THE EFFECTS OF BEHAVIORAL, GEOMETRIC AND HEAVY VEHICLE TRAFFIC FLOW CHARACTERISTICS ON CAPACITY AND EMISSIONS AT ROUNDABOUTS

By

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Presented to the Faculty of the Graduate School of

The University of Texas at Arlington in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF SCIENCE IN CIVIL ENGINEERING

THE UNIVERSITY OF TEXAS AT ARLINGTON

MAY 2010

ACKNOWLEDGEMENTS

I would like to thank my advisor, Dr. James C. Williams, for leading me through this thesis. His guidance was crucial for the development of this document. I would also like to thank Dr. Sia Ardekani, Dr. Melanie Sattler and Dr. Behruz Paschai for their valuable involvement and input.

I would like to recognize the support and encouragement provided to me by my family: mom and dad, Laureate, Minerva, Bonaventure, Brillant and Nick. I would also like to thank my brother-in-law Benard and my friends Flavious, Dr. Richard, Ako, Glenn, Mary and Einstien, who where there for me when I needed them.

May 6, 2010

ABSTRACT

THE EFFECTS OF BEHAVIORAL, GEOMETRIC AND HEAVY

VEHICLE TRAFFIC FLOW CHARACTERISTICS

ON CAPACITY AND EMISSIONS

AT ROUNDABOUTS

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Modern roundabouts, first constructed in England in the early 1960s, are becoming increasingly popular replacements for signalized and stop controlled intersections in the United States. Roundabouts were introduced to replace traditional traffic circles and rotaries. With the characteristics of entering traffic that yield to circulating traffic and geometric constraints that slow entering vehicles, roundabouts have proven to be more efficient than traffic circles and in some cases than signalized and stop-controlled intersections.

Roundabouts often require drivers to decelerate from, and reaccelerate to, highway speeds, and can involve one or multiple stops. One concern about congested roundabouts is that vehicle emissions will increase because of the occurrence of excessive delays, queue formation and speed change cycles for approaching traffic. These occurrences could have a significant impact on congestion and air quality in the surrounding urban area.

There are many methodologies that allow the evaluation of roundabout capacity (analytical and statistical models) and emissions at roundabouts. Each of these techniques considers some aspects of the roundabout like geometric elements, vehicular flow and behavioral parameters. Due to the fact that each method is distinctively different from the other, obtained results are usually not similar.

This thesis presents the results of a wide survey conducted on an ample range of roundabout scenarios by the use of the simulation model VISSIM. Each scenario describes a fixed roundabout scenario using the following variables: geometric element (inscribed circle radius); characteristics of traffic flow (percentage truck, turning movements of major and minor street) and behavioral features (time gap). These scenarios are then analyzed to see how these different parameters affect capacity and emissions at roundabouts.

These parameters showed different relationships with both capacity and emissions. Radius had a positive effect, that is a direct relationship to capacity while truck percentage and time gap showed an inverse relationship to capacity. These parameters all show a direct relationship with emissions generated.

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

1.1 Introduction

There are two main documents used in this paper; they are the NCHRP 572 and FHWA roundabout guide. These reports were developed as guidelines on planning, performance, and design of roundabouts. The NCHRP 572, which is an extension of the NCHRP 3-65, was based on a comprehensive evaluation of roundabouts in the United States. The primary objective of the NCHRP 572 research was to produce a set of operational, safety and design tools calibrated to U.S. roundabout field data which would enable a person who is already competent in analysis or geometric design of typical at-grade intersections to be able to specify a roundabout that is safe, performs well, and conforms to applicable or refined U.S. engineering codes. On the other hand, the FHWA roundabout guide provides information and guidance on roundabouts, resulting in designs that are suitable for a variety of typical conditions in the United States. The scope of this guide is to provide general information, planning techniques, evaluation procedures for assessing operational and safety performance, and design guidelines for roundabouts. The FHWA roundabout guide was developed with the input from transportation practitioners and researchers from around the world. In many cases, items from national and international practices and research indicated considerable consensus, and these items were included in this guide. Where international consensus was not apparent, a reasonable approach was presented that the authors believe is most appropriate for the United States.

Modern roundabouts were first introduced in England in the early 1960s. They were introduced in order to solve the problems of traffic circles. Roundabouts are made up of a one-way circulating roadway which has priority over approaching traffic. The approaching traffic which has to yield to the circulating traffic can make a right turn only into the intersection (circulating roadway). At the yield line, the driver has only one decision to make and that is whether the gap in the circulating traffic is large enough for him to merge.

1.2 Literature Review

Good roundabout design requires entering vehicles to negotiate a small enough radius to slow speeds to no greater than 30 mph. Once within the circulatory roadway, vehicles' paths are further deflected by the central island. Figure 1.1 is a representation of vehicles paths deflected by central island.

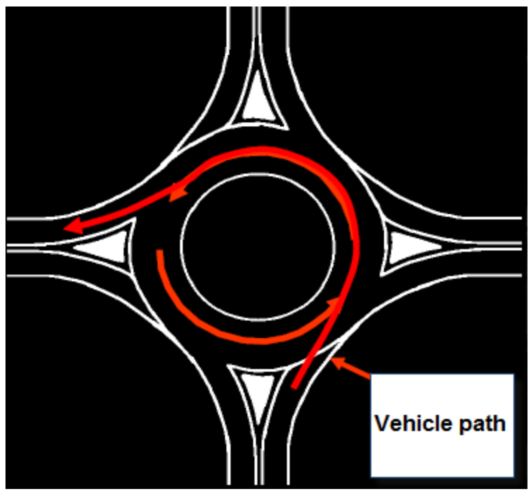

Figure 1.1 Deflections of vehicle paths by central island

All except mini-roundabouts have raised splitter islands. The splitter islands are designed to separate traffic moving in opposite directions as they approach and depart from the roundabout and to provide opportunities for pedestrians to cross in two stages. Mini-roundabouts may have splitter islands defined only by pavement marking (*FHWA. 2000*).

Roundabouts have proven to be more efficient than traffic circles and in some cases signalized and stop controlled intersections. Differences between roundabouts and traffic circles are summarized in Table 1.1.

Table 1.1 Differences between roundabouts and traffic circles (*FHWA. 2000*)

	Roundabouts	Traffic circles
Traffic control	Yield control is used on all entries. The circulatory roadway has no control.	Some traffic circles use stop control, or no control, on one or more entries.
Priority to circulating vehicles	Circulating vehicles have the right-of way.	Some traffic circles require circulating traffic to yield to entering traffic.
Pedestrian access	Pedestrian access is allowed only across the legs of the roundabout, behind the yield line.	Some traffic circles allow pedestrian access to the central island.
Parking	No parking is allowed within the circulatory roadway or at the entries.	Some traffic circles allow parking within the circulatory roadway.
Direction of circulation	All vehicles circulate counter-clockwise and pass to the right of the central island.	Some neighborhood traffic circles allow left-turning vehicles to pass to the left of the central island.

Roundabouts have 8 conflict points (single lane roundabouts) as compared to 32 conflict points for a traditional intersection (conflict points are for four single-lane approaches) (*FHWA, 2000*). Details of conflict points for traditional intersections and roundabouts are shown in Figure 1.2.

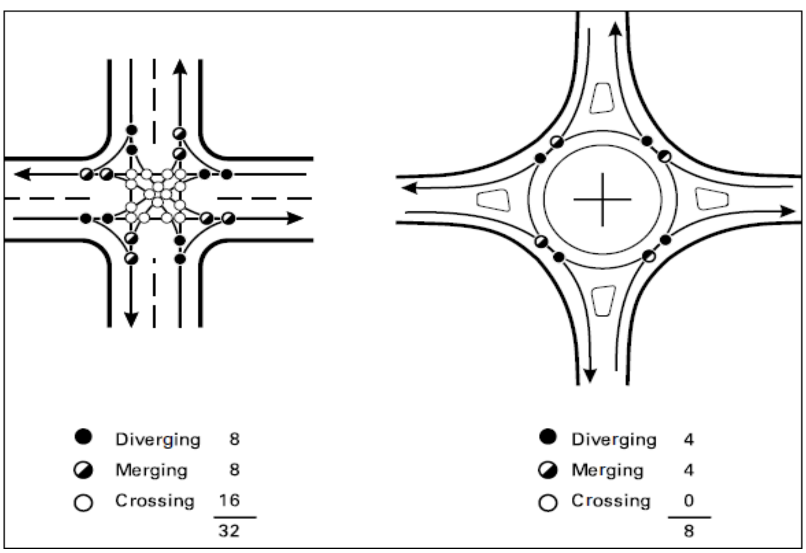

Figure 1.2 Comparison of vehicle-vehicle conflict points for intersections with four single-lane approaches (*FHWA. 2000*)

Roundabouts have a number of advantages over traffic signals depending on the conditions. They reduce the severity of crashes, since head-on conflicts are nearly eliminated. They reduce through traffic speed to provide a calmer roadway environment. Many studies have shown that roundabouts can be safer and effective with the two key characteristics of requiring entering traffic to yield to circulating traffic and geometric constraints that slow entering vehicles. The drivers are not required to stop; hence, the facility is more efficient under a broad range of traffic volume as drivers need only to find an acceptable gap in the circulating traffic to merge.

When roundabouts operate at capacity, they offer lower vehicle delays than at other intersection forms (*Rahmi, A. 2009*). It is unnecessary for traffic at a roundabout to come to a complete stop when there are no conflicts. Unlike stop controls or traffic signal intersections, queues that do form will continue to move, which is more bearable to drivers depending on the entering flow.

1.2.1. Basic definitions

There are several concepts and characteristics that are unique to roundabouts and for that reason, the following characteristics of roundabouts will be referred to in this thesis.

Roundabouts are made up of a circulatory roadway and three or more approaches with entry and/or exit lanes. When looking at one approach, the vehicles entering the facility are described as the ‘entering flow’ and are described by which lane they occupy, either the right or left lane. The vehicles on the circulatory roadway, passing in front of the approach are described as the ‘circulating flow’ and are described as occupying the inside or outside lane, the inside lane being the closest to the center island. Figure 1.3 represents these definitions.

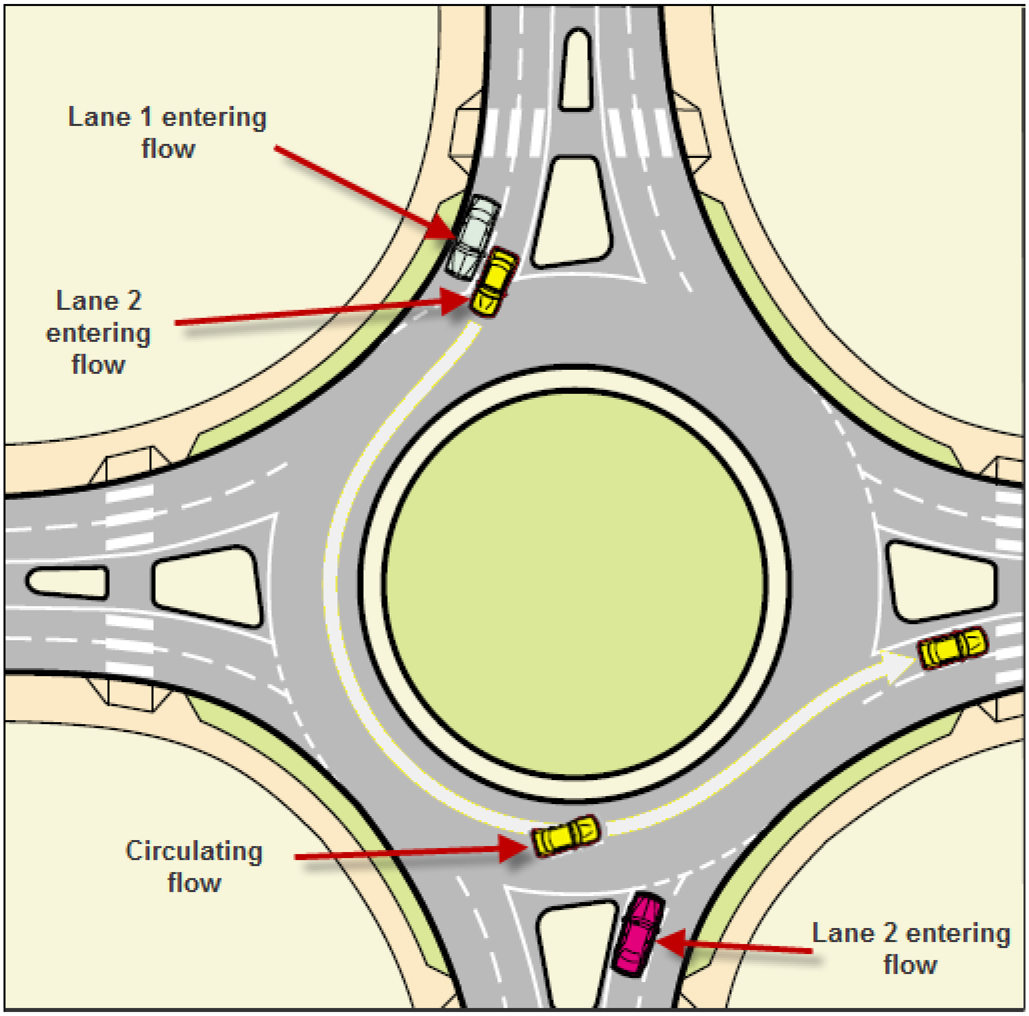

Figure 1.3 Entering flows and circulating flows at roundabouts

A “model” will pertain to a simulation model that evaluates many characteristics and performances of an intersection, corridor or network.

A “gap” is defined as the time span between two consecutive vehicles that create conflict with an entering vehicle (*Flannery, A. et al, 1996*). This time span is measured only when the entering driver is at the yield line when the gap begins.

A “follow up time” is defined as the time span between two queued vehicles entering the circulating stream in the same gap (*Flannery, A. et al, 1996*).

A “conflict marker” is a green bar used in VISSIM by vehicles at the stop line (red bar) to check for conditions such as time gap or minimum headway to get into the intersection or to wait.

A “time gap” (during the simulation) is determined every time step by the time an approaching vehicle will require to reach the conflict marker (green bar) - provided that it continues traveling at its current speed.

A “minimum headway” is defined as the length of the conflict area in VISSIM. During the simulation the current headway is determined by the distance between the conflict marker and the first vehicle approaching it.

The capacity of each entry leg of a roundabout is the maximum rate at which vehicles can sensibly be expected to enter the roundabout during a given time under prevailing traffic and geometric features (*FHWA, 2000*). The capacity is calculated as a function of traffic on the conflicting approach which in this case is the circulating traffic. Some relationships could be drawn such as:

- **Speed:** gaps depend on the speed of the circulating traffic, that is, the faster the circulating traffic, the larger the gaps must be before the merging/entering traffic will accept one. The speed of the circulating traffic is going to cause most of the entering traffic to stop at the yield line and for them to accelerate, they will need an even larger gap in the circulating traffic. This will lead to even greater delays. Thus, the speed at a roundabout is a function of its geometric features.
- **Circulating flow:** Delays at roundabouts also depend on the circulating flow. The lower the flow, the smaller the delay for drivers at the entry lanes to enter the roundabout. With lower flows, the greater the gaps for the merging traffic, and more than one vehicle may enter this gap considering that there are no pedestrian or bicycle traffic. The rate of vehicles entering the circulating flow decreases as the flow increases and the gaps grow shorter.

- **Pavement markings:** Pavement markings work together with roundabout signing and design to provide guidance to motorists approaching, circulating and exiting. The goal is to enhance safety and operations; that is, the pavement markings must help motorists to easily drive through the intersection without confusion. Figure 1.4 shows an example of roundabout pavement markings.
- **Geometric factors:** Geometric factors include entry width, circulating roadway width, number of lanes (entry and circulating roadway), inscribed circle diameter and entry radius. Geometric dimensions and some definitions are illustrated in Figure 1.5 and Table 1.2.

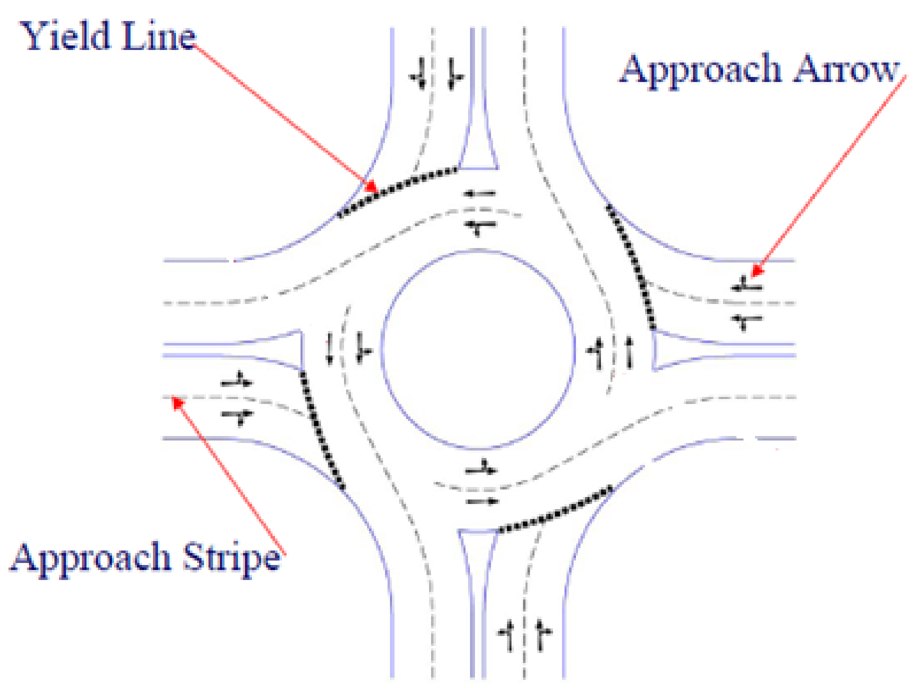

Figure 1.4 Roundabout pavement markings (Vaiana, R. 2007)

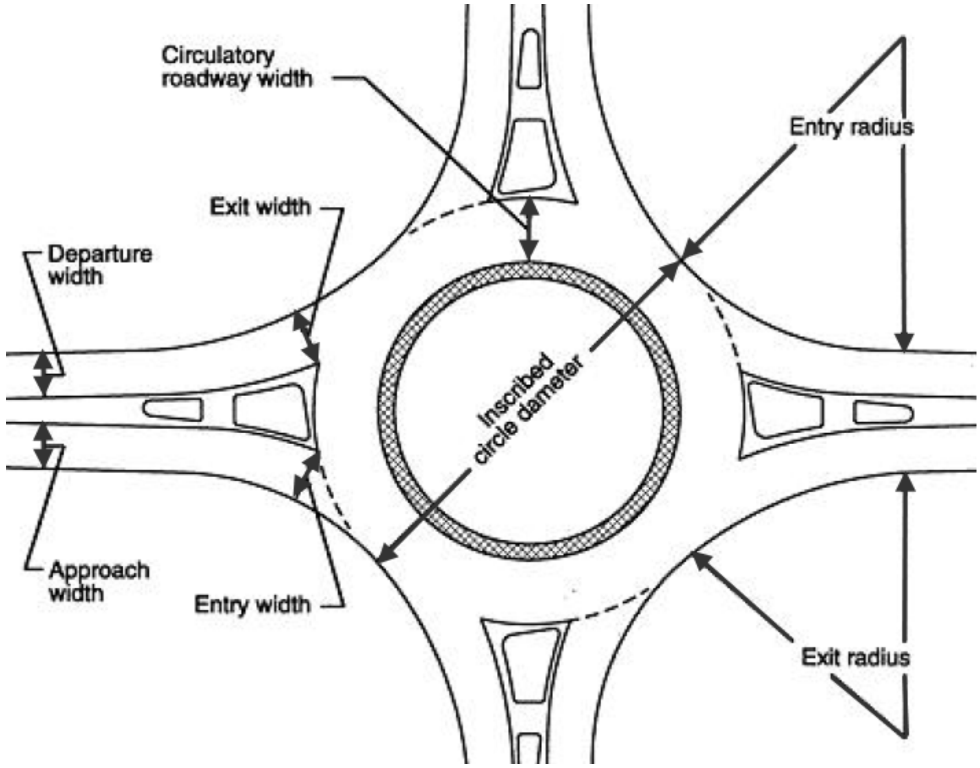

Figure 1.5 Basic geometric elements of roundabouts (NCHRP 3-65. 2004)

Table 1.2 Basic roundabout definitions (*FHWA. 2000*)

Dimension	Description
Inscribed circle diameter	The *inscribed circle diameter* is the basic parameter used to define the size of a roundabout. It is measured between the outer edges of the circulatory roadway.
Circulatory roadway width	The *circulatory roadway width* defines the roadway width for vehicle circulation around the central island. It is measured as the width between the outer edge of this roadway and the central island. It does not include the width of any mountable apron, which is defined to be part of the central island.
Approach width	The *approach width* is the width of the roadway used by approaching traffic upstream of any changes in width associated with the roundabout. The approach width is typically no more than half of the total width of the roadway.
Departure width	The *departure width* is the width of the roadway used by departing traffic downstream of any changes in width associated with the roundabout. The departure width is typically less than or equal to half of the total width of the roadway.
Entry width	The *entry width* defines the width of the entry where it meets the inscribed circle. It is measured perpendicularly from the right edge of the entry to the intersection point of the left edge line and the inscribed circle.
Exit width	The *exit width* defines the width of the exit where it meets the inscribed circle. It is measured perpendicularly from the right edge of the exit to the intersection point of the left edge line and the inscribed circle.
Entry radius	The *entry radius* is the minimum radius of curvature of the outside curb at the entry.
Exit radius	The *exit radius* is the minimum radius of curvature of the outside curb at the exit.
Splitter island	*Splitter islands* (also called separator islands or median islands) should be provided on all roundabouts, except those with very small diameters at which the splitter island would obstruct the visibility of the central island. Their purpose is to provide shelter for pedestrians (including wheelchairs, bicycles, and baby strollers), assist in controlling speeds, guide traffic into the roundabout, physically separate entering and exiting traffic streams, and deter wrong-way movements.

