbound Approach

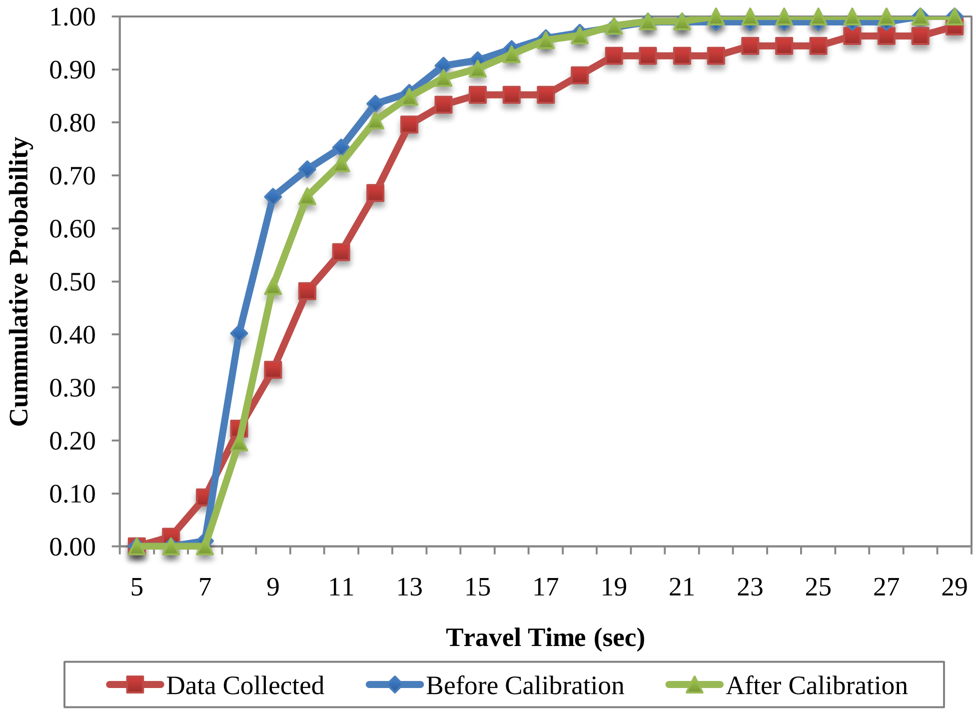

Figure A. 3: Calibration Results for Northbound Approach

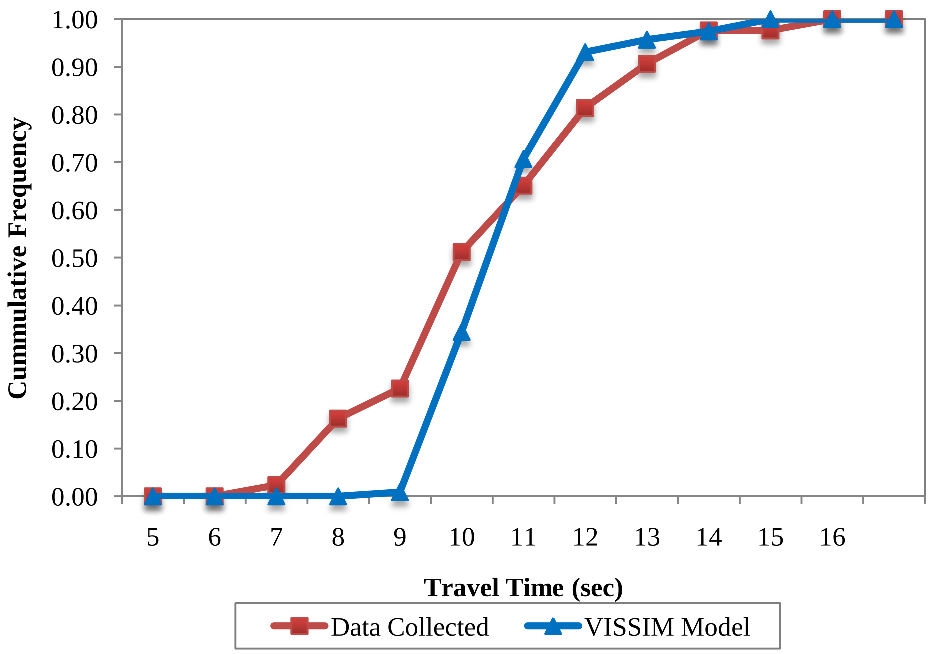

Figure A.4: Validation Results for Southbound Approach

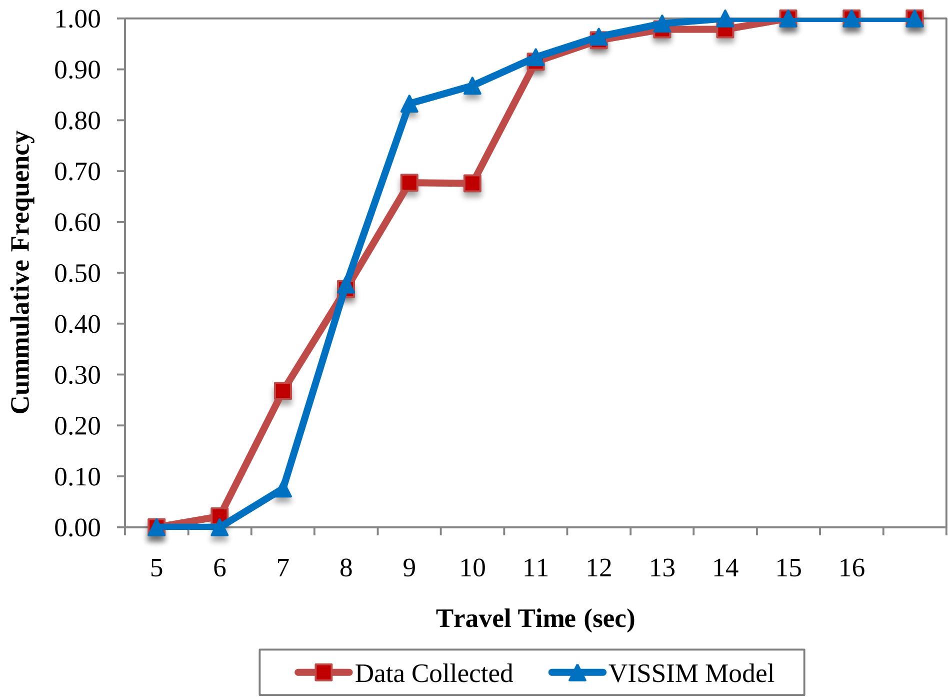

Figure A. 5: Validation Results for Eastbound Approach

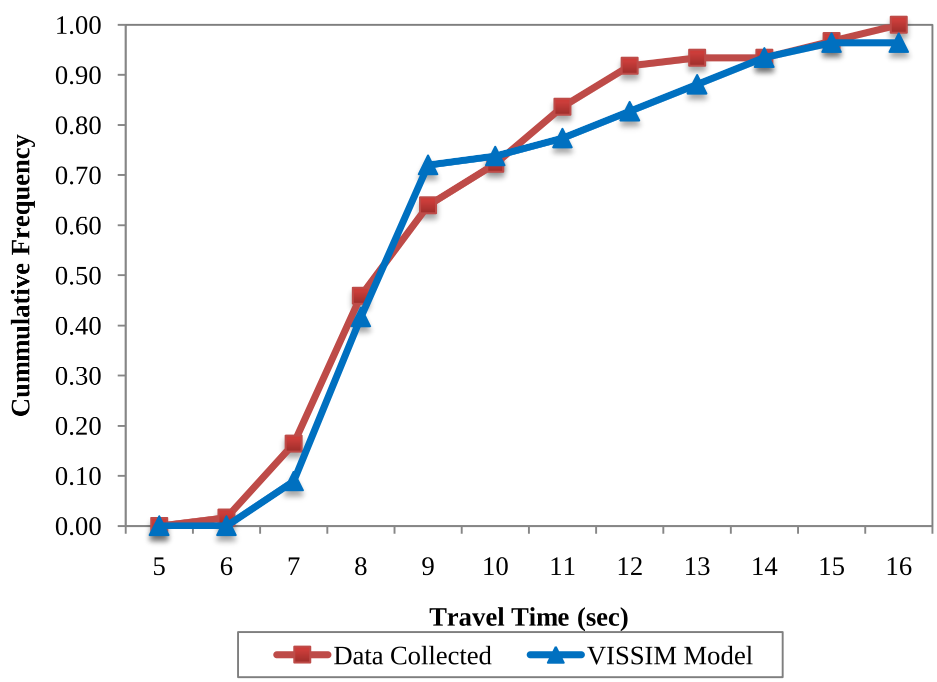

Figure A. 67: Validation Results for Northbound Approach

Vita

Marilyn Valdez was born and raised in El Paso, Texas. She is the fifth born child from Manuel Valdez and Cruz Valdez. She attended Canutillo High School and graduated top 4th of 263 students in 2003. Due to her academic achievements, she received the Presidential Scholarship from the University of Texas at El Paso (UTEP). She pursued her education in Bachelor's of Science in Civil Engineering and obtained her degree in 2008. In May 2006, Marilyn had her first son, Jimmy Aidan Edwards. During her studies, Marilyn worked part-time as a research assistant in the Border Intermodal Gateway (BIG) Transportation Laboratory at UTEP under the direction of Dr. Kelvin Cheu. She was part of a team of student that won the UTEP Civil Engineering departmental award for Best Senior Design. Marilyn was involved in student organizations such as the American Society of Civil Engineers (ASCE), Institute of Transportation Engineers (ITE) and Chi Epsilon, National Civil Engineering Honor Society. She was the treasurer for both ITE and Chi Epsilon and was elected president of Chi Epsilon her last semester and continued her presidency during her graduate