1.3 Problem Statement and Research Objective

In the United States increasing traffic volumes and congestion are two quickly developing problems facing our modern society. As a consequence, traffic engineers are looking for new solutions to these problems. More and more, circular traffic control measures are being installed throughout the country, including the State of Texas, due to their advantageous traffic flow and safety attributes (*HCM, 2000*). As cities grow and change, so too should the transportation infrastructure. As more vehicles use the road system each day, transportation management agencies have a civic obligation to evaluate and update existing infrastructures to meet the public demands of today and tomorrow.

Currently, drivers in the United States appear to use roundabouts less efficiently than models suggest is the case in other countries around the world. In addition, geometry in the aggregate sense has a clear effect on the capacity of a roundabout entry. The FHWA capacity model is based on German and UK research which assumes default values for each geometric parameter. The HCM 2000 model is not intended to predict capacity of a multilane entry. Other models include the Australian, French and Swiss capacity models (*NCHRP 572.b, 2007*). Each method, when formulated, has to consider some aspects of roundabout circulation in comparison to others such as geometric elements (circulatory roadway width, inscribed circle diameter, and splitter island width), characteristics of traffic flow (approach speed, circulating flow and entering flow) and behavioral features (minimum gap, rejected gap and follow up time).

1.3.1. Potential effects of vehicular emissions at roundabouts

Also, vehicular emissions have increased considerably over the years with the increase in traffic. Modern roundabouts can improve traffic flow as well as reduce vehicular emissions and fuel consumption by reducing the vehicle idle time at intersections and thereby creating a positive impact on the environment. Vehicular emissions contain a wide variety of pollutants, principally carbon monoxide (CO), carbon dioxide (CO_2), oxides of nitrogen (NO_X), particulate matter (PM_{10}), oxides of sulfur (SO_x) and hydrocarbons (HC) or volatile organic compounds (VOCs), which have a major impact on air quality. These emissions vary with the engine design, the air-to-fuel ratio, and vehicle operating characteristics. With increasing vehicle speed, there is a decrease in NO_X emissions in grams/mile up to 30-40 mph and then an increase. With increasing vehicular speed, there is a decrease in CO, PM_{10} and HC or VOC_s emissions grams/mile. The emissions of CO_2 and SO_x vary directly with fuel consumption and for any given vehicle and fuel combination. Aggregate emission levels vary according to the distance traveled and the driving patterns (Russell et al., 2002).

Road and street intersections force vehicular traffic to slow down and stop in varying patterns of interruption of ideal, constant traffic flow at an ideal speed. The longer the stops, the more fuel that is consumed, and vehicular emissions increase. With vehicular emission problems worsening, it has become prudent to choose effective traffic control devices (TCDs) that can improve traffic flow on the roads and reduce emissions per vehicle mile traveled while enhancing mobility.

Alper et al. 2001 carried out a study on the effect of arterial traffic signal timing and coordination on vehicle emissions. They found out that though delay was a factor in the amount of emission released, acceleration face in the driving cycle generated more emissions than the amount generated during the idling face. At roundabouts, vehicles would have to slow down and sometimes come to a stop before accelerating and merging with the circulating traffic.

The NCHRP 572 capacity model was based on data from existing roundabouts with low percent trucks. There was a slight improvement in the root mean square error of the predicted capacity when the flow inputs were adjusted for heavy vehicles. Furthermore, the measured entry capacity was larger when converted to passenger car units, and hence the difference between measured and predicted entry capacity (the average error) was smaller. Larger equivalency factors could be used to reduce the error further; however, this exercise would not realistically indicate the extent of the influence of heavy vehicles on entry capacity. This then lead the researchers to suggest that a more detailed examination of truck factors should be performed outside the model calibration.

A refined simulation analysis model of vehicular circulation for roundabouts would allow improved estimation of roundabout capacity and emissions. Since not all possible scenarios can be observed at existing roundabouts and not enough data could be collected, using simulation models makes it easy to create these conditions and study them.

CHAPTER 2

METHODOLOGY

Intersection analysis models are classified into two types as noted in the Highway Capacity Manual 2000: analytical and empirical models. Analytical models estimate capacity based on gap-acceptance relationships that do not require observations under congested conditions. Empirical models use observations at many different intersections under all types of conditions to develop regression equations that match intersection characteristics with intersection capacity.

This thesis presents the results of a wide survey conducted on an ample range of roundabout scenarios by the use of the simulation model VISSIM. Each scenario is developed using the following variables: geometric elements (inscribed circle radius), characteristics of traffic flow (truck percentage, turning movements of major and minor street) and behavioral features (time gap). These scenarios were analyzed to see how these different parameters affect capacity and emissions at roundabouts.

Since a wide variety of traffic scenarios can be created and a large amount of data collected, regression equations can be developed to describe to clearly investigate the interaction between geometric elements, characteristic of traffic flow and behavioral features with capacity and emissions at roundabouts.

2.1 Performance Measures of Roundabout Intersections

A roundabout has three interesting basic performance measures. The first global measure which represents the ability of roundabout to process traffic when all approach arms have queues and will be referred to as the roundabout capacity (*Fisk C.S., 1990*). Without taking geometric and behavioral features into consideration, this measure relies on the origin-destination (O-D) flow.

The second measure consists of under saturated approach lanes. The third set of measures consists of delays and queue lengths for each approach lane under given operating conditions (*Fisk C.S., 1990*).

2.2 Empirical Models vs Analytical Models

There exist two distinct methods on which capacity equations are based. These are the analytical or gap-acceptance based method and the empirical or regression based method.

Empirical methods correlate geometric features and performance measures, such as capacity, average delay and queue length, through the regression of field data. Via this method they generate a linear or exponential relationship between the entering flow of an approach and the circulating flow in front of it (*NCHRP 3-65, 2004*). Empirical methods require a large number of oversaturated or congested roundabouts to calibrate and may have poor transferability to other countries (*NCHRP 572.b, 2007*). Empirical models were developed by the British and the models underestimate capacity for low circulating flows and overestimate capacity for high circulating flows (*Rahmi,A. 2003*). The British empirical models were derived with a relatively small number of data points with low circulating flow, and reflect UK geometric designs. The NCHRP 572 report also concluded that empirical models provide no real understanding of the underlying traffic flow theory of determining the accepted gaps upon entering the intersection. The models are typically based on driver behavior in oversaturated conditions, thus requiring sites with continuous queuing. Each situation (traffic volume pattern and/or geometric conditions) must be observed in order to develop an appropriate model, (which requires a large data collection effort).

From uncongested sites, analytical models (gap-acceptance models) can be developed. The driver in the entering flow needs to select an acceptable gap in the circulating traffic to enter the circulating roadway. The gap is the headway between two consecutive vehicles in the circulating flow; therefore, the "critical gap" (t_c) is the minimum headway an entering driver would find acceptable (*NCHRP 572.a, 2007*). This means the driver would reject any gap less than the critical gap and accepts any gap greater than the minimum gap. As such, a driver's largest rejected gap will typically be less than the critical gap, and the accepted gap will be greater than the critical gap (*NCHRP 572a, 2007*). If the gap accepted is greater than the minimum, then more than one driver can enter the roundabout: the time required for an additional vehicle to use the same gap in traffic, is defined as "follow-up time" (t_f) (*Vincenzo. G. et al., 2008*).

The gap acceptance theory assumes consistent driver behavior constant values for critical gap and follow-up time, exponential distribution of the gaps into the circulating stream and constant traffic volumes for each traffic flow. These assumptions make these models less accurate. Other limitations to these models include: difficulty in the estimation of critical gaps, geometric factors are not directly taken into account, inconsistent gaps are not accounted for in theory (forced right of way when traffic is congested, circulating drivers give up right of way, different gaps accepted by different vehicles, rejection of large gap before accepting a smaller one, etc.).

Fisk, (1990) writes that because a regression model requires a great deal of data for calibration, it may work well at a specific facility but cannot be universal. Fisk also thinks gap acceptance models demonstrate reliable predictions for both capacity and delay of New Zealand roundabouts. He believes that by changing vehicle class parameters or providing a range of critical gap values, gap acceptance modeling could be used universally.

List et al. (1994) investigated a traffic circle in Latham, New York, outside of Albany using the gap acceptance based models. They concluded that it appears possible to transfer capacity equations from abroad to the United States but that it is important to develop unique formulations for U.S conditions by modifying those developed abroad.

For the purpose of this thesis, empirical models were used since a wide variety of traffic scenarios can be created and a large amount of data collected to develop regression equations to clearly investigate the interaction between geometric elements, characteristics of traffic flow and behavioral features with capacity and emissions at roundabouts.

2.3 Traffic Scenarios

Recent interest in the use of roundabouts as an effective and safe method for intersection control stresses the need for accurate modeling tools. Traffic simulation has been used to study the performance of non-signalized and signalized intersections but has not often been used in modeling or study of roundabouts. This is due to the difficulty in modeling different roundabout parameters using simulation software. The theory of gap-acceptance has led to complex assumptions regarding driver behavior and often it is not easy to obtain good results for a typical roundabout geometry (*Gallelli, V. et al., 2007*).

Not all simulation software allows the user to model roundabouts exactly. There are two categories of simulation software used for roundabouts: deterministic and stochastic simulation models. Deterministic models such as SIDRA, Rodel, Arcady and Kreisel, analyze roundabout performance with a series of equations, correlating features such as delay, queues and capacity with a set of variables (*Vaiana, R., 2008*). Stochastic models such as VISSIM, Paramics and Integration use an interval-based simulation to depict traffic operations. A summary of the main roundabout software packages is shown in Table 2.1.

Table 2.1 Principal roundabout software packages (*Gallelli, V. et al., 2007*)

Country	**Name**	**Model**
U.K.	RODEL	Deterministic
U.K.	ARCADY	Deterministic
U.K.	PARAMICS	Stochastic
Australia	SIDRA	Deterministic
Germany	KREISEL	Deterministic
Germany	VISSIM	Stochastic
U.S.A	INTEGRATION	Stochastic
U.S.A.	HCS/SYNCHRO	Deterministic
France	GIRABASE	Deterministic

The NCHRP 3-65 report compared capacity and delay estimates produced by RODEL and SIDRA with field estimates. It pointed out that typically when queues persisted for a full minute, RODEL's and SIDRA's delay estimates were low. With partial queuing under a minute, RODEL's delay exceeded the field values and SIDRA's estimates were lower. CORSIM, which is a widely-used simulation software model developed by the FHWA, does not model roundabouts. Macroscopic models (RODEL and SIDRA) should be used to analyze high-capacity roundabouts only for unsaturated conditions or for isolated locations with standard geometry, and microscopic models (VISSIM and Paramics) be used when over-saturated conditions are present in the study area or unique roadway geometry features are present (*David. S. et al., 2004*).

VISSIM and CORSIM provide some advantages over many other traffic simulation models since they are based on human psychology and behavior. The actual movements of the vehicles in VISSIM are based on behavioral assumptions regarding the desired speed and gap acceptance of drivers. As an initial assumption, vehicles follow each other with the same speed. If a vehicle is below its desired speed, it will accelerate to that speed using the maximum possible acceleration (as specified by the user) for the given speed and vehicle type. As the vehicle closes on any vehicle in front, the vehicle will, after a slight reaction delay, decelerate to match the speed of the vehicle being followed. Should the desired gap distance be too small, then the vehicle will react to avoid an accident by a sharp reduction in speed. Lane changing movements are also based on human decisions that are influenced by perceptions of surrounding vehicles in a similar fashion. These movements are based on a natural distribution of various behavioral elements. These include differences in driving abilities, human perception, desired safety and speed, and the relative levels of driver aggressiveness characterized by different maximum values for accelerations and decelerations. These phenomena are normally distributed within the model allowing random selection of various values during the simulation process *(Reiter, U. 1994)*.

For the purpose of this thesis, the microscopic model VISSIM was used. Geometric features, traffic flow characteristics and behavioral features were varied for the different simulation runs, which entails modeling specific driving behaviors and complex roadway geometry. As vehicles approach a roundabout, they are supposed to yield to those in the circulating stream. Simulating this type of driving behavior requires the ability to specify gap parameters on a link-by-link basis (*Michael, T. et al. 2003*). VISSIM has the ability to specify gaps on a lane-by-lane basis to more accurately simulate these types of operations present at roundabouts.

2.4 VISSIM Calibration

VISSIM, developed by the German traffic engineering software company PTV, is a microscopic, time step and behavior based simulation model developed to model urban traffic and public transit operations. The program can analyze traffic and transit operations under constraints such as lane configuration, traffic composition, traffic signals, transit stops, etc., thus making it a useful tool for the evaluation of various alternatives based on transportation engineering and planning measures of effectiveness. The simulation package VISSIM consists internally of two different programs; the simulation generates an online visualization of traffic operations, and offline, output files are generated for gathering statistical data such as travel times and queue lengths (*VISSIM. AG, 2005*).

For roundabouts, the user can control the junction geometry, the location of the stop line, as well as the gap acceptance and driver behavioral-type parameters. Among several other measures, the model can report the roundabout's approach delay (*VISSIM. AG, 2005*). VISSIM is able to import CAD layout and to set it as a background on which links can be precisely drawn. Individual driver behavior and vehicle characteristics are used to model traffic operations to provide the output measures of effectiveness (delay, speed, etc.) and vehicle animation for visual inspection. The flexibility of VISSIM allows for fine-tuning of gap acceptance parameters for each approach to a roundabout. To obtain a correct simulation, there are four very important principal features to set: (1) approach speed, driver behavior; (2) reduced speed zones, circulating speed; (3) priority rules; and (4) traffic assignment. These are discussed in more detail below.

2.4.1. Approach Speed, Reduced Speed Zones and Circulating Speed

Accurately defining the vehicle speed is essential to achieve a good simulation of a roundabout. With VISSIM, it is possible to define the speed of every type of vehicle once it enters into the network. The approach speed of every leg of the roundabout is taken in a range defined by an empirical speed curve which is created by the user and is typically normally distributed. The vehicles maintain the desired speed until traffic conditions or geometric features require them to change it (*VISSIM. AG, 2005*).

To change the desired speed, VISSIM uses reduced speed zones. Since the approach speed at a roundabout changes due to its geometry, the reduced speed zone assigns a new speed distribution to the vehicles which begin to decelerate before they attain the new speed in the roundabout. The vehicles start accelerating to the previous speed at the end of the reduced speed zones if no new speed has been assigned to them. Typically for roundabouts, after the reduced speed area for the entry, the circulating roadway is assigned a circulating speed distribution which is derived from equation 2.1. Equation 2.1 is the relationship between travel speed and horizontal curvature used in highway design (*AASHTO, 2004*).

$$\boldsymbol{V} = \sqrt{\boldsymbol{15} * \boldsymbol{R} * (\boldsymbol{e} + \boldsymbol{f})} \qquad 2.1$$

Where:

V = Circulating speed

R = Radius of circulating roadway

e = Superelevation

f = Friction factor

The FHWA roundabout guide speed prediction is based on this formula. The guide presents its speed methodology using a series of graphs to demonstrate the relationship between the parameters in equation 6, recognizing that side friction factor varies with speed.

The NCHRP 572 report simplifies this process by fitting an equation to the relationship between speed and path radius for the two most common super elevation values (+0.02 and -0.02). With R^2 exceeding 0.997, these fitted equations are

$$V = 3.4415R^{0.3861}, for\ e = +0.02 \quad (2.2)$$

$$V = 3.4415R^{0.3673}, for\ e = -0.02 \quad (2.3)$$

The original FHWA graph and the associated fitted equations are shown in Figure 2.1.

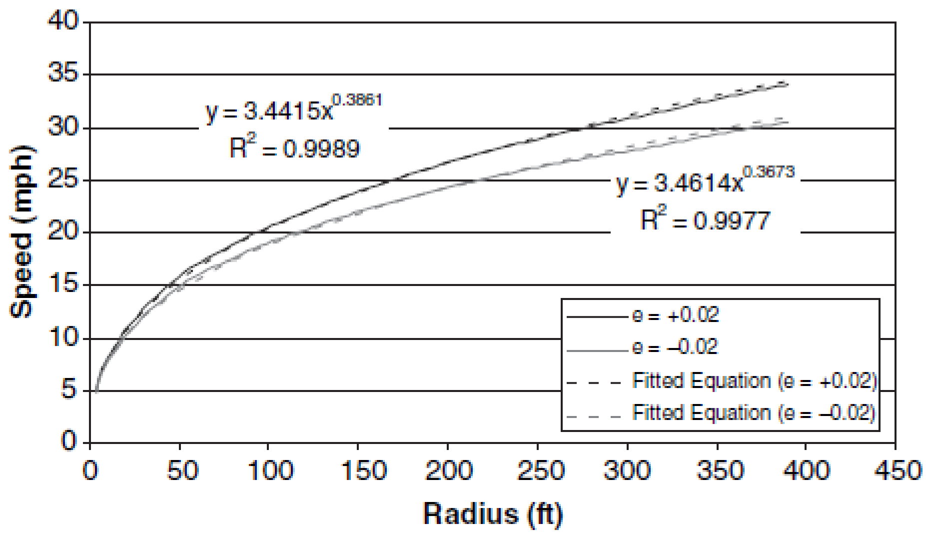

Figure 2.1 Fitted equations for FHWA speed-radius curve (NCHRP 572a. 2007)

2.4.2. Priority Rules

In VISSIM, gaps accepted by drivers are controlled by priority rules. The use of “priority rules” enables the simulation of roundabouts to be close to what might be expected in the real world. To model an entry of a roundabout, several priority rules are necessary, each of them serving different tasks. Priority rules are placed according to the following criteria:

- Stop lines represent the typical waiting position represented by a red bar. If more than one green bar (conflict Markers) refers to the same stop line, it is important to model them as multiple green bars to the same red bar (not as separate priority rule pairs) as long as the conditions for the red bar are the same, e.g. it is not possible to combine two red bars into one if they have different vehicle classes assigned.

- Conflict markers used for minimum headways are to be placed shortly before the position where the connector enters the roundabout link. If they would be placed after the entry of the connector it could result in a situation where a vehicle would wait for itself and thus drastically reduce capacity of the roundabout.
- A green bar used for min. gap time only should be placed around the same distance away from the conflict areas as the associated stop line.

Figure 2.2 is an example that defines priority rules for vehicles entering a roundabout.

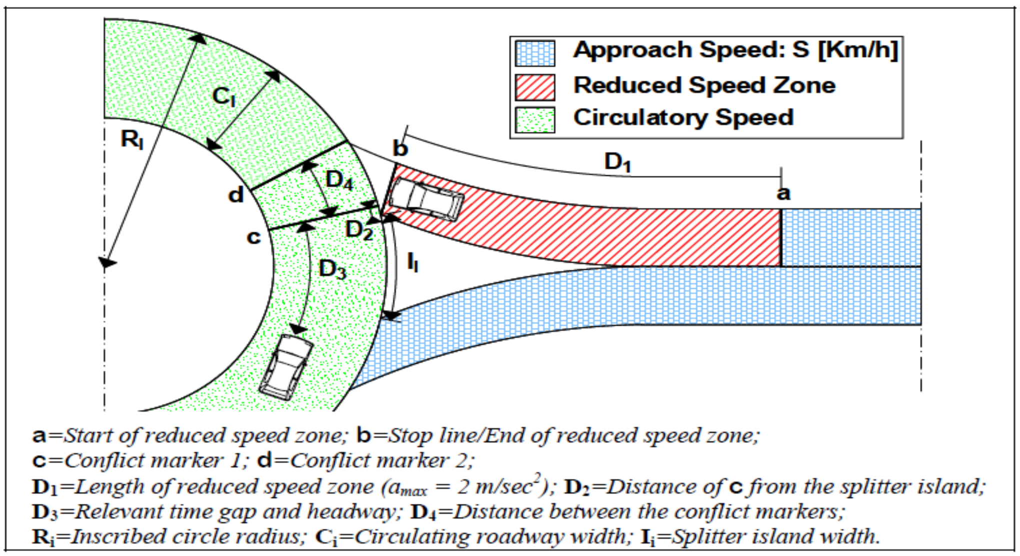

Figure 2.2 Principal parameters used in VISSIM for circulation rules (*Vaiana, R. et al., 2008*)

A vehicle which is standing at the stop-line **b** enters the circulatory roadway only when the time gap and minimum headway $\mathbf{D_3}$ measured from the conflict markers which are **d** and **c** are greater than the minimum values specified by the user. A priority rule is usually composed of a stop line (**b**) and one or more conflict markers, **c** and **d** in this case. In particular, conflict marker **c**, placed distance $\mathbf{D_2}$ beyond the right corner of the splitter island, is used to set the minimum gap time and the minimum headway for normal traffic conditions, while conflict marker **d** placed distance $\mathbf{D_4}$ beyond the conflict marker 1 (**c**) is used to define only the minimum headway for congested conditions. It is possible to set different values of critical gap or headway for any type of vehicle (*Gallelli, V. et al., 2007*).

Figure 2.3 is a second example that defines priority rules for vehicles entering a roundabout. The values used in this figure (in metric units) for minimum gap time, minimum headway and maximum speed have been determined through research.

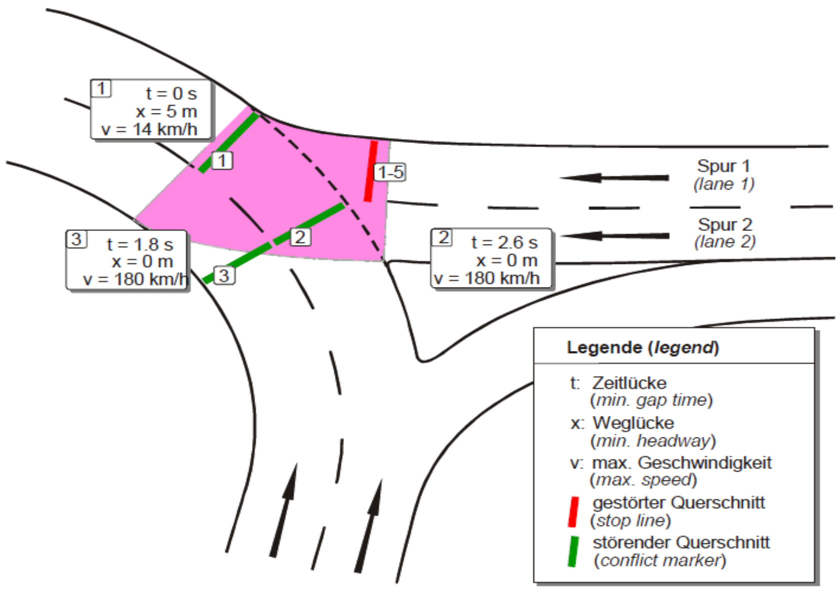

Figure 2.3 Priority rules for a two-lane roundabout with a two-lane entry (*PTV, AG. 2004*)

There are different positions, each for time gap and headway, to model a more realistic vehicle flow. Thus a vehicle within the roundabout driving faster than 14 km/h will not be detected by the minimum headway but only by the time gap condition. Therefore a vehicle wanting to enter the roundabout can start to enter even if the vehicle within the roundabout has not left the conflict area completely. Priority rules 1 and 2 model this behavior, and are valid for all vehicle classes. No. 1 secures the conflict area during slow moving and congestion within the roundabout; No. 2 contains the conditions for normal traffic conditions (time gap). Because traffic from the inner lane of the roundabout also affects entering vehicles of lane 1, an additional priority rule is required (No. 3). This one only needs a small gap time condition, which again is valid for all vehicle classes (*PTV, AG, 2004*).

2.4.3. Traffic Assignment

This module allows the user-behavior to be set for routing decisions, so as traffic input data, VISSIM uses only an O/D matrix, which contains the number of movements for each origin/destination during a specific time range.

2.4.4. Driver Behavior

VISSIM uses a traffic flow model which is discrete, stochastic, time-step-based microscopic model with driver-vehicle-units as single entities (*PTV, AG, 2005*). This model contains a psycho-physical car following model and a rule-based algorithm for lateral movements developed by Wiedemann at University of Kalsruhe during the early 1970s. The basic concept of this model is that the driver of a faster moving vehicle starts to decelerate as he/she approaches a slower moving vehicle. Since he/she can not exactly determine the speed of that vehicle, his/her speed will fall below that vehicle's speed until he/she starts to slightly accelerate again, which then results in an iterative process of acceleration and deceleration (*Wiedemann, R. 1974*). Four driving modes are taken into consideration in this model, which are correlated to combinations of speed difference and distance between two vehicles.

- Free driving mode: the vehicle maintains its desired speed and it is not influenced by preceding vehicles;
- Approaching mode: the vehicle adapts its speed to a lower one of a preceding vehicle by a deceleration that finishes when the speed difference between the vehicle is zero;
- Following mode: without accelerating or decelerating, the vehicle follows the preceding one;
- Braking mode: the vehicle makes a medium-high deceleration because the separation between vehicles is lower than the desired safety distance.

Therefore each mode presents an acceleration which is the result of speed, speed difference, distance and the individual driver and vehicle characteristics (*Michael, T. 2003*).

In order to calibrate VISSIM and run the simulations, data needs to be collected at an existing roundabout that operates at capacity. This data is used to determine values for headways and gaps accepted at the model roundabout.

CHAPTER 3

DATA COLLECTION

This section presents the details of data collection, data extraction, time gap measurements results and analyses and how the different scenarios were set up. Building scenarios requires certain parameters such as traffic flow, speed (approach and circulating speed) etc in VISSIM to be set to match real life situations and create different traffic conditions possible. Data collection at existing roundabouts that operate at capacity is necessary so as to be able to determine what range of time gaps to be used during calibration.

3.1 Field Data Collection

This data collection was carried out in Southlake, Texas, at the intersection of E. Continental Blvd and S. Carroll Avenue. Field data collection involved mainly the videotaping of headway and gap-acceptance characteristics. A video was recorded during a weekday peak period when high traffic volumes could be observed (that is, when the intersection might be operating at capacity). The video was recorded for one hour. The observed roundabout is a single-lane facility. Pedestrian and bicycle use of this facility was light; therefore, the impact of pedestrians or bicyclists on a driver’s critical gap and follow-up time was ignored. The digital video camera was mounted on a tripod and was strategically placed south of the yield sign on the eastbound direction of E. Continental Blvd in order to capture the queue on S. Carroll Ave and the approaching traffic on E. Continental Blvd. Figure 3.1 shows the position of the camera at the data collection site.

Figure 3.1 Data collection site (*Google Earth Inc. 2009*)

3.2 Data Extraction

A DVD of the video was analyzed frame by frame with the use of MAGIX Movie Edit Pro 15 Plus software (*MAGIX AG. 2009*). Time events that were necessary to define various accepted and rejected gaps events were extracted for critical gap and follow-up time calculations. Three time events were evaluated: the time when the entering vehicle stops at the yield line, the time the circulating vehicles travel past the conflicting approach and the time when the entering vehicle left the yield line. The passage time of the circulating vehicles that directly block the entering vehicles define the start and end of major stream headways that were either accepted or rejected by the entering vehicles. During the frame by frame analyses of the video, the time on each frame was used to estimate the accepted gap, rejected gap and follow-up time. In order to determine the critical gap of entering drivers, both accepted and rejected gaps for each driver were estimated.

Appendix A shows the values of the accepted and rejected gaps, maximum rejected gap and follow-up times. Since the distribution of gaps is assumed to be log-normal (*NCHRP 572a, 2007*), the probability density functions of the rejected and accepted gaps were plotted against the gaps (accepted and rejected) and they are both skewed to the right, as can be seen in Figure 3.2. They are assumed to be log-normal as they have the shape of a log-normal curve.

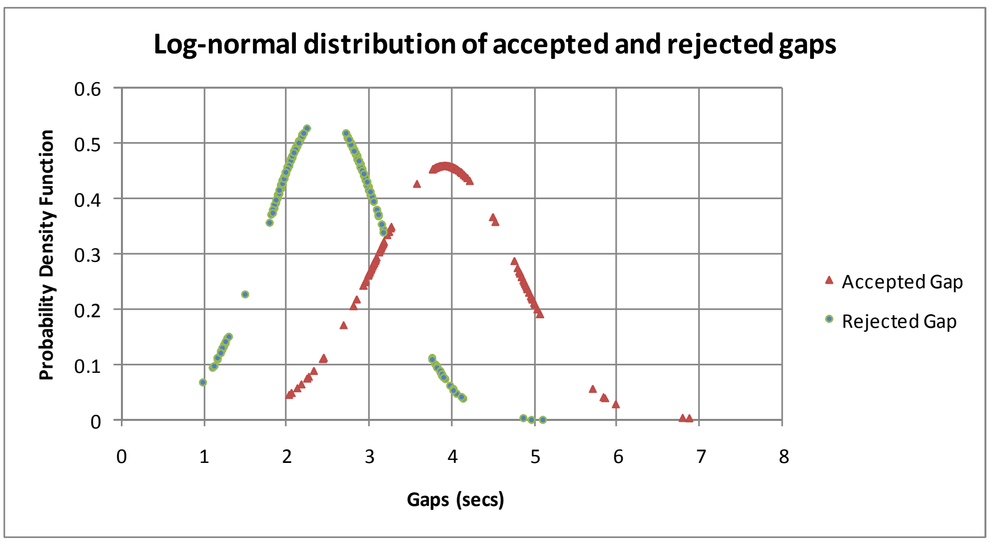

Figure 3.2 Probability density functions of accepted and rejected gaps

<u>3.3 Critical Gap Measurements</u>

Werner Brilon (1995) reviewed the different methods of estimating the critical gap and concluded that the maximum likelihood technique gave the best results in regards to having a high correlation between the true critical gap and the predicted critical gap.

Troutbeck (1992) provided the results of research by Alan Miller, which used nine different techniques to estimate the mean critical gap for a population. Table 3.1 shows his findings.

Table 3.1 Comparison between different techniques in estimating the mean critical gap (*Troutbeck, R. 1992*)

Method	Difference between mean of the estimates of the mean and the 'true' mean	Coefficient of variance of the estimates of the mean
Raff	-0.211	0.065
Probit analysis	0.029	0.059
Ashworth	-0.023	0.038
Blunden, Clissold and Fisher	-0.138	0.057
Drew	2.72	0.081
Dawson	1.413	0.048
Miller	-0.544	0.036
McNeill and Morgan	-0.019	0.063
Maximum Likelihood	-0.011	0.034
Famsey and Routledge (0.5s intervals)	0.257	0.037

Troutbeck concluded that the maximum likelihood method provided the best results. The NCHRP 572 report used the maximum likelihood method to analyze roundabouts in the United States; this also gave weight to the choice of this method for this study.

The critical gap cannot be estimated directly from the recorded video. The maximum likelihood methodology provides an estimate of the average critical gap of all the drivers by assuming that a single driver's critical gap ranges between his/her largest rejected gap and the accepted gap (*XU, F. et al. 2008*). A probabilistic distribution of the critical gap must be assumed. Troutbeck (1992) used a log-normal distribution for the critical gaps: the distribution has non-negative values and is skewed to the right, as was observed for this case in Figure 3.2. A computer program was developed by Troutbeck (1992) to resolve the complex algorithms of the likelihood methodology. The FORTRAN code to do this calculation can be found in Appendix C. The mean critical gap t_c and the variance s^2 can then be computed by:

$$\boldsymbol{t_c = e^{(\mu+0.5\sigma^2)}} \quad 3.1$$

$$\boldsymbol{s^2 = t_c^2\left(e^{\sigma^2} - 1\right)} \quad 3.2$$

Where:

μ= mean of the distribution of the logarithms of the individual driver's critical gaps

σ^2= variance of the distribution of the logarithms of the individual driver's critical gap

The mean and the variance are determined from an iterative process using the following two equations:

$$\sum_{i=1}^{n} \frac{f(x_i)-f(y_i)}{F(y_i)-F(x_i)} = 0 \qquad 3.3$$

$$\sum_{i=1}^{n} \frac{(x_i-\mu)f(x_i)-(y_i-\mu)f(y_i)}{F(y_i)-F(x_i)} = 0 \qquad 3.4$$

Where:

y_i= the logarithm of the gap accepted by the *i*th driver

x_i= the logarithm of the largest gap rejected by the *i*th driver. x_i = 0 if no gap was rejected

f()= probability density function for the normal distribution

F()= cumulative distribution function for the normal distribution

Equation 3.3 is used first to estimate μ after assuming a value of σ^2 based on the variance of all the y_i and x_i values. This estimate of μ is then used in equation 3.4 to improve the estimate of σ_2. This process is repeated until the obtained values of μ and σ_2 stabilize. From the values obtained from this process, the mean and variance of the critical gap distribution can then be calculated using equations 3.1 and 3.2.

From the observed field values, and after several iterative processes, the mean critical gap and variance are: 4.21 secs and 0.89 $secs^2$, respectively. These values are then used to determine a range of the critical gap that would be used in building the different scenarios.

CHAPTER 4

EXPERIMENTAL DESIGN

4.1 Setting Up Scenarios for Capacity Verification

To determine the effects of behavioral, geometric and traffic flow characteristics on capacity and emissions using VISSIM model, scenarios that depict different traffic conditions were developed. This was done so as to increase the variability in traffic conditions and to increase the sample size for the output data.

The different variables for the different sets of scenarios are:

- **Traffic volumes (TF):** to increase the range of traffic events, three different sets of traffic volumes between the major and the minor street were set as shown in table 4.1

Table 4.1 Traffic volumes vph for major and minor streets

Major street	Minor street
200	100
300	200
600	400

- **Turning movements:** two categories of turning percentages were used for the major and minor: major street (left/through/right) 10/80/10 and 15/70/15, and minor street (left/through/right) 30/40/30 and 40/20/40.

  For the influence of truck traffic on roundabouts, a different set of turning percentages were generated to produce a wider range of traffic events. Table 4.2 shows the different turning percentages.

Table 4.2 Turning percentages for entering flows

Left turn	Through	Right Turn
10	50	40
10	65	25
10	80	10
25	35	40
25	50	25
25	65	10
40	20	40
40	35	25
40	50	10

- **Number of lanes (NL):** the number of lanes used for this paper was a 2/1 (two lanes on the major street and one lane on the minor).
- **Radius of circulating roadway (R):** the diameter of the inscribed circle varied between 100 and 300ft. The following radii were used: R_1 = 100ft, R_2 = 200ft and R_3 = 300ft.
- **Splitter island width (SIW):** in the NCHRP 572 report, it was observed that some entering drivers into the roundabout tend to hesitate during an exiting vehicle event. That is, the entering vehicles cannot tell if the approaching vehicle is exiting the roundabout or continuing to circulate. Due to this, longer follow-up headways were observed. The width of the splitter island is plausibly correlated because it physically separates the entry and exiting movements (*NCHRP 572a, 2007*). For the purpose of this paper, the splitter island width is being taken as 45 ft measured, as shown in Figure 3.3.

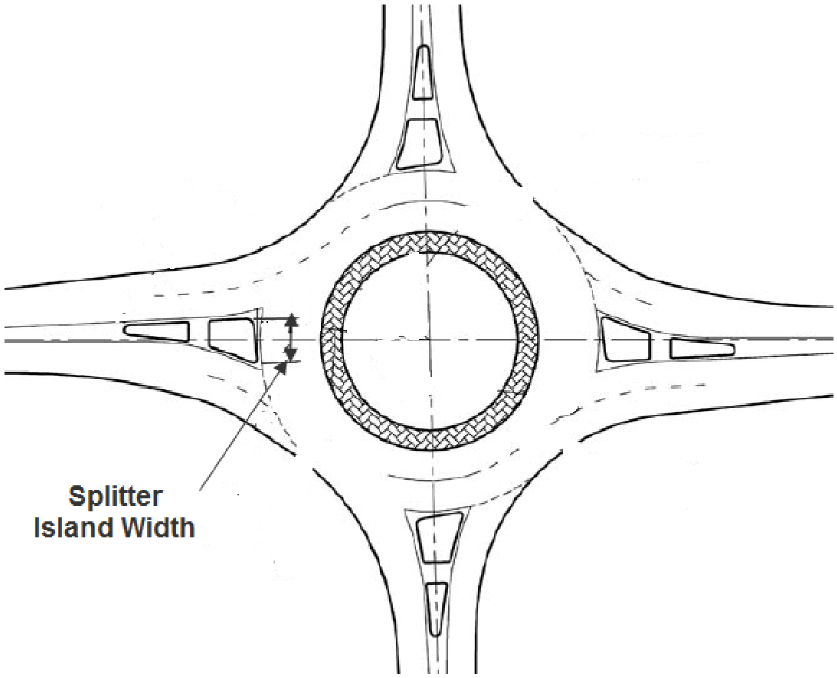

Figure 4.1 Measurement of splitter island

- **Approach Speed (AS):** International studies have shown that increasing the vehicle path curvature decreases the relative speed between entering and circulating vehicles. FHWA roundabout guide suggest a 25 mph approach speed at about 325 ft from the center of a 100 ft urban double lane roundabout, as shown in Figure 4.2, which shows the operating speeds of a typical vehicle approaching and negotiating a roundabout. Using Figure 4.2, with the radii 100ft, 200ft and 300ft, the following approach speeds were estimated: 25, 30 and 35 mph, to conduct the different scenario runs for passenger cars, and 20, 25 and 30 mph for trucks.

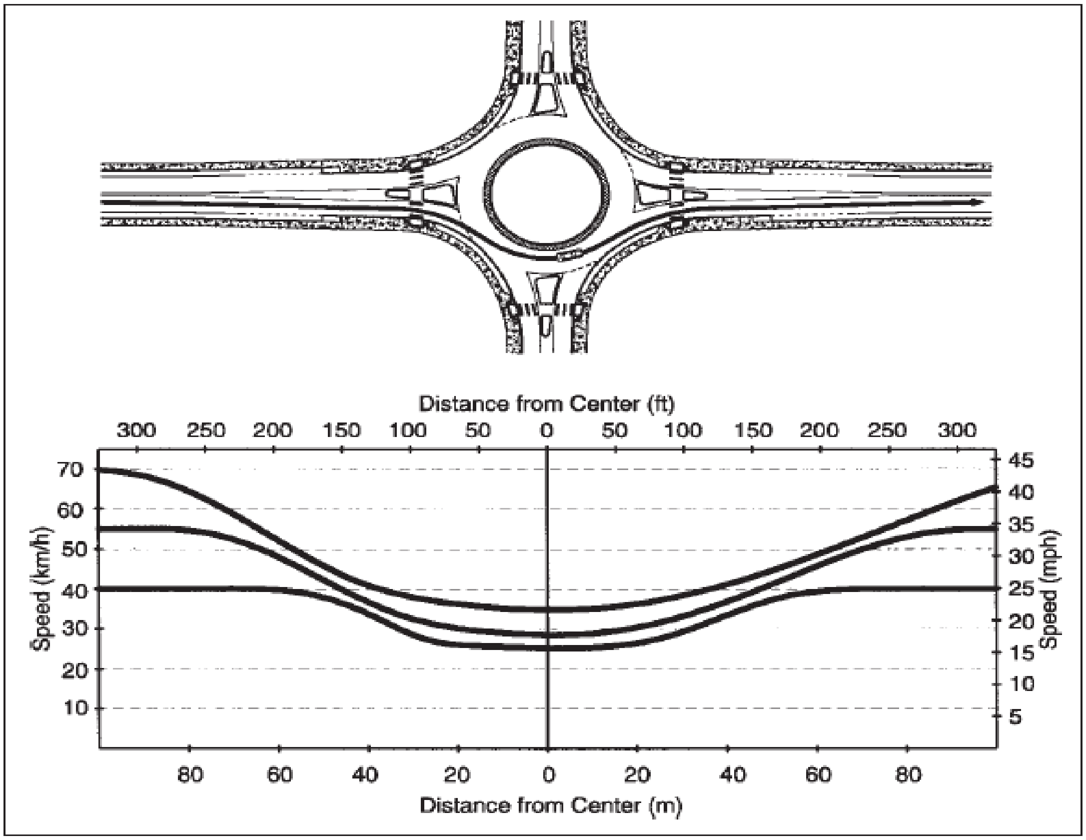

Figure 4.2 Sample theoretical speed profile (Urban Compact Roundabout) (*FHWA. 2000*)

- **Circulating speed:** Since the circulating speed depends on the radius of the vehicle path, Figure 2.1 was used to determine the circulating speed for this study. With the diameters chosen for this study, the estimated circulating speeds are shown in Table 4.3.