career. Marilyn enrolled at UTEP in the fall semester of 2008 to pursue a Master's of Science in Civil Engineering Degree. She continued to work as a part-time research assistant at the BIG lab under the supervision of Dr. Cheu until the summer of 2009. In the same summer, Marilyn presented a poster titled "Effectiveness of Visualization to Improve Public Participation in Transportation Planning" at the National ITE Conference, which was a research founded by the Federal Highway Administration. During the same conference, Marilyn was awarded the TexITE Outstanding Student Award. She worked part-time as an intern at Walter P Moore and Associates, an engineering consulting firm, while enrolled full-time as a graduate student. During her second year in graduate school, Marilyn received the Patricia and Jonathan Rogers for Graduate

Engineering Student Scholarship and the Dwight D. Eisenhower Transportation Fellowship sponsored by the Federal Highway Administration. She traveled to Washington DC for the Transportation Research Board Conference under the fellowship. Marilyn with other team members traveled to Stuttgart, Germany to receive a bronze award from the Mondialogo Engineering Award by Daimler and UNESCO for a project entitled “Simulation Tools to Promote Roundabouts as Green, Safe and Low Cost Intersections” which was done in collaboration with a Chinese team. Marilyn received her Master’s of Science in Civil Engineering in the summer of 2010.

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This thesis was typed by Marilyn Valdez.