Table 4.3 Radii and their corresponding circulating speeds

Radius (ft)	Circulating speed (mph) for passenger cars	Circulating speed (mph) for trucks
100	15	12
200	20	17
300	25	22

- **Critical Gap:** from the time gap calculated from the collected data, the following range of values were used for the simulation: 3 secs,

  4 secs and 5 secs for passenger cars and 4 secs, 5 secs and 6 secs for trucks.

- **Truck percentage**: truck percentages within the traffic stream of 0%, 10%, 20% and 30% were selected at random and used.
- **Reduced speed zones**: since only right turns can be made when entering or exiting a roundabout and right turns occur at low speeds, right turn speeds assumed were: 9.3 to 12.4 mph for passenger cars and 7.5 to 9.3 mph for trucks (low speed range used in VISSIM).
- **Desired speed**: the speed distributions were assumed to be normally distributed with 75 percent of the drivers within the speeds chosen for this study.
- **Design vehicle**: Commonly, WB-50 vehicles are the largest vehicles along collectors and arterials; the design vehicle used was the WB-50 with a total length of 55ft.
- **Driver behavior parameters**: default driver behavior parameters were used and waiting time before diffusion was taken as 10 secs. Waiting time before diffusion defines the maximum amount of time a vehicle can wait at the emergency stop position waiting for a gap to change lanes in order to stay on its route. When this time is reached, the vehicle is taken out of the network (diffusion) and a message will be written to the error file denoting the time and location of the removal (*PTV, AG. 2004*).
- Default values for maximum acceleration and deceleration values of passenger cars and trucks in VISSIM were used for this study.

4.2 Setting Up of Scenarios for Emissions Verification

Similarly, the same sets of parameters used in the capacity scenarios were used to run scenarios for emissions at roundabouts. There are several measures of effectiveness (MOEs) used in VISSIM to estimate emissions, but only three were considered relevant to evaluate the effect of geometric, behavioral and traffic flow characteristics on emissions at roundabouts. This was because these three MOEs are the main bproducts of gasoline combustion. The three MOEs are:

- Carbon Monoxide (CO)
- Nitrogen Oxides (NOx)
- Volatile Organic Compounds VOCs

In total, 90 scenarios were run for effect of geometric, behavioral and traffic flow characteristics on emissions at roundabouts. To test for the effect of radius on emissions, behavioral and traffic flow characteristics were kept constant, to test for the effect of time gap on emissions at roundabouts geometric and traffic flow characteristics were kept constant and geometric and behavioral characteristics were kept constant when checking for the effect of truck percentage on emissions. A traffic split of 60/40 between the minor and the major street was used, and the same turning percentages as shown in Table 4.2 were used. These turning percentages generated the circulating flows for the different scenarios as shown in Table 4.4.

Table 4.4 Circulating flows for the effect of geometric, behavioral and traffic flow characteristics on emissions at roundabouts

Left turn	Through	Right Turn	Circulating flow for 100ft radius (vph)	Circulating flow for 200ft radius (vph)	Circulating flow for 300ft radius (vph)
10	50	40	350	481	557
10	65	25	412	546	618
10	80	10	477	611	679
25	35	40	421	551	627
25	50	25	484	617	680
25	65	10	547	681	749
40	20	40	496	620	688
40	35	25	548	685	735
40	50	10	622	750	810

4.3 Determining Number of Multiruns (Replications)

The accuracy of the outputs from VISSIM relies on the number of replications (multiruns, as referred to in VISSIM). In contrast to single simulation runs, the random seeds are changed for every simulation run of a multirun simulation. Multiruns are used to automatically run multiple simulations.

In order to determine the number of multiruns to be carried out for each scenario, the throughput on each entry leg was plotted against the run and the averages for all the runs plotted as well as shown in Figure 4.3.

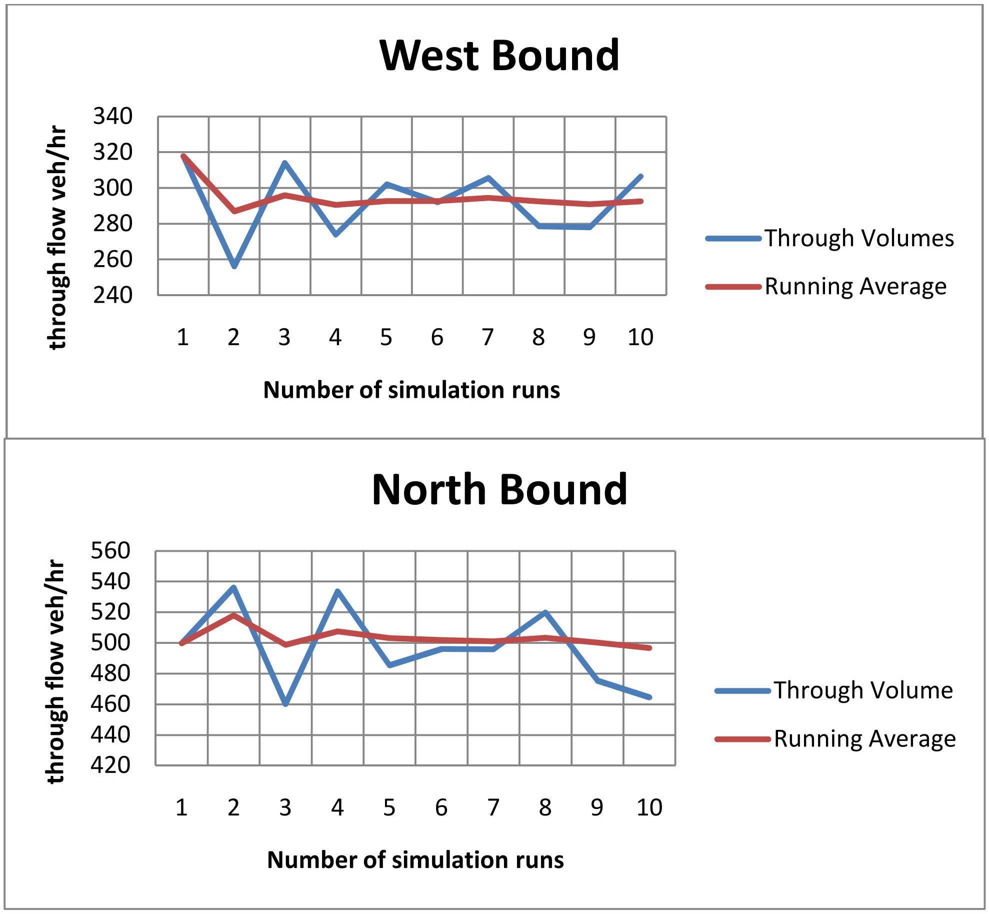

Figure 4.3 Throughput (vph) vs number of runs

The arithmetic mean of the throughput volumes of the ten runs was obtained and the arithmetic mean of the first two runs, first three runs and first four runs were also obtained, including their standard deviations. A t-test was performed at a 95% confidence level to compare the mean of the ten runs and the other means to see if they are significantly different from each other.

The two sample t test for unpaired data is defined as (Montgomery, D., C. et al 2007):

H_0:	$\mu_1 = \mu_2$	4.1
H_1:	$\mu_1 \neq \mu_2$	4.2
Test Statistic:	$T = \frac{\bar{Y}_1 - \bar{Y}_2}{\sqrt{\frac{S_1^2}{N_1}+\frac{S_2^2}{N_2}}}$ Where: N_1 and N_2 are the sample sizes, $\bar{Y}_1$ and $\bar{Y}_2$ are the sample means, and S_1^2 and S_2^2 are the sample variances.	4.3
Significance Level:	α	
Critical Region:	Reject the null hypothesis that the two means are equal if $T < -t_{(\propto/2,v)}$ or $T > t_{(\propto/2,v)}$ where $t_{(\propto/2,v)}$ is the critical value of the t distribution with $\boldsymbol{v}$ degrees of freedom where : $\frac{(S_1^2/N_1+S_2^2/N_2)^2}{(S_1^2/N_1)^2/(N_1-1)+(S_2^2/N_2)^2/(N_2-1)}$	4.4

The values in Table 4.5 are those obtained from the east bound entry leg.

Table 4.5 T-test on the means of 10 runs vs the first 2, first 3 and first 4 Runs at 95% confidence level.

10 Runs		**First 2 runs**		**First 3 runs**		**First 4 runs**	
Base size:	10	Base size:	2	Base size:	3	Base size:	4
Mean:	288	Mean:	272	Mean:	287	Mean:	279
Standard deviation:	22.318	Standard deviation:	25.845	Standard deviation:	31.649	Standard deviation:	30.310
		T:calculated	0.910	**T: calculated**	0.063	**T: calculated**	0.619
		Degrees of Freedom:	10	**Degrees of Freedom:**	11	**Degrees of Freedom:**	12
		$t_{(0.05/2,10)}$	2.228	$t_{(0.05/2,11)}$	2.201	$t_{(0.05/2,12)}$	2.179

Since all the calculated t-values are less than the t-tabulated values ($t_{(\propto/2,v)}$), we fail to reject the null hypothesis ($\mu_1 = \mu_2$). It can then be concluded that the mean of the ten runs is not significantly different from the means of the first four running averages.

A maximum of 4 multiruns was thus used for each scenario.

CHAPTER 5

OPERATIONAL FINDINGS

To measure capacity, the northbound entry was selected. The idea was to push as much traffic as possible from this entry and to measure the entry throughput. High traffic volumes were input from the northbound entry to ensure that after the initial period of the simulation, a long queue of vehicles would always be present and ready to enter the roundabout. The simulations were also setup to avoid collisions at the selected entry and exit points. It is assumed that the throughput at the northbound entry is its capacity (*Bared, J. G. 2009*).

The average of the throughput for the four multiruns were taken after each increase in volume till there was no significant change in the throughput within the one hour scenario run period. The volumes at the other legs of the intersection were varied as shown in Table 4.2, and the turning movements were varied to create different circulating flows for the northbound movement. Tables 5.1, 5.2, 5.3, 5.4 and 5.5 shows the results from the different scenarios with:

- TG- Time Gap (TG1-3/4 secs, TG2-4/5 secs, TG3-5/6 secs) for passenger cars and trucks e.g, 3/4 indicates 3 secs for passenger cars and 4 secs for trucks
- T%- Truck Percentages (T%0-0%, T%1-10%, T%2-20%, T%3-30%)
- Conf- Circulating flows in vehicle per hour
- R- Radius of circulating roadway (R_1-100ft, R_2-200ft, R_3-300ft)

Table 5.1 Capacity results (vph) for geometric/behavioral effects at roundabouts

Time gap (3/4 secs) /10% Trucks			
R1	R2	R3	Circ flow
1562	1641	1825	282
1550	1659	1837	262
1651	1740	1913	238
1623	1757	1914	231
1751	1828	1996	196
1670	1802	1991	200

Time gap (3/4 secs) /20% Trucks			
R1	R2	R3	Circ flow
1408	1491	1665	282
1395	1512	1695	262
1483	1572	1765	238
1468	1575	1755	231
1579	1644	1835	196
1577	1630	1838	200

Time gap (3/4 secs) /30% Trucks			
R1	R2	R3	Circ flow
1244	1382	1515	282
1268	1352	1541	262
1345	1427	1594	238
1302	1420	1577	231
1410	1505	1693	196
1370	1473	1677	200

Time gap (4/5 secs) /10% Trucks			
R1	R2	R3	Circ flow
1342	1453	1722	282
1353	1506	1771	262
1434	1520	1828	238
1401	1556	1839	231
1535	1638	1908	196
1478	1610	1902	200

Time gap (4/5 secs) /20% Trucks			
R1	R2	R3	Circ flow
1217	1318	1551	282
1207	1346	1585	262
1296	1402	1639	238
1269	1402	1650	231
1373	1461	1761	196
1349	1514	1724	200

Time gap (4/5 secs) /30% Trucks			
R1	R2	R3	Circ flow
1063	1183	1384	282
1097	1237	1450	262
1183	1286	1503	238
1151	1278	1506	231
1250	1328	1599	196
1217	1325	1556	200

Time gap (5/6 secs) /10% Trucks			
R1	R2	R3	Circ flow
1092	1225	1463	282
1078	1271	1531	262
1166	1302	1559	238
1136	1338	1607	231
1272	1381	1679	196
1214	1391	1679	200

Time gap (5/6 secs) /20% Trucks			
R1	R2	R3	Circ flow
1013	1090	1318	282
1010	1153	1390	262
1061	1185	1447	238
1064	1219	1470	231
1150	1268	1548	196
1115	1278	1523	200

Time gap (5/6 secs) /30% Trucks			
R1	R2	R3	Circ flow
916	1008	1222	282
928	1043	1248	262
974	1101	1305	238
958	1106	1325	231
1043	1148	1404	196
1022	1170	1381	200

Values in Table 5.1 under rows R_1, R_2 and R_3 are estimated capacity values for all three radii at different circulating flows. For example' for a circulating flow of 282 vph, time gap of 3/4 secs and a truck percentage of 10%, the capacity for a 100 ft (R_1) radius, the capacity is 1562 vph, for a 200 ft radius, the capacity is 1641 vph and for a 300 ft radius, the capacity is 1825 vph.

Table 5.2 Capacity results for truck effect at roundabouts

0% trucks		10% trucks		20% trucks		30% trucks	
Circ flow vph	Capacity vph	Circ flow vph	Capacity vph	Circ flow vph	Capacity vph	Circ flow vph	Capacity vph
80	2227	80	2027	80	1863	80	1665
95	2357	95	2128	95	1914	95	1737
110	2329	110	2121	110	1956	110	1762
110	2124	110	1935	110	1747	110	1586
125	2206	125	2022	125	1827	125	1633
140	2174	140	2002	140	1843	140	1661
140	2027	140	1862	140	1698	140	1540
155	2112	155	1911	155	1735	155	1579
170	2125	170	1891	170	1746	170	1555
150	2076	150	1872	150	1690	150	1525
180	2124	180	1899	180	1706	180	1540
210	2063	210	1865	210	1703	210	1519
195	1948	195	1750	195	1581	195	1421
225	1978	225	1760	225	1593	225	1414
255	1922	255	1736	255	1566	255	1395
240	1861	240	1672	240	1508	240	1339
270	1873	270	1698	270	1502	270	1346
300	1846	300	1656	300	1477	300	1311
300	1713	300	1516	300	1336	300	1180
360	1631	360	1424	360	1254	360	1099
420	1514	420	1319	420	1162	420	1007
390	1537	390	1317	390	1176	390	1024
450	1435	450	1218	450	1069	450	951
510	1322	510	1140	510	998	510	878
480	1410	480	1193	480	1043	480	938
540	1303	540	1133	540	988	540	855
600	1175	600	1026	600	902	600	784

Table 5.2 shows estimated capacity values for different circulating flows and different truck percentages for a fixed radius of 300 ft and fixed time gap of 4/5 secs.

Table 5.3 Emissions from different roundabout radii (emission values in grams/hr)

100 ft radius				200 ft radius				300 ft radius			
Circ flow vph	VOC g/hr	NOx g/hr	CO g/hr	Circ flow vph	VOC g/hr	NOx g/hr	CO g/hr	Circ flow vph	VOC g/hr	NOx g/hr	CO g/hr
350	571	479	2463	481	665	558	2869	557	713	599	3078
412	579	486	2496	546	677	569	2922	618	730	613	3149
421	583	489	2514	551	678	569	2926	627	734	617	3169
477	594	499	2564	611	696	584	3002	679	747	627	3223
484	598	502	2580	617	693	582	2992	680	753	632	3247
496	594	499	2563	620	692	581	2987	688	759	637	3275
547	613	515	2646	681	710	596	3065	735	773	649	3333
548	621	521	2679	685	713	599	3078	749	773	649	3333
622	637	535	2747	750	729	612	3147	810	798	670	3441

Table 5.3 shows values of VOCs, NOx and CO emissions in grams per hour estimated at different circulating flows for all three radii with truck percentage set at 0% and time gap 4/5 secs. For example; for a 100 ft radius and 350 vph circulating flow 571 grams of VOCs are emitted at the roundabout.

Table 5.4 Emissions from different truck percentages (emission values in grams/hr)

	0% trucks			10% trucks			20% trucks			30% trucks		
Circ flow vph	VOC	NOx	CO	VOC	NOx	CO	VOC	NOx	CO	VOC	NOx	CO
557	713	599	3078	722	607	3117	735	617	3172	746	626	3218
618	730	613	3149	740	621	3192	765	642	3102	771	648	3329
627	734	617	3169	750	630	3237	765	642	3299	784	658	3383
679	747	627	3223	771	647	3325	782	656	3374	805	676	3475
680	753	632	3247	770	646	3323	797	669	3437	819	688	3535
688	759	637	3275	767	644	3307	801	673	3458	818	687	3529
735	773	649	3333	797	669	3437	824	692	3556	907	762	3915
749	773	649	3333	803	674	3463	837	703	3612	880	739	3798
810	798	670	3441	827	695	3570	894	751	3858	975	819	4207

For a 300 ft radius and 4/5 secs time gap, emissions were estimated for different values of truck percentages. Table 5.4 show values of VOCs, NOx and CO emissions in grams estimated for different circulating flows.

Table 5.5 Emissions from different time gaps

	Time gap 3/4 secs			Time gap 4/5 secs			Time gap 5/6 secs		
Circulating flow vph	VOC	NOx	CO	VOC	NOx	CO	VOC	NOx	CO
557	708	594	3054	713	599	3078	738	619	3183
618	722	606	3114	730	613	3149	760	638	3278
627	726	610	3134	734	617	3169	769	645	3316
679	737	619	3180	747	627	3223	788	662	3401
680	740	622	3194	753	632	3247	796	669	3436
688	745	625	3212	759	637	3275	812	682	3504
735	758	636	3271	765	642	3299	839	704	3619
749	758	636	3269	773	649	3333	844	708	3641
810	775	650	3342	798	670	3441	914	767	3944

Fixing the radius at 300 ft with a fixed truck percentage of 0%, time gaps were varied and table 5.5 shows VOCs, NOx and CO emissions in grams estimated.

5.1 Comparisons and Analyses of Results

With the assumption that the exponential relationship between entering capacity and circulating flows found in previous studies is correct, entering capacity was treated as an exponential function of circulating flows. To evaluate the fit of the raw data, Figure 5.1, Figure 5.2 and Figure 5.3 were generated.

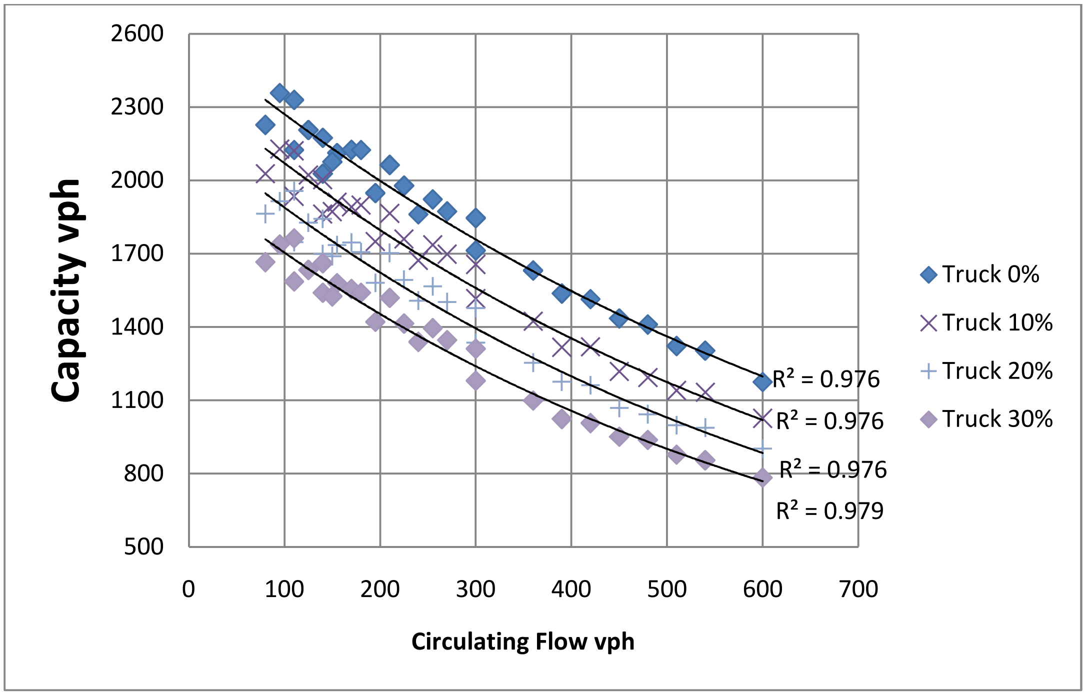

Figure 5.1 Effect of truck percentage on capacity

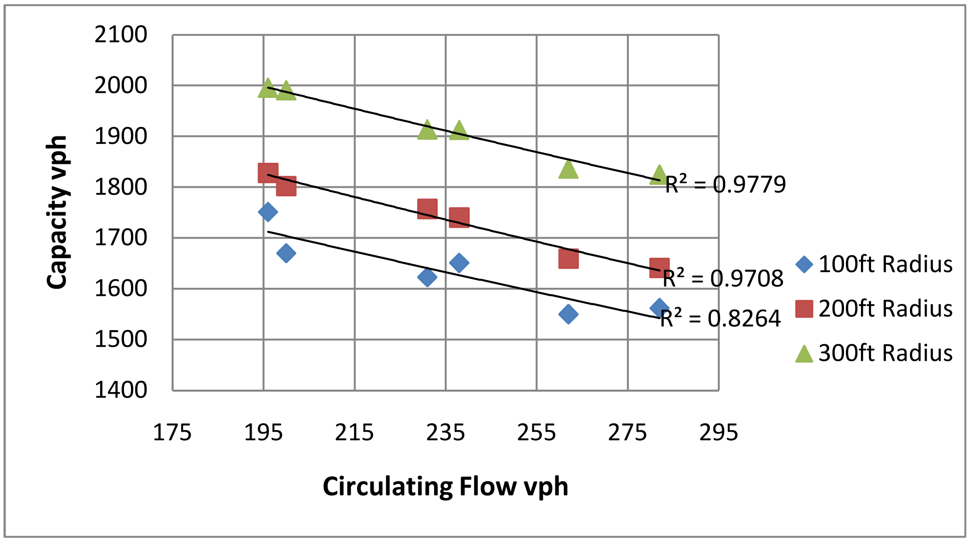

Figure 5.2 Effect of radius on capacity (at 10% trucks with a time gap of 3 secs passenger cars and 4 secs trucks)

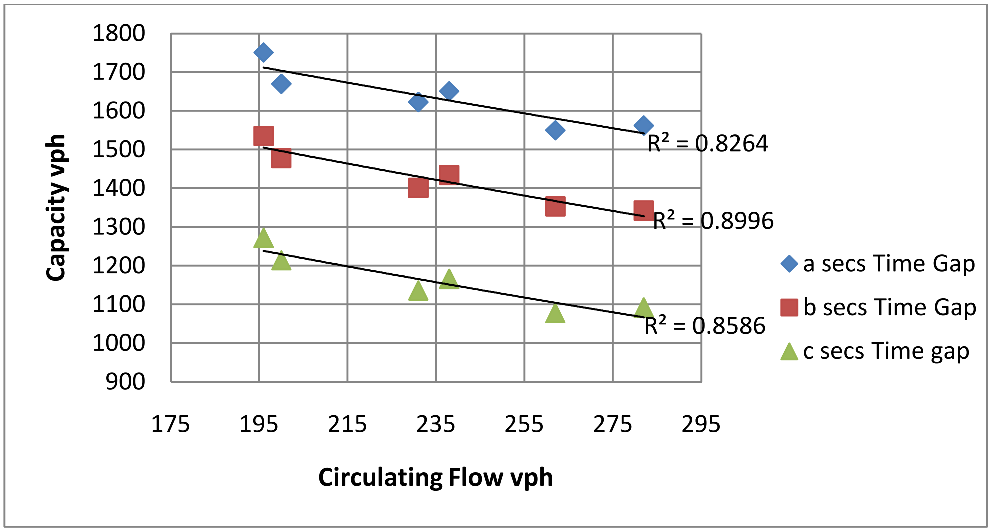

Figure 5.3 Effect of time gap on capacity

Where a: 3 secs for passenger cars and 4 secs trucks

b: 4 secs for passenger cars and 5 secs trucks

c: 5 secs for passenger cars and 6 secs trucks

The R squared values from Figures 5.1, 5.2 and 5.3 are very close to 1, which shows a good fit of the regression lines to the data from the simulations. Using the R squared values, the collected data can be validated for further testing to see how each of the factors (truck percentage, radius and time gap) affects on capacity.

From the Figure 5.1, the trend in the graph is expected as with an increase in truck percentage increases the delay because trucks would need a longer gap to merge into the circulating traffic and they take a longer time to accelerate from idling.

An inverse trend was expected when the radii were increased. Increasing the radius, increases travel time hence giving more space within the circulating traffic for vehicles to merge.

A higher time gap would reduce capacity because vehicles would have to wait longer before merging into the circulating traffic.

The raw data for the emission scenarios were also represented in graphical format. Since emissions at intersection are a function of circulating flows, the emissions recorded from the simulation were plotted against the circulating flow for each of the scenarios.

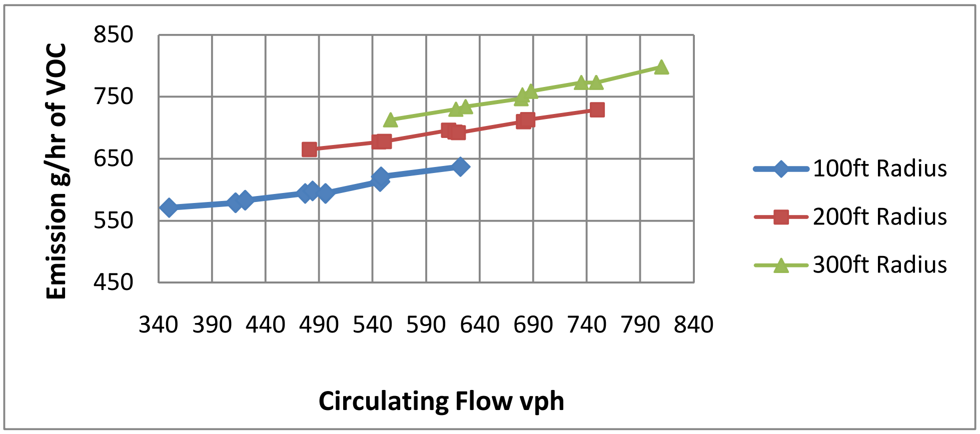

Figure 5.4 Effect of radius of circulation on VOC emissions

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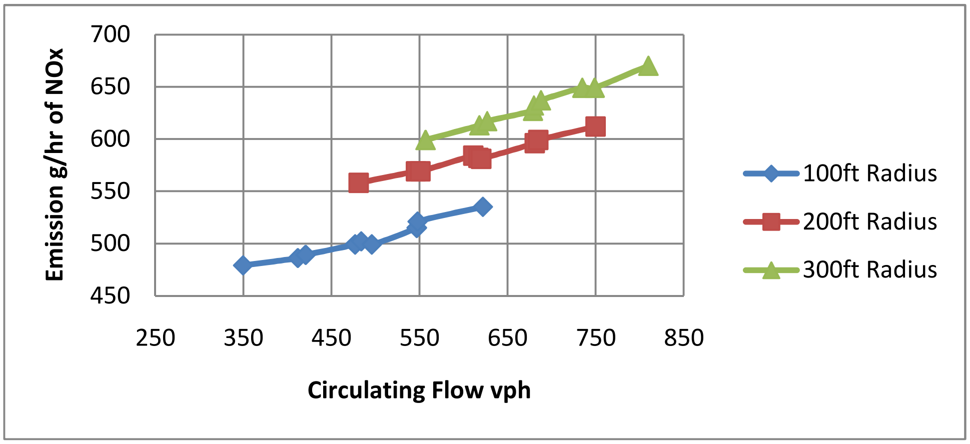

Figure 5.5 Effect of radius of circulation on NOx emissions

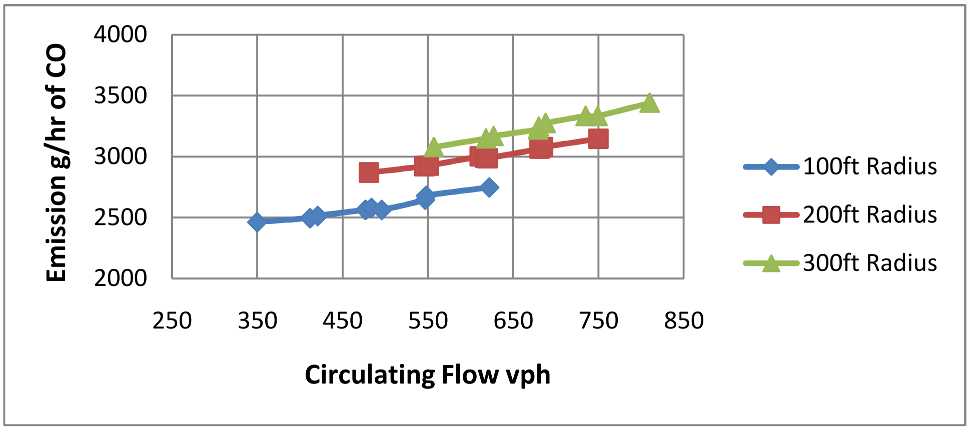

Figure 5.6 Effect of radius of circulation on CO emissions

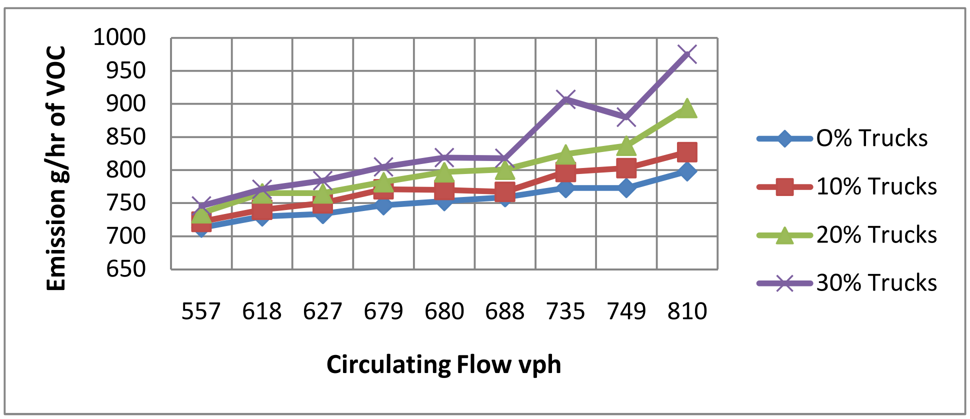

Figure 5.7 Effect of truck percentage on VOC emissions

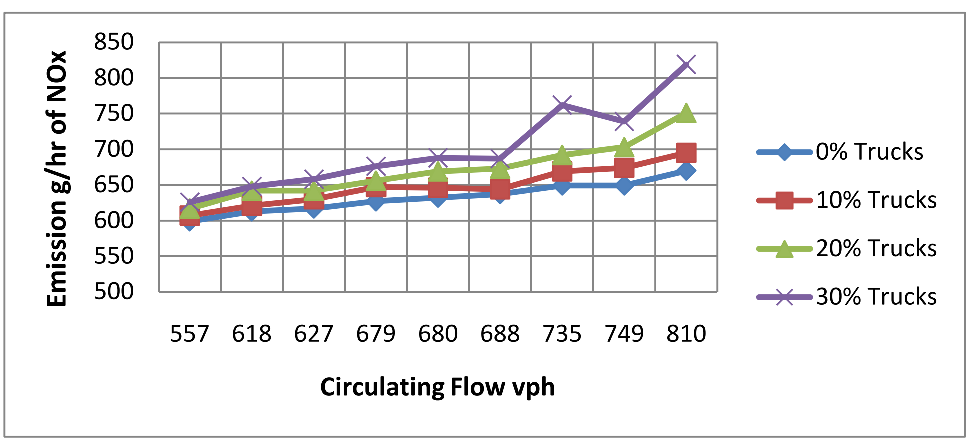

Figure 5.8 Effect of truck percentage on NOx emissions

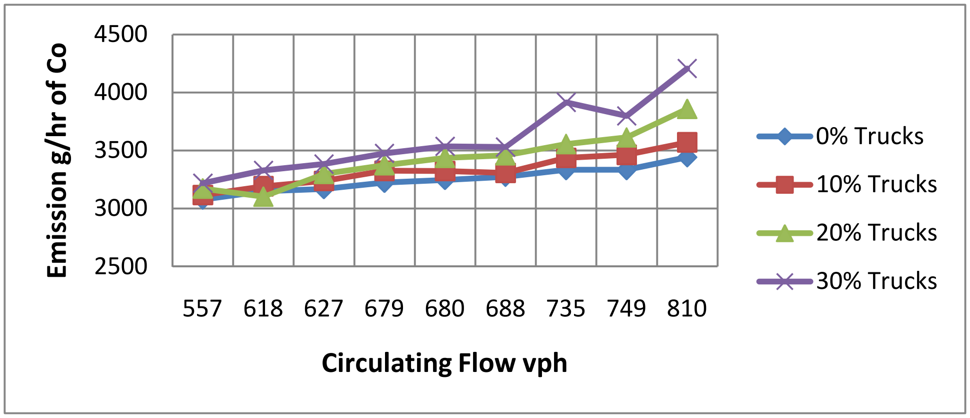

Figure 5.9 Effect of truck percentage on CO emissions

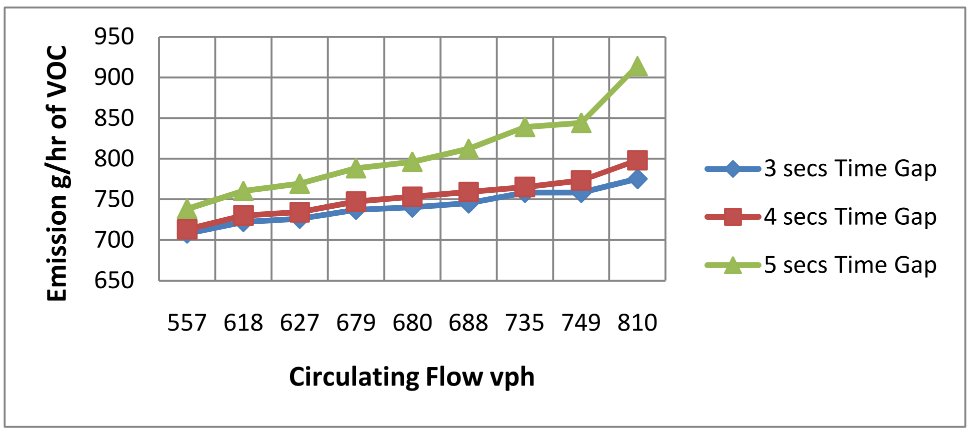

Figure 5.10 Effect of time gap on VOC emissions

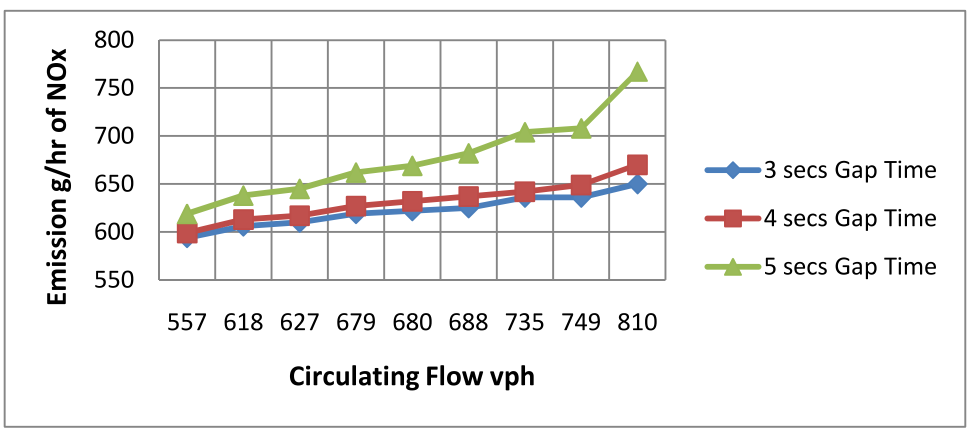

Figure 5.11 Effect of time gap on NOx emissions

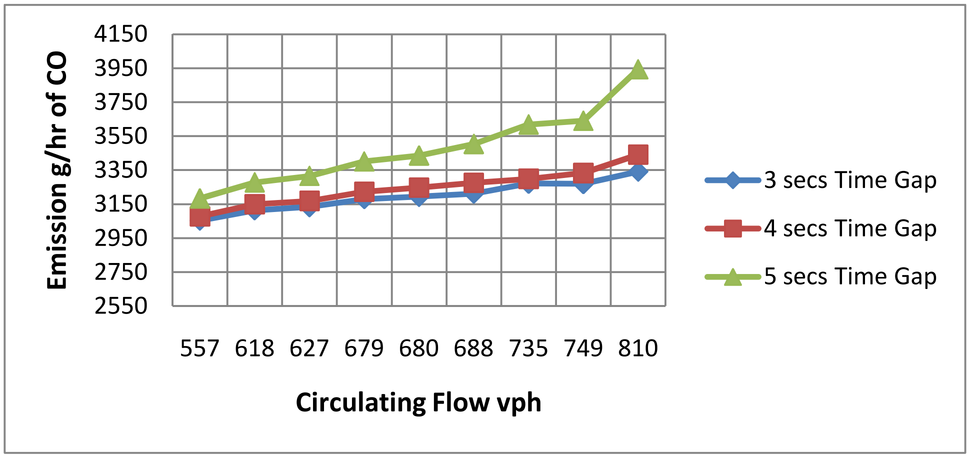

Figure 5.12 Effect of time gap on CO emissions

Figures 5.4 to 5.12 all show the same trend, that is they all show an increase in emissions with an increase in the variables (Truck percentage, radius and time gap).

This is a trend that would be expected as increasing truck percentage means reducing capacity and increasing delay times, also trucks generally produce more emissions than passenger cars.

Increasing the radius would mean increase capacity and more vehicles would be present within the roundabout and and travel time would increase as well thus more emissions would be generated.

To further investigate the effect of truck percentage, radius and time gap on capacity and emissions at roundabouts, all the data were transferred to SAS statistical Software (*SAS Institute Inc. 2009*) for further evaluation.

The following were used to represent the different variables in SAS:

tg: time gap

tp: truck percentage

cf: circulating flow

radius: radius of circulation

cirf: circulating flow

et: emission type

cp: capacity

emissions: emissions emitted

At a 95% confidence level, the effects of the radius, time gap, circulating flow and truck percentages were evaluated using the data from Table 5.1. Appendix D shows the complete results from SAS. The interaction between the following variables were tested: truck percentage and time gap, truck percentage and radius, truck percentage and circulating flow, radius and time gap, circulating flow and time gap and radius and circulating flow and the Table 5.6 was generated with an R squared value of 0.98 which determines the overall fit of the model.

Table 5.6 Effect of geometric, traffic flow and behavioral parameters on capacity

Source	DF	Type III SS	Mean Square	F Value	Pr > F
truck percentage	1	34241.5755	34241.5755	31.76	<.0001
time gap	2	116812.1860	58406.0930	54.17	<.0001
radius	1	92753.9023	92753.9023	86.03	<.0001
circulating flow	1	44396.3923	44396.3923	41.18	<.0001
truck percentage * time gap	2	34928.1296	17464.0648	16.20	<.0001
truck percentage * radius	1	11679.0139	11679.0139	10.83	0.0012
truck percentage * circulating flow	1	1796.2799	1796.2799	1.67	0.1988
radius * time gap	2	61030.6852	30515.3426	28.30	<.0001
circulating flow * time gap	2	108.4306	54.2153	0.05	0.9510
radius * circulating flow	1	2869.7149	2869.7149	2.66	0.1049

From Table 5.6 shows that the interaction between the variables truck percentage with circulating flow, circulating flow with time gap, and radius with circulating flow do not have any significant effect on the estimated capacity values, as their p-values are greater than 0.05.

Truck percentage with circulating flow, circulating flow with time gap, and radius with circulating flow were then eliminated from the model and the procedure was carried out again. Table 5.7 was generated, which shows that the rest of the variables do have a significant effect on the result (capacity) with the p-values less than 0.05 and a new R squared value of 0.99.

Table 5.7 Effect of geometric, traffic flow and behavioral parameters on capacity

Source	DF	Type III SS	Mean Square	F Value	Pr > F
truck percentage	2	2055259.123	1027629.562	2680.50	<.0001
time gap	2	3627125.531	1813562.765	4730.54	<.0001
radius	2	3279163.568	1639581.784	4276.73	<.0001
circulating flow	1	619540.274	619540.274	1616.02	<.0001
truck percentage * radius	4	12662.358	3165.590	8.26	<.0001
radius * time gap	4	64833.617	16208.404	42.28	<.0001
truck percentage * time gap	4	35205.951	8801.488	22.96	<.0001

With this new model, the radii were compared among each other to see if there is a significant change in capacity with a change in radius. The same was done for time gap. Tables 5.8 and 5.9 show these comparisons.

Table 5.8 Effect of radius on capacity of a roundabout

radius	cp LSMEAN	LSMEAN Number
100	1279.31481	1
200	1397.22222	2
300	1622.27778	3

Least Squares Means for effect radius Pr > |t| for H0: LSMean(i)=LSMean(j) Dependent Variable: cp			
i/j	1	2	3
1		<.0001	<.0001
2	<.0001		<.0001
3	<.0001	<.0001	

From Table 5.8, it can be concluded that there is a significant effect on capacity values with an increase or decrease in radius of a roundabout as the null hypothesis is rejected.

Table 5.9 Effect of time gap on capacity

tg	cp LSMEAN	LSMEAN Number
a	1605.40741	1
b	1452.88889	2
c	1240.51852	3

Least Squares Means for effect tg Pr > |t| for H0: LSMean(i)=LSMean(j) Dependent Variable: cp			
i/j	1	2	3
1		<.0001	<.0001
2	<.0001		<.0001
3	<.0001	<.0001	

Also looking at Table 5.9, the conclusion that there is a significant effect on capacity with an increase or decrease in the time gap can also be drawn as the null hypothesis is rejected.

To evaluate the effect of truck traffic on capacity of roundabouts, data from Table 5.2 was used. These data were analyzed and the SAS results are present in Appendix E. The first model generated is represented in Table 5.10 with an R squared value of 0.99.

Table 5.10 Effect of truck percentage on capacity

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Truck percenntage	3	3881439.79	1293813.26	102.66	<.0001
Circulating flow	23	10665636.75	463723.34	36.79	<.0001
truck percentage * circulating flow	69	39920.73	578.56	0.05	1.0000

From Table 5.10, the interaction between circulating flow with truck percentage does not show a significant effect on the capacity, with its p-value greater than 0.05; thus, it was eliminated. Table 5.11 shows the new model with an R squared value of 0.99.

Table 5.11 Effect of truck percentage on capacity

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Truck percenntage	3	4102824.52	1367608.17	579.49	<.0001
Circulating flow	23	10665636.75	463723.34	196.49	<.0001

This new model was then tested to see if an increase in truck percentage produces a significant change in capacity at roundabouts. Table 5.12 shows the results of this test.

Table 5.12 Effect of truck percentage on capacity

tp	cp LSMEAN	LSMEAN Number
0	1845.72569	1
10	1648.72569	2
20	1481.68866	3
30	1320.98495	4

Least Squares Means for effect tp Pr > |t| for H0: LSMean(i)=LSMean(j) Dependent Variable: cp				
i/j	1	2	3	4
1		<.0001	<.0001	<.0001
2	<.0001		<.0001	<.0001
3	<.0001	<.0001		<.0001
4	<.0001	<.0001	<.0001	

Comparing the effect of truck traffic on capacity with the truck percentages 0%, 10%, 20% and 30% shows from Table 5.12 that there is a significant effect on capacity with an increase in the percentage of trucks at a roundabout as the null hypothesis is rejected for all cases.

SAS was also used to evaluate the effect of geometric, behavioral and traffic flow characteristics on emissions at roundabouts. Data from Table 5.3 was used to evaluate the effects of radius on emissions at roundabouts. Appendix F has the complete model results from SAS. In Table 5.13, the variables were checked to see if they all have a significant effect on emissions and also if the interaction between the variables contribute to an added effect on emissions generated. This model yielded an R squared value of 0.99.

Table 5.13 Effect of radius on emissions

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Circulating flow	1	42412.911	42412.911	137.75	<.0001
Emission type	2	1077113.813	538556.907	1749.15	<.0001
radius	1	15732.561	15732.561	51.10	<.0001
Circulating flow *radius	1	214.145	214.145	0.70	0.4071
Circulating flow * emission type	2	101877.953	50938.977	165.44	<.0001
radius* emission type	2	157239.292	78619.646	255.35	<.0001

From Table 5.13, it can be seen that the interaction between the circulating flows and the radius of circulation does not contribute a significant effect on emissions produced. These values were eliminated from the model and the procedure was repeated with the other variable and generated a new R squared value of 0.999. Table 5.14 shows the other parameters do have a significant effect on emissions produced at a roundabout.

Table 5.14 Effect of radius on emissions

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Circulating flow	1	147428.1705	147428.1705	1000.61	<.0001
Emission type	2	898812.5456	449406.2728	3050.16	<.0001
radius	2	265426.5818	132713.2909	900.74	<.0001
Circulating flow *radius	2	89661.4695	44830.7347	304.27	<.0001
radius* emission type	4	161863.2521	40465.8130	274.65	<.0001

With this new model, test procedures were carried out to check if there is a significant effect on emissions with an increase or decrease in the radius of roundabouts. Table 5.15, shows the results from this procedure.

Table 5.15 Effect of radius on emissions

radius	emission LSMEAN	LSMEAN Number
100	1290.32250	1
200	1413.42214	2
300	1495.47758	3

Least Squares Means for effect radius Pr > |t| for H0: LSMean(i)=LSMean(j) Dependent Variable: emission			
i/j	**1**	**2**	**3**
1		<.0001	<.0001
2	<.0001		<.0001
3	<.0001	<.0001	

In table 5.15 the three radii chosen all show a significant difference in the way they affect the emissions at roundabouts; that is, with an increase in radius, there is a significant increase in emissions.

Similarly, the presence of trucks at roundabouts were also verified to see if an increase or decrease in their percentage affects the amount of emissions generated at roundabouts. Table 5.16 shows the first model (using data from Table 5.4), which checks for variables that show a significant effect on the generation of emissions and the interaction between these variables to see if they have an added effect on emissions generated. This model generated an R squared value of 0.99. The complete result for the SAS procedure is found in Appendix G.

Table 5.16 Effect of truck percentage on emissions

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Circulating flow	1	68896.9018	68896.9018	31.68	<.0001
Emission type	2	352590.3657	176295.1828	81.05	<.0001
Truck percentage	1	73477.2762	73477.2762	33.78	<.0001
Circulating flow * Truck percentage	1	115308.9427	115308.9427	53.01	<.0001
Circulating flow * Emission type	2	502209.0870	251104.5435	115.45	<.0001
Truck percentage * Emission type	2	242514.7111	121257.3556	55.75	<.0001

This model showed all variables having a significant effect on the amount of emissions generated at roundabouts. This model was then tested for the effect of increasing or decreasing the truck volume on the amount of emissions generated. Table 5.17 shows the result of this procedure.

Table 5.17 Effect of truck percentage on emissions

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tp	emission LSMEAN	LSMEAN Number
0	1545.22222	1
10	1583.37037	2
20	1633.81481	3
30	1711.00000	4

Least Squares Means for effect tp Pr > |t| for H0: LSMean(i)=LSMean(j) Dependent Variable: emission				
i/j	1	2	3	4
1		0.0174	<.0001	<.0001
2	0.0174		0.0007	<.0001
3	<.0001	0.0007		<.0001
4	<.0001	<.0001	<.0001	

Similar to the radii comparison, the changes in the percentages of trucks in the traffic at a roundabout shows a strong effect in the amount of emissions released. Since emissions would increase depending on intersection delay, average delay was evaluated as well for all four levels of truck percentages. Figure 5.13 shows a plot of average delay against circulating flow to determine the effect on delay of increase or decrease in truck percentages.

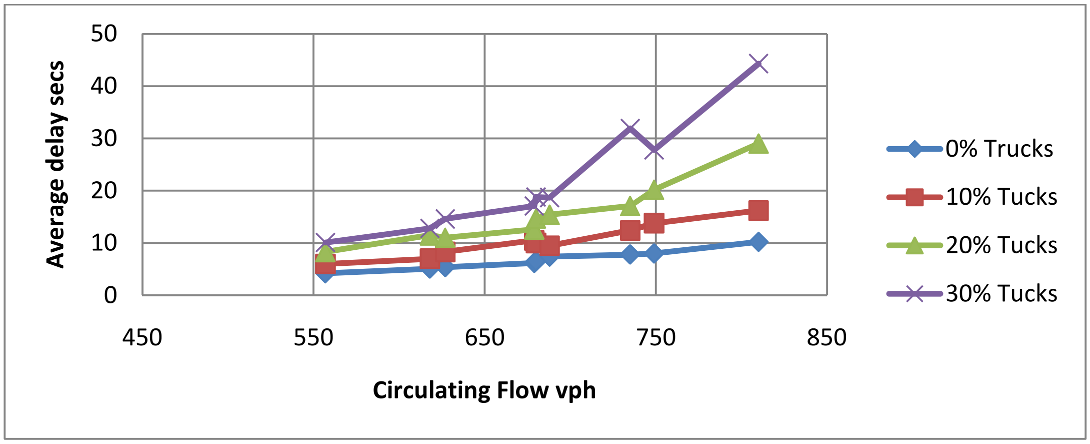


Figure 5.13 Effect of truck percentage on average delay

From Figure 5.13, it can be seen that there is a large amount of increase in average delay with an increase in truck percentage.

To verify if an increase or decrease in the gap time at a roundabout affects the amount of emissions generated, data from Table 5.5 was analyzed in SAS to check for this effect. Table

5.18 shows the first model with all variables and their interactions with one another with an R squared value of 0.99 and Appendix H contains the complete analyses carried out in SAS.

Table 5.18 Effect of time gap on emissions

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Circulating flow	1	52152.782	52152.782	26.09	<.0001
Emission type	2	2105402.663	1052701.332	526.65	<.0001
Time gap	1	131458.883	131458.883	65.77	<.0001
Circulating flow * Time gap	1	133828.563	133828.563	66.95	<.0001
Circulating flow * emission type	2	157195.331	78597.665	39.32	<.0001
Time gap*emission type	2	385.004	192.502	0.10	0.9083

From Table 5.18, it can be seen that the interaction between time gap and emission type does not show any significant effect on the amount of emissions emitted. This interaction was eliminated from the model and the procedure carried out again, with results represented in Table 5.19 and a new R squared value of 0.999.

Table 5.19 Effect of time gap on emissions

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Circulating flow	1	329306.074	329306.074	192.82	<.0001
Emission type	2	2259578.866	1129789.433	661.54	<.0001
Time gap	2	69153.878	34576.939	20.25	<.0001
Circulating flow * Time gap	2	69381.295	34690.648	20.31	<.0001
Circulating flow * emission type	2	306471.104	153235.552	89.73	<.0001

From Table 5.19 all the parameters and their interactions show a strong effect on the amount of emissions released at roundabouts. The Tuky method of comparison was then applied to the model to see if there is a significant effect in emissions generated with the difference in time gaps at roundabout intersections. Table 5.20 shows this comparison.

Table 5.20 Effect of time gap on emissions

tg	emission LSMEAN	LSMEAN Number
3	1576.31832	1
4	1530.09841	2
5	1530.75409	3

Least Squares Means for effect tg Pr > |t| for H0: LSMean(i)=LSMean(j) Dependent Variable: emission			
i/j	1	2	3
1		0.0145	0.0448
2	0.0145		0.9990
3	0.0448	0.9990	

Looking at Table 5.20, it can be seen that there is no significant change in emissions between time gaps of 4 secs and 5 secs and there is a significant difference in emissions between gaps 3 secs and 4 secs, 3 secs and 5 secs. Time gap 3 secs has a mean emission rate which is higher than time gap 4 secs and 5 secs. A conclusion could be drawn that at time gaps closer to 3 secs and lower, the amount of emissions emitted at a roundabout increases due to the fact that vehicles will have to accelerate faster from almost zero speed to merge in the circulating traffic.

The effect of geometric, traffic flow and behavioral parameters were evaluated using the Bonferoni and Tuky methods with SAS statistical software.

Increasing the size of a roundabout increases the amount of emissions. Also, an increase in the volume of heavy vehicles yields an increase in emissions. It is thus necessary to consider all these parameters when building an emission model for roundabouts.

5.2 Adjustment for Heavy Vehicles

Heavy vehicles are defined as those with more than four tires touching the pavement (*HCM, 2000*). In order for existing capacity models to take into account the effect of heavy vehicles, a heavy vehicle factor is to be determined to adjust circulating flow rates, exiting flows rates and critical gap values or to adjust capacity estimates directly. This heavy vehicle factor will account for capabilities of heavy vehicles compared to passenger cars (*Rahmi, A. 2009*). According to the HCM 2000, the passenger car equivalent (E_T) used for each heavy vehicle is

2.0 passenger cars. The HCM 2000 provides the following formula to estimate a heavy vehicle factor:

$$f_{HV} = \frac{100}{100+\%HV(E_T-1)} \qquad 5.1$$

f_{HV} – Heavy Vehicle factor

$\%HV$ – % heavy vehicle for lane group volume

Applying this formula to the truck percentages used for this paper, the following heavy vehicle factors were obtained:

$f_{HV}(10\%\ trucks) = 0.909$

$f_{HV}(20\%\ trucks) = 0.833$

$f_{HV}(30\%\ trucks) = 0.769$

These heavy vehicle factors were then applied to 0% truck data from Table 5.2 to see if they will yield a similar value to the capacity values from the simulations using 10%, 20% and 30% truck volumes. These data were then plotted against each other for comparison. Figures 5.14, 5.15 and 5.16 show these comparisons. This data can be found in Appendix I.

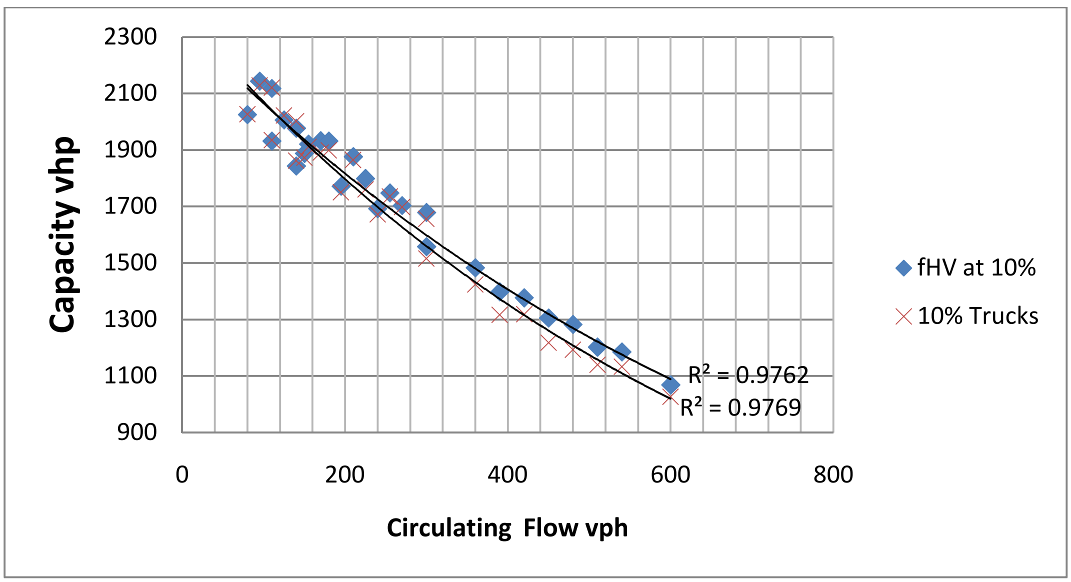


Figure 5.14 Comparison between data with 10% trucks and data with f_{HV} (10% trucks)

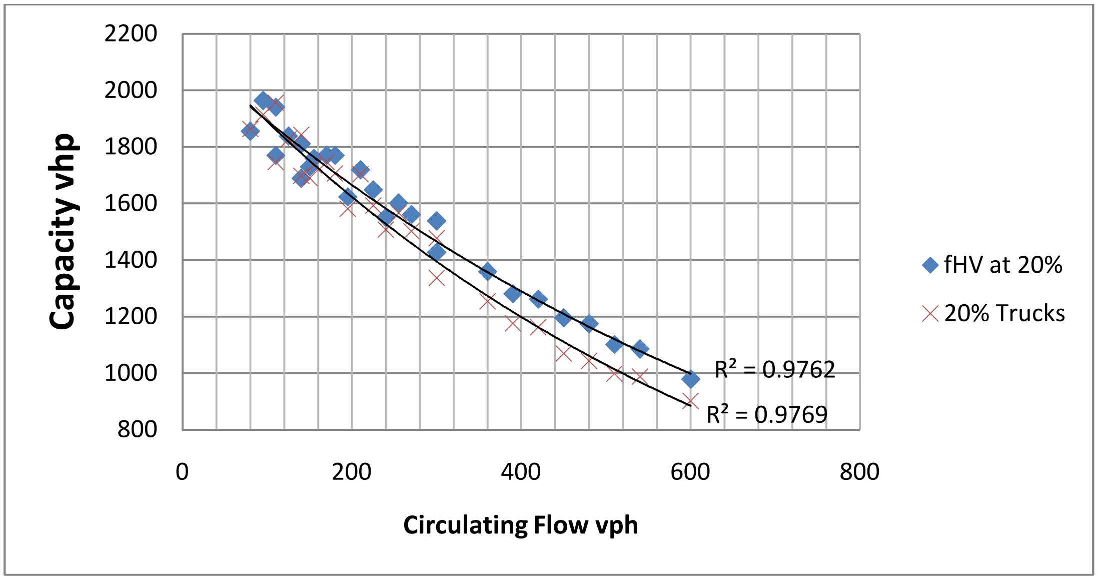


Figure 5.15 Comparison between data with 20% trucks and data with f_{HV} (20% trucks)

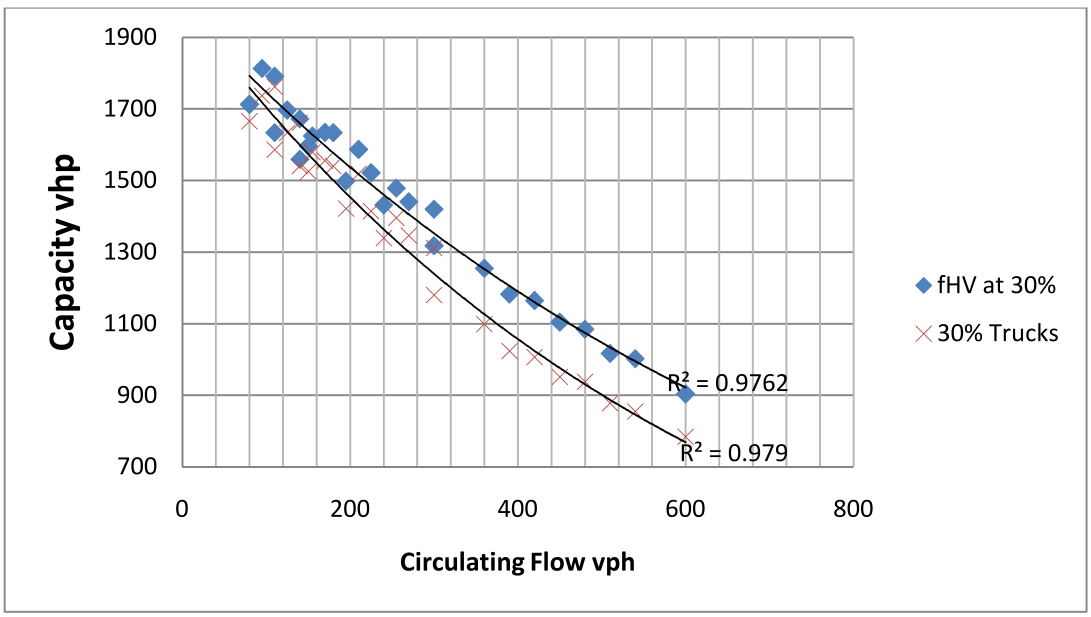


Figure 5.16 Comparison between data with 30% trucks and data with f_{HV} (30% trucks)

It is easy to conclude from the trends of the regression lines that at low circulating flows, using heavy vehicle factors will predict the same capacity value as a model with truck percentages as a variable. As the circulating flow increases, using a heavy vehicle factor produces higher capacity values. Also as the truck percentage increase, the regression lines move further away from each other, indicating higher predicted capacity values at higher truck percentages when using the HCM 2000 heavy vehicle factor equation.

CHAPTER 6

CONCLUSIONS AND FUTURE RESEARCH

This chapter presents the conclusions of this research and suggestions for future study of this topic.

The purpose of this thesis was to evaluate the effect of geometric, traffic flow and behavioral parameters on capacity and the amount of emissions emitted at roundabouts. Findings are based on simulation results which closely predict real-life traffic scenarios and my conclusions can be easily transferred or referred to any roundabout condition.

Data were collected at an existing roundabout at Southlake, Texas, in order to determine what range of values to use for accepted gaps in the simulation. Though drivers in the United States would accept different gaps from those in other countries due to driver unfamiliarity, an upper and lower bound was taken for the gap accepted so as to create a wide range to capture conditions in different areas. Certain variables were turned into constant parameters in order to maintain a low level of complexity. Other researchers as quoted in the literature review have proven that leaving these parameters constant has small effects, so that the capacity and emission results should not have been too sensitive to change.

6.1 Conclusions Based on Capacity Scenarios

After running the experiment and evaluating the results, it was statistically proven that:

- There is a significant increase in capacity with an increase in radius.
- There is a significant decrease in capacity with an increase in truck percentages.
- There is a significant decrease in capacity when longer critical gaps are accepted by entering drivers.

6.2 Conclusions Based on Emission Scenarios

Similarly experimental results from VISSIM were statistically evaluated for the effect of radius, truck percentage and time gap on emissions. The following conclusions were drawn after the SAS analyses:

- Emissions increase significantly with an increase in radius.
- Emissions increase significantly with an increase in truck percentages.
- At time gaps closer to 3 secs and lower, the amount of emissions emitted at a roundabout increases due to the fact that vehicles will have to accelerate faster from almost zero speed to merge in the circulating traffic (acceleration is the stage during driving cycle that produces the most emissions).

6.3 Future Work

Further research could be conducted to determine how the parameters used in this thesis plus the presence of high pedestrian traffic would affect capacity and emissions and how these emissions could directly affect human health. Since there might not be any existing roundabout with such conditions, it is preferable to use micro simulation software for this study in order to model every single parameter.

APPENDIX A

EXTRACTED ACCEPTED GAP, REJECTED GAP AND FOLLOW-UP TIME VALUES IN SECONDS FROM DATA COLLECTION

Rej Gap	Max rejected	accepted	follow up time		Rej Gap	Max rejected	accepted	follow up time
1.9	0	4.5	2.76		1.95	0	2.93	2.88
2.12	0	3.8	3.78		1.99	0	4.02	1.96
3.17	0	3.91	2.95		1.94	0	3.16	2.12
4.98	0	4.11	2.89		1.95	2.97	4.98	1.94
2.82	3.03	4.03	1.97		2.2	1.94	4.09	2.84
3.8	0	2.18	2.07		1.94	0	4.13	2.94
2.14	1.83	4.15	2.05		1.99	0	4.05	3.01
1.93	1.9	4.82	2		3.86	0	5.07	3.06
2.21	0	3.07	2.96		2	0	3.16	2.95
2.88	0	4.89	2.84		1.16	0	4.98	1.88
2.8	4.9	2.93	2.95		2.78	0	3.15	2.15
2.79	2.77	4	2.99		2	0	5.07	3.01
2.83	0	4.02	3.74		1.97	0	3.95	2.11
2.81	0	4.94	2.01		2.9	0	3.98	2.85
2.92	2.01	4.04	2.91		2.04	2.83	4.17	2.12
3.12	0	2.69	1.92		3.01	1.88	4.83	1.92
2.03	0	3.27	2.13		2.85	0	3.98	2.01
1.23	0	5.71	2.14		2.94	0	2.06	3.93
3.91	0	4.06	2.16		2.95	1.97	3.9	1.96
2.87	0	4.92	1.95		1.96	0	3.07	2.04
2.06	0	3.93	2.9		2	3.05	4.01	2.9
2.02	0	3.86	2		1.93	0	3.09	2.99
2.95	0	3.05	2.02		2.05	0	3.84	2.13
2.08	0	4.97	2.96		2.13	0	4	2.88
3.91	0	3.04	3		2.96	0	4.01	2.06
2.89	2.73	4.11	2.16		2.11	0	3.78	2.99
3.99	0	3.17	2.1		5.11	0	3.12	2.22
1.24	0	3.13	2.86		1.96	3.73	4.85	2.12
2.82	2.91	4.06	2.05		1.21	1.9	3.92	3.04
2.91	2.95	3.92	3.93		2.95	0	3.93	2.92
2.15	0	3.08	3.02		2.05	0	3.86	1.26
2.91	0	4.85	2.12		3.82	4.11	3.96	3.01
2.05	0	5.01	1.86		1.26	3.01	4.94	2.12
3.06	0	4.03	2.01		1.94	0	3	2.01
1.82	0	2.81	1.98		2.09	0.94	3.88	2.08
1.95	0	3.86	2.18		2.04	0	3.07	1.98

2.01	0	4.01	3.05		2.96	4.89	6.88	2.22
2.86	0	4.02	1.93		1.93	0	4.92	2.03
4.02	0	4.97	2.05		2.9	0	3.96	2.84
1.93	0	4.83	3.77		2.86	1.92	5.86	3.89
2.11	0	3.02	3.01		2.02	2.93	4.83	2.2
1.98	0	3.03	1.97		1.22	3.02	4.91	1.99
2.75	0	3.81	1.95		2.89	0	4.22	1.16
2.21	0	3.93	2.05		1.96	2.92	4.01	2.89
2.04	0	3.17	1.89		2	0	4.19	2.99

Rej Gap	Max rejected	accepted	follow up time		Rej Gap	Max rejected	accepted	follow up time
2.07	1.9	4.96	3.15		1.89	0	3.24	3.07
3.83	0	5.99	1.95		2.92	0	4.03	2.78
2.96	0	3.26	2.98		1.86	0	4.11	1.19
2.19	0	3.93	2.02		1.97	0	3.87	2.83
2.95	0	4.87	2.89		2.15	0	4.02	2.83
2.97	0	4.04	2.74		1.89	1.96	3.22	2.11
2.8	0	3.06	2.92		2.07	1.85	4.96	3.07
1.9	0	2.21	2.08		2.1	0	4.9	2.06
1.94	2.09	4.83	2.01		1.79	2.95	4.15	1.87
2.86	0	2.27	1.94		2.06	0	3.83	2.08
2.16	0	2.99	2.86		2.09	0	4.76	2.74
2.11	0	2.03	2		3	0	4.02	2.23
1.95	0	3.8	2.88		2.96	2	5.84	3.81
1.87	0	2.13	2.93		1.1	0	4.12	2.06
3.11	0	3.14	1.99		3.76	0	3.86	2.81
2.82	0	3.17	2.98		2.06	0	2.45	2.89
1.85	1.93	3.97	3.04		2.01	0	4	3.17
4.07	0	3.95	2.03		2.16	0	4.82	2.83
1.94	0	3.89	2.02		2.85	0	3.01	2.06
1.17	1.92	4.02	1.88		2.92	0	3.07	3.05
2.78	0	3.08	2.1		2.93	0	2.96	3.09
2.12	1.81	2.99	2.03		4.88	0	5.07	2.02
1.96	0	3.24	2.74		1.93	0	3.06	3.02
3.02	3.02	5	1.29		1.91	0	2.99	2.92
4.03	0	3.08	2.84		3.01	0	6.8	1.92
2.93	0	3.06	2.05		2.17	0	3.82	1.99

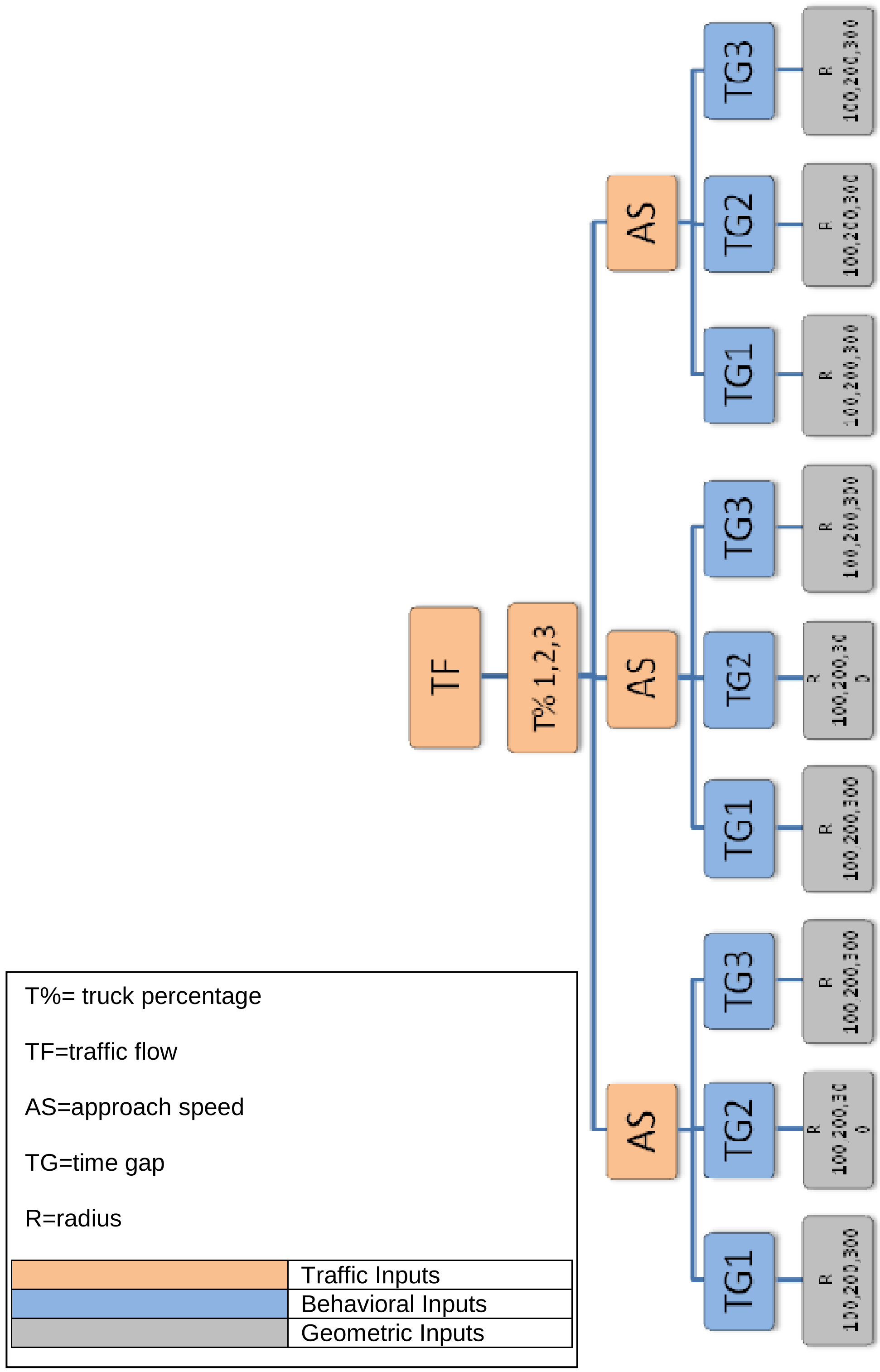
3.04	0	3.18	2.74		2.9	2.03	4.01	1.98
0.99	3.06	4.92	1.24		2.01	0	3.82	2.12
2.05	0	4.53	3.74		3.06	0	5.04	1.85
1.95	2.09	4.8	2.07		2.03	3.06	3.94	2.06
1.91	0	4.05	2.93		1.99	3.12	4.85	2.96
2.91	0	4.88	2.88		2.25	0	4	2.89
3.09	0	3.58	2.14		2.99	0	4.96	2.91
3.15	0	2.25	3.07		2.72	3.08	4.07	1.99
2.75	0	3.97	1.87		2.84	0	2.33	2.96
2.13	0	2.95	2.12		1.91	0	2.99	2
2.94	0	4.83	2.86		1.88			1.15
3.91	0	3.85	2.23		3.09			2.82
2.08	0	2.85	3		3			2.92
3.89	0	2.93	2.1		3.04			2.01
2.11	0	3.77	2.9		2.99			2.94
3.02	0	3.94	0.1		2.95			2.21
1.98	0	2.95	2.89		1.29			2.08
1.97	0	3.77	2.24		1.97			2.02
2.9	0	3.82	2.01		1.23			2.06

Rej Gap	Max rejected	accepted	follow up time		Rej Gap	Max rejected	accepted	follow up time
2.75			2.8		2.09			3.17
1.3			1.26		2.01			2.87
3.04			2.13		2.88			1.21
2.03			2.04		2.16			1.93
3.03			2.02		3.83			1.84
2.19			2.85		1.84			1.91
1.96			1.25		2.04			2.87
1.91			2.21		4.15			2.09
1.91			2.02		1.25			2.18
2.77			2.74		1.12			2.78
1.17			3.01		1.83			3.03
2.11			2		1.98			2.2
2.96			2.78		2.14			2.87
3.04			1.96		2.02			2.83
2.13			2.01		2.98			2.93
2.78			2.08		1.97			2.27

2.89			2.95		2.79			3.77
2.09			3.06		3.15			2.05
1.17			1.99		2.92			2.26
1.92			2.91		3.06			2.01
3.01			2.94		2.21			1.96
2.98			3.05		1.27			2.76
2.03			2.94		1.12			2.82
3.06			2.92		1.95			2.85
2.05			1.95		1.95			2.1
2.02			1.18		2.15			2.12
2.1			2.08		2.02			1.83
3.18			2.8		2.96			3.78
3.92			1.95		1.99			1.21
2.83			2.03		2			2.84
2.01			3.06		2			2.2
3.11			2.86		2.1			2.21
1.2			2.8		3.86			1.98
2.04			2.06		2.91			2.18
3.12			1.23		3.09			1.87
2.98			1.98		2.05			2.05
1.97			2.2		2.05			1.92
3.03			1.91		3.91			3
2.01			2.84		1.23			1.94
2.88			2.1		2.89			2.05
2.87			2.01		1.95			2.85
2.09			2.05		2.93			2.08
2.9			2.06		2.83			
1.95			2.04		1.97			
2.92			2.04		2.74			

APPENDIX B

SETS OF SCENARIOS ANALYZED


TF
T% 1,2,3
AS
AS
AS
TG1
TG2
TG3
R
100,200,300
T%= truck percentage
TF=traffic flow
AS=approach speed
TG=time gap
R=radius
Traffic Inputs
Behavioral Inputs
Geometric Inputs

APPENDIX C

FORTRAN CODE FOR MEAN CRITICAL GAP LIKELIHOOD

```
  program Maximum likelihood
     character fnme*30,fnmee*50,fnmee2*50
     real
ac(1000),re(1000),aa(1000),rr(1000),ltf,m1,m2,m3,v1,v2,v3,mlast,vlast,ml,vl,mtemp,vtem
p,mm,vv,m,v,ss(30)
    logical endd

    fnme=' '
    fnmee=' '
    fnmee2=' '
    rf=log(0.99)
    diff=0.0005

c     open file

    write (9,'(''Name of data file ?'') ')
    read (9,'(a)') fnme
c    open
(1,file=fnme,access='sequential',form='unformatted',1status='old',err=999,iostat=ieee)
    open (1,file=fnme,status='old',err=999,iostat=ieee)
    do 83 i=30,1,-1
    if (fnme(i:i).ne.' ') then
      ifnme=i
      goto 84
    end if
  83 continue
    ifnme=1
  84 fnmee(1:ifnme)=fnme(1:ifnme)
    fnmee(ifnme+1:ifnme+7)=' - out1'
    write (9,'(''output file '',a)') fnmee
c
    open (2,file=fnmee)
c
    rewind (1)
    rewind (2)
    write (9,'(read in data'')')
c
c    read in data
c
    i=0
 100 endd=.false.
    i=i+1
    read (1,'(f10.2,f10.2)',iostat=ieee) ac(i),re(i)
    if ((ac(i)+at(i).le.0.01).or.(ac(i).ge.1000.0).or.1(at(i).ge.1000.0)) i=i-1
    if ((ieee.it.0)) goto 200
    goto 100
c
c
 200 n=i
    write (2,'(5x,1hi,6x,6haccept,6x,6hreject,2x,110hlog accept,2x,10hlog reject)')
c
c    calculated largest rejected gap and the accepted gap.
c
```

```
      do 210 i=1,n
      if (ac(i).le.0.001) then
        aa(i)=-10.0
      else
        aa(i)=log(ac(i))
      end if
c
      if (re(i).le.0.001) then
        rr(i)=-10.0
      else
        rr(i)=log(re(i))
      end if
      if (rr(i).ge.aa(i)) rr(i)=aa(i)+rf
      write (2,'(i6,2f12.2,2f12.4)') i,ac(i),re(i),aa(i),rr(i)
  210 continue
      write (9,'("all data read")')
c
c    calculate a mean and a variance
c
      s1=0.
      s2=0.
      s3=0.
      do 230 i=1,n
      s1=s1+aa(i)
      s2=s2+aa(i)*aa(i)
      s3=s3+1.
      if (rr(i).gt.-9.99) then
        s1=s1+rr(i)
        s2=s2+rr(i)*rr(i)
        s3=s3+1.0
      end if
  230 continue
      mm=s1/s3
      vv=sqrt((s2-mm*mm*s3)/(s3-1.))
      write (2,'("mean",f10.4)') mm
      write (2,'("standard deviation",f10.4)') vv
      write (9,'("mean",f10.4)') mm
      write (9,'("standard deviation",f10.4)') vv
      m2=mm
      v2=vv
c
c
c
c    ****************************************************
c
      find a new solution
c
c    ****************************************************
c
      mlast=m2
      vlast=v2
c
c    calculate a new mean
```

```
c
 310 ml=m2
     vl=v2
     im=0
     if (m2>9.9) goto 400
     if (V2>9.9) goto 400
     m1=m2/1.5
     m3=m2*1.5
     v1=v2/1.5
     v3=v2*1.5
 320 s1=0.
     s2=0.
     s3=0.
     im=im+1
     do 300 i=1,n
     v=aa(i)
     call cumn(v,m1,v2,d1,c1)
     if (c1.eq.c2) then
       m1=(m1+m2)*0.5
       goto 320
     else
       s1=s1+(d2-d1)/(c1-c2)
     end if
c
     v=aa(i)
     call cumn(v,m2,v2,d1,c1)
     v=rr(i)
     call cumn(v,m3,v2,d2,c2)
     s2=s2=(d2-d1)/(c1-c2)
c
     v=aa(i)
     call cumn(v,m3,v2,d1,c1)
     v=rr(i)
     call cumn(v,m3,v2,d2,c2)
     if (c1.eq.c2) then
       m3=(m3+m2)*0.5
       goto 320
     else
       s3=s3+(d2-d1)/(c1-c2)
     end if
 300 continue
     write (2,'(3x,3f8.3,8x,f8.3,8x,3f15.2)') m1,m2,m3,v2,s1,s2,s3
     if (s1.gt.0.) then
       if ((s2.gt.0.) .and. (s3.gt.0.)) then
         mtemp=(m1*s3-m3*s1)/(s3-s1)
         if (mtemp.gt.m3) then
           m1=m2
           m2=m3
           m3=mtemp*1.2
           if (m3.gt.10.0) m3=10.
           else
             m3=m2
             m2=m1
```

```
          m1=mtemp*0.8
          if (m1.lt.0.1) m1=0.1
         end if
        else if ((s2.gt.0.) .and. (s3.le.0.)) then
         mtemp=(m3*s2-m2*s3)/(s2-s3)
         m1=m2
         m2=mtemp
         m3=2.*m2-m1
        else if ((s2.le.0.) .and. (s3.gt.0.)) then
         goto 999
        else if ((s2.le.0.) .and. (s3.le.0.)) then
         mtemp=(m2*s1-m1*s2)/(s1-s2)
         m3=m2
         m2=mtemp
         m1=2.*m2-m3
        end if
       else
      if ((s2.gt.0.) .and. (s3.gt.0.)) then
        mtemp=(m2*s1-m1*s2)/(s1-s2)
        m3=m2
        m2=mtemp
        m1=2.*m2-m3
      else if ((s2.gt.0.) .and. (s3.le.0.)) then
        goto 999
      else if ((s2.le.0.) .and. (s3.gt.0.)) then
        mtemp=(m3*s2-m2*s3)/(s2-s3)
        m1=m2
        m2=mtemp
        m3=2.*m2-m1
      else if ((s2.le.0.) .and. (s3.le.0.)) then
        mtemp=(m1*s3-m3*s1)/(s3-s1)
        if (mtemp.gt.m3) then
          m1=m2
          m2=m3
          m3=mtemp*1.2
          if (m3.gt.10.) m3=10.
        else
          m3=m2
          m2=m1
          m1=mtemp*0.8
          if (m1.lt.0.1) m1=0.1
        end if
      end if
     end if
     if (im.gt.20) then
      goto 400
     end if
     if (abs(m2-m1).gt.diff) then
      m1=m2
      goto 320
     end if
c
c   calculate a new standard deviation
```

```
c
     write (2,'(3h* ,3f8.3,8x,f8.3)') m1,m2,m3,v2
     write (9,'(3h* ,3f10.3,10x,f10.3)') m1,m2,m3,v2
     iv=0
 360 s1=0.
     s2=0.
     s3=0.
     iv=iv+1
     do 340 i=1,n
     v=aa(i)
     call cumn(v,m2,v1,d1,c1)
     v=rr(i)
     call cumn(v,m2,v1,d2,c2)
     if (c1.eq.c2)then
       v1=(v1=V2)*0.5
       goto 360
     else
       s1=s1+((rr(i)-m2)*d2-(aa(i)-m2)*d1)/(c1-c2)
     end if
c
     v=aa(i)
     call cumn(v,m2,v2,d1,c1)
     v=rr(i)
     call cumn(v,m2,v2.d2.c2)
     s2=s2+((rr(i)-m2)*d2-(aa(i)-m2)*d1)/(c1-c2)
c
     v=aa(i)
     call cumn(v,m2,v3,d1,c1)
     v=rr(i)
     call cumn(v,m2,v3,d2,c2)
     if (c1.eq.c2) then
       v3=(v3+v2)*0.5
       goto 360
     else
       s3=s3+((rr(i)-m2)*d2-(aa(i)-m2)*d1)/(c1-c2)
     end if
 340 continue
     write (2,'(11x,f8.3,8x,3f8.3,3f15.2)') m2,v1,v2,v3,s1,s2,s3
c     write (9,'(13x,f10.3,10x,3f10.3)') m2,v1,v2,v3
     if (s1.gt.0.) then
       if ((s2.gt.0.) .and. (s3.gt.0.)) then
         vtemp=(v1*s3-v3*S1)/(s3-s1)
         if (vtemp.gt.v3) then
           v1=v2
           v2=v3
           v3=min(vtemp*1.2,v3*1.4)
c            if (v3.gt.10.0) v3=10.0
         else
           v3=v2
           v2=v1
           v1=max(vtemp*0.8,v1/1.4)
c            if (v1.lt.0.1) v1=0.1
         end if
```

```
      else if ((s2.gt.0.) .and. (s3.le.0.)) then
        vtemp=(v3*s2-v2*S3)/(s2-s3)
        v1=v2
        v2=vtemp
        v3=2.*v2-v1
      else if ((s2.le.0.) .and. (s3.gt.0.)) then
        goto 999
      else if ((s2.le.0.) .and. (s3.le.0.)) then
        vtemp=(v2*s1-v1*s2)/(s1-s2)
        v3=v2
        v2=vtemp
        v1=2.*v2-v3
      end if
    else
      if ((s2.gt.0.) .and. (s3.gt.0.)) then
        vtemp=(v2*s1-v1*S2)/(s1-s1)
        v3=v2
        v2=vtemp
        v1=2.*v2-v3
      else if ((s2.gt.0.) .and. (s3.le.0.)) then
        goto 999
      else if ((s2.le.0.) .and. (s3.gt.0.)) then
        vtemp=(v3*s2-v2*S3)/(s2-s3)
        v1=v2
        v2=vtemp
        v3=2.*v2-v1
      else if ((s2.le.0.) .and. (s3.le.0.)) then
        vtemp=(v1*s3-v3*S1)/(s3-s1)
        if (vtemp.gt.v3) then
          v1=v2
          v2=v3
          v3=min(vtemp*1.2,v3*1.4)
          IF (v3.gt.10.0) v3=10.0
        else
          v3=v2
          v2=v1
          v1=max(vtemp*0.8,v1/1.4)
          if (v1.lt.0.1) v1=0.1
        end if
      end if
    end if
    if (abs(v2-v1).gt.diff) then
      vl=v2
      goto 360
    end if
c
c    check solution
c
    am=abs(m2-mlast)
    av=abs(v2-vlast)
    write (2.'(2h**,9x,f8.3,8x,3f8.3,4f10.3)') m2,v1,v2,v3,mlast,am
    lvlast,av
    write (9,'(2h**,11x,f10.3,10x,5f10.3)') m2,v1,v2,v3,am,av
```

```
      if ((am.gt.diff).or.(av.gt.diff)) then
        mlast=m2
        vlast=v2
        goto 310
      end if
c
c     calculate the likelihood
c
      s1=0
      do 630 i=1,n
      a=aa(i)
      call cumn(a,m2,v2,d1,c1)
      r=rr(i)
      call cumn(r,m2,v2,d2,c2)
      if (c1.eq.c2) then
       s1=-999999.99
       goto 620
      else
       s1=s1+log(c1-c2)
      end if
  630 continue
  620 write (2,'("likelihood =",f20.4)') s1
      write (9,'("likelihood =",f20.4)') s1
      goto 999
c
c     ****************************************************
c
c     Write out data for the case when the data does not converge
c
c     ****************************************************
c
  400 continue
c
c     find values for the sums
c
      write (2,'(//10h**********//)')
      write (9,'(//10h**********//)')
c
      m2=aint(mm*10)/10.0-1.0
      V2=aint(vv*10)/10.0-0.8
c
      do 740 i=1,22
  740 ss(i)=v2+float(i-1)/10.
      write (2,'(8x,1h,,22(f8.2,1h,))') (ss(i),i=1,22)
      do 710 im=1,31
      m=m2+float(im-1)/10.
      do 720 iv=1,22
      v=v2+float(iv-1)/10.
      ss(iv)=0.
      do 730 i=1,n
      a=aa(i)
      call cumn(a,m,v,d1,c1)
      r=rr(i)
```

```
      call cumn(r,m,v,d2,c2)
      if (c1.eq.c2) then
        ss(iv)=-999999.99
        goto 720
      else
        ss(iv)=ss(iv)+log(c1-c2)
      end if
  730 continue
  720 continue
      write (2,'(f8.2,1h,,22(f8.2,1h,))') m,(ss(i),i=1,22)
      write (9,'(f8.3)') m
  710 continue
c
c
c    calculate the likelihood
c
      s1=0
      do 670 i=1,n
      a=aa(i)
      call cumn(a,m2,v2,d1,c1)
      r=rr(i)
      call cumn(r,m2,v2,d2,c2)
      if (c1.eq.c2) then
        s1=-999999.99
        goto 660
      else
        s1=s1+log(c1-c2)
      end if
  670 continue
  660 write (2,'("likelihood = ",f20.4)') s1
      write (9,'("likelihood = ",f20.4)') s1
c
c
  999 stop
      end
      subroutine cumn(a,m,v,d,c)
      real a,m,v,d,c,x,y,u
      x=(a-m)/v
      if (x.lt.-11.) then
        c=0.
        d=0.
      else if (x.gt.11.) then
        c=1.
        d=0.
      else
        d=exp(-x*x/2)/sqrt(6.28318*v*v)
        if (x.gt.0) then
          y=x*(0.04417*x*x+1.)
          u=exp(1.5976*y)
          c=u/(1+u)
        else
          y=-x*(0.04417*x*x+1.)
u=exp(1.5976*y) c=1.-u/(1+u)  end if end if return     end
```

APPENDIX D

SAS EVALUATION FOR THE EFFECT OF RADIUS, GAP TIME AND TRUCK PERCENTAGES ON CAPACITY OF ROUNDABOUTS

Class Level Information		
Class	Levels	Values
tg	3	a b c

Number of Observations Read	162
Number of Observations Used	162

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	14	9589735.550	684981.111	635.31	<.0001
Error	147	158493.833	1078.189		
Corrected Total	161	9748229.383			

R-Square	Coeff Var	Root MSE	cp Mean
0.983741	2.291501	32.83579	1432.938

Source	DF	Type III SS	Mean Square	F Value	Pr > F
tp	1	34241.5755	34241.5755	31.76	<.0001
tg	2	116812.1860	58406.0930	54.17	<.0001
radius	1	92753.9023	92753.9023	86.03	<.0001
cf	1	44396.3923	44396.3923	41.18	<.0001
tp*tg	2	34928.1296	17464.0648	16.20	<.0001
tp*radius	1	11679.0139	11679.0139	10.83	0.0012
tp*cf	1	1796.2799	1796.2799	1.67	0.1988
radius*tg	2	61030.6852	30515.3426	28.30	<.0001
cf*tg	2	108.4306	54.2153	0.05	0.9510
radius*cf	1	2869.7149	2869.7149	2.66	0.1049

Class Level Information		
Class	**Levels**	**Values**
tg	3	a b c
tp	3	10 20 30
radius	3	100 200 300

Number of Observations Read	162
Number of Observations Used	162

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	19	9693790.422	510199.496	1330.82	<.0001
Error	142	54438.961	383.373		
Corrected Total	161	9748229.383			

R-Square	Coeff Var	Root MSE	cp Mean
0.994416	1.366417	19.57991	1432.938

Source	DF	Type III SS	Mean Square	F Value	Pr > F
tp	2	2055259.123	1027629.562	2680.50	<.0001
tg	2	3627125.531	1813562.765	4730.54	<.0001
radius	2	3279163.568	1639581.784	4276.73	<.0001
cf	1	619540.274	619540.274	1616.02	<.0001
tp*radius	4	12662.358	3165.590	8.26	<.0001
tg*radius	4	64833.617	16208.404	42.28	<.0001
tg*tp	4	35205.951	8801.488	22.96	<.0001

tp	cp LSMEAN	LSMEAN Number
10	1572.03704	1
20	1430.61111	2
30	1296.16667	3

Least Squares Means for effect tp Pr > |t| for H0: LSMean(i)=LSMean(j) Dependent Variable: cp			
i/j	**1**	**2**	**3**
1		<.0001	<.0001
2	<.0001		<.0001
3	<.0001	<.0001	

radius	cp LSMEAN	LSMEAN Number
100	1279.31481	1
200	1397.22222	2
300	1622.27778	3

Least Squares Means for effect radius Pr > |t| for H0: LSMean(i)=LSMean(j) Dependent Variable: cp			
i/j	**1**	**2**	**3**
1		<.0001	<.0001
2	<.0001		<.0001
3	<.0001	<.0001	

tg	cp LSMEAN	LSMEAN Number
a	1605.40741	1
b	1452.88889	2
c	1240.51852	3

Least Squares Means for effect tg Pr > |t| for H0: LSMean(i)=LSMean(j) Dependent Variable: cp			
i/j	**1**	**2**	**3**
1		<.0001	<.0001
2	<.0001		<.0001
3	<.0001	<.0001	

APPENDIX E

SAS EVALUATION FOR EFFECT ON TRUCK VOLUMES ON CAPACITY OF A ROUNDABOUT

Class Level Information		
Class	**Levels**	**Values**
cf	24	80 95 110 125 140 150 155 170 180 195 210 225 240 255 270 300 360 390 420 450 480 510 540 600
tp	4	0 10 20 30

Number of Observations Read	108
Number of Observations Used	108

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	95	14808382.00	155877.71	12.37	<.0001
Error	12	151242.00	12603.50		
Corrected Total	107	14959624.00			

R-Square	Coeff Var	Root MSE	cp Mean
0.989890	7.035637	112.2653	1595.667

Source	DF	Type III SS	Mean Square	F Value	Pr > F
tp	3	3881439.79	1293813.26	102.66	<.0001
cf	23	10665636.75	463723.34	36.79	<.0001
cf*tp	69	39920.73	578.56	0.05	1.0000

Class Level Information		
Class	**Levels**	**Values**
cf	24	80 95 110 125 140 150 155 170 180 195 210 225 240 255 270 300 360 390 420 450 480 510 540 600
tp	4	0 10 20 30

Number of Observations Read	108
Number of Observations Used	108

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	26	14768461.27	568017.74	240.68	<.0001
Error	81	191162.73	2360.03		
Corrected Total	107	14959624.00			

R-Square	Coeff Var	Root MSE	cp Mean
0.987221	3.044507	48.58018	1595.667

Source	DF	Type III SS	Mean Square	F Value	Pr > F
tp	3	4102824.52	1367608.17	579.49	<.0001
cf	23	10665636.75	463723.34	196.49	<.0001

tp	cp LSMEAN	LSMEAN Number
0	1845.72569	1
10	1648.72569	2
20	1481.68866	3
30	1320.98495	4

Least Squares Means for effect tp Pr > |t| for H0: LSMean(i)=LSMean(j) Dependent Variable: cp				
i/j	1	2	3	4
1		<.0001	<.0001	<.0001
2	<.0001		<.0001	<.0001
3	<.0001	<.0001		<.0001
4	<.0001	<.0001	<.0001	

APPENDIX F

SAS EVALUATION FOR EFFECT OF THE SIZE OF THE RADIUS ON EMISSIONS AT A ROUNDABOUT

Class Level Information		
Class	**Levels**	**Values**
et	3	CO Nox VOC

Number of Observations Read	81
Number of Observations Used	81

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	9	99193304.96	11021478.33	35796.1	<.0001
Error	71	21860.59	307.90		
Corrected Total	80	99215165.56			

R-Square	Coeff Var	Root MSE	emission Mean
0.999780	1.253586	17.54696	1399.741

Source	DF	Type III SS	Mean Square	F Value	Pr > F
cirf	1	42412.911	42412.911	137.75	<.0001
et	2	1077113.813	538556.907	1749.15	<.0001
radius	1	15732.561	15732.561	51.10	<.0001
cirf*radius	1	214.145	214.145	0.70	0.4071
cirf*et	2	101877.953	50938.977	165.44	<.0001
radius*et	2	157239.292	78619.646	255.35	<.0001

Class Level Information		
Class	**Levels**	**Values**
et	3	CO Nox VOC
radius	3	100 200 300

Number of Observations Read	81
Number of Observations Used	81

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	99204999.20	9018636.29	61210.3	<.0001
Error	69	10166.36	147.34		
Corrected Total	80	99215165.56			

R-Square	Coeff Var	Root MSE	emission Mean
0.999898	0.867183	12.13831	1399.741

Source	DF	Type III SS	Mean Square	F Value	Pr > F
cirf	1	147428.1705	147428.1705	1000.61	<.0001
et	2	898812.5456	449406.2728	3050.16	<.0001
radius	2	265426.5818	132713.2909	900.74	<.0001
cirf*et	2	89661.4695	44830.7347	304.27	<.0001
et*radius	4	161863.2521	40465.8130	274.65	<.0001

radius	emission LSMEAN	LSMEAN Number
100	1290.32250	1
200	1413.42214	2
300	1495.47758	3

Least Squares Means for effect radius
Pr > |t| for H0: LSMean(i)=LSMean(j)
Dependent Variable: emission

i/j	1	2	3
1		<.0001	<.0001
2	<.0001		<.0001
3	<.0001	<.0001	

APPENDIX G

SAS EVALUATION FOR THE EFFECT OF TRUCK PERCENTAGES ON EMISSIONS AT ROUNDABOUTS

Class Level Information		
Class	**Levels**	**Values**
et	3	CO Nox VOC

Number of Observations Read	108
Number of Observations Used	108

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	9	174171371.2	19352374.6	8897.34	<.0001
Error	98	213157.4	2175.1		
Corrected Total	107	174384528.6			

R-Square	Coeff Var	Root MSE	emission Mean
0.998778	2.881802	46.63770	1618.352

Source	DF	Type III SS	Mean Square	F Value	Pr > F
cirf	1	68896.9018	68896.9018	31.68	<.0001
et	2	352590.3657	176295.1828	81.05	<.0001
tp	1	73477.2762	73477.2762	33.78	<.0001
cirf*tp	1	115308.9427	115308.9427	53.01	<.0001
cirf*et	2	502209.0870	251104.5435	115.45	<.0001
tp*et	2	242514.7111	121257.3556	55.75	<.0001

tp	emission LSMEAN	LSMEAN Number
0	1545.22222	1
10	1583.37037	2
20	1633.81481	3
30	1711.00000	4

Least Squares Means for effect tp
Pr > |t| for H0: LSMean(i)=LSMean(j)
Dependent Variable: emission

i/j	1	2	3	4
1		0.0174	<.0001	<.0001
2	0.0174		0.0007	<.0001
3	<.0001	0.0007		<.0001
4	<.0001	<.0001	<.0001	

APPENDIX H

SAS EVALUATION FOR EFFECT OF TIME GAP ON EMISSIONS AT ROUNDABOUTS

Class Level Information		
Class	**Levels**	**Values**
et	3	CO Nox VOC

Number of Observations Read	81
Number of Observations Used	81

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	9	123059347.9	13673260.9	6840.56	<.0001
Error	71	141918.5	1998.9		
Corrected Total	80	123201266.3			

R-Square	Coeff Var	Root MSE	emission Mean
0.998848	2.842870	44.70852	1572.654

Source	DF	Type III SS	Mean Square	F Value	Pr > F
cirf	1	52152.782	52152.782	26.09	<.0001
et	2	2105402.663	1052701.332	526.65	<.0001
tg	1	131458.883	131458.883	65.77	<.0001
cirf*tg	1	133828.563	133828.563	66.95	<.0001
cirf*et	2	157195.331	78597.665	39.32	<.0001
tg*et	2	385.004	192.502	0.10	0.9083

Class Level Information		
Class	**Levels**	**Values**
et	3	CO Nox VOC
tg	3	3 4 5

Number of Observations Read	81
Number of Observations Used	81

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	9	123080010.8	13675556.8	8007.59	<.0001
Error	71	121255.5	1707.8		
Corrected Total	80	123201266.3			

R-Square	Coeff Var	Root MSE	emission Mean
0.999016	2.627776	41.32583	1572.654

Source	DF	Type III SS	Mean Square	F Value	Pr > F
cirf	1	329306.074	329306.074	192.82	<.0001
et	2	2259578.866	1129789.433	661.54	<.0001
tg	2	69153.878	34576.939	20.25	<.0001
cirf*tg	2	69381.295	34690.648	20.31	<.0001
cirf*et	2	306471.104	153235.552	89.73	<.0001

tg	emission LSMEAN	LSMEAN Number
3	1576.31832	1
4	1530.09841	2
5	1530.75409	3

Least Squares Means for effect tg Pr > |t| for H0: LSMean(i)=LSMean(j) Dependent Variable: emission			
i/j	**1**	**2**	**3**
1		0.0145	0.0448
2	0.0145		0.9990
3	0.0448	0.9990	

APPENDIX I

DATA WITH HEAVY VEHICLE FACTORS

10% trucks	
Circulating Flow vph	Capacity vph
80	2027
95	2128
110	2121
110	1935
125	2022
140	2002
140	1862
155	1911
170	1891
150	1872
180	1899
210	1865
195	1750
225	1760
255	1736
240	1672
270	1698
300	1656
300	1516
360	1424
420	1319
390	1317
450	1218
510	1140
480	1193
540	1133
600	1026

20% trucks	
Circulating Flow vph	Capacity vph
80	1863
95	1914
110	1956
110	1747
125	1827
140	1843
140	1698
155	1735
170	1746
150	1690
180	1706
210	1703
195	1581
225	1593
255	1566
240	1508
270	1502
300	1477
300	1336
360	1254
420	1162
390	1176
450	1069
510	998
480	1043
540	988
600	902

30% trucks	
Circulating Flow vph	Capacity vph
80	1665
95	1737
110	1762
110	1586
125	1633
140	1661
140	1540
155	1579
170	1555
150	1525
180	1540
210	1519
195	1421
225	1414
255	1395
240	1339
270	1346
300	1311
300	1180
360	1099
420	1007
390	1024
450	951
510	878
480	938
540	855
600	784

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BIOGRAPHICAL INFORMATION

Cho’s academic career has been great, with most of his research focused on traffic analyses from his bachelor’s degree to his current master’s degree. Cho is planning on pursuing a PhD in transportation to do more research on traffic studies.