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Establishing Delay-Based Criteria for Installing Traffic Signals at Two-Lane Roundabouts

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ESTABLISHING DELAY-BASED CRITERIA FOR INSTALLING TRAFFIC SIGNALS AT TWO-LANE ROUNDABOUTS

by

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DEDICATION

I dedicate this thesis to the Almighty God who has been my only source of strength throughout the period of this research

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First, my profound gratitude goes to the Almighty God, the author and finisher of my faith who made it possible for me to complete this thesis.

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A roundabout is a circular intersection where drivers travel counterclockwise around a center island in the United States. Roundabouts can be more beneficial than the conventional intersections because they increase the capacity of the intersection and reduce delays and crashes at the intersection. However, the performance of roundabouts can be severely affected by unbalanced traffic flows among the approaches. While the resulting delays can be mitigated by installing traffic signals, there is a lack of clear criteria on when to install a traffic signal at a roundabout. This research focuses on establishing criteria for installing traffic signals at two-lane roundabouts using delay as the measure of the effectiveness of the performance. These criteria are applicable to two-lane roundabouts with unbalanced flow between the legs of the roundabout and when adding lanes is not an option.

The analysis was carried out using VISSIM 9.0 by creating a microscopic simulation model according to the study area geometric features and traffic inputs. Five different cases were considered to quantify the impact of geometric features and traffic inputs on the delay at a roundabout. Criteria for installing a traffic signal were established and are presented in this report.

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1 INTRODUCTION

1.1 Background

Traffic engineering deals with the planning, geometric design, and traffic operation of roads, streets, and highways, their networks, terminals, abutting lands and connection with other modes of transportation, it is a branch of transportation engineering. Traffic refers to different entities such as pedestrians, vehicles, cyclist, trains or streetcars which use a specific facility to travel from an origin to a destination. Roadway is one of the most used transportation facility. Roadway traffic engineers communicate with road users using traffic control devices which can be classified into three categories namely: traffic markings, traffic signs, and traffic signals. The number of vehicles passing a given point at a specific time is called traffic flow. The capacity of a roadway is an important feature which helps in the design of a roadway. It can be simply defined as the maximum volume of traffic that can pass a given point at a specific time in an orderly manner.

A roundabout is a circular intersection where drivers travel counterclockwise around a center island in the United States (HCM, 2016). At a roundabout, entering vehicles are required to yield to vehicles already in the circle. The construction of roundabouts has increased in recent years around the world. There are over 80 roundabouts in Michigan. Roundabouts improve traffic flow at an intersection and reduce potential vehicle conflicts and pedestrians as shown in Figure 1-1 and 1-2. Also, well designed roundabouts can be aesthetically more appealing compared to other intersection design. They also help to reduce speed at an intersection, which may decrease the severity of crashes. Due to the traffic volume and different road users, signs and signals are used at intersections to guide road users on how to interact with each other so as to avoid accidents and maximize the usage of the intersection. A roundabout has some basic key features as shown in figure 1-3.

Studies have shown that roundabouts increase traffic capacity by 30 – 50 percent compared to a conventional intersection (FHWA, 2010). Roundabouts have a high level of safety by reducing the type of crashes where people are seriously hurt or killed by 78-82% when compared to conventional stop-controlled and signalized intersections (FHWA, 2010). A roundabout can be controlled by signs or signals depending on the traffic volume and geometry design of the roundabout. The capacity of a roundabout and its approaches is affected by the entering flow, circulating flow and exiting flow. This research focuses on establishing criteria for installing traffic signals at two-lane roundabouts using delay as the measure of the effectiveness of the performance of this geometry design. Various cases and scenarios were considered to quantify the effect geometry features (width of the circle, number of lanes) and traffic parameters (speed, traffic volume, pedestrian volumes) have on the approach delay for each leg of a roundabout. This was observed using a computer software VISSIM 9.0. An unsignalized two-lane roundabout was selected as the case study for this research. The traffic volume and road geometry served as the basis for the microscopic model created in VISSIM and observed delays were used to validate the model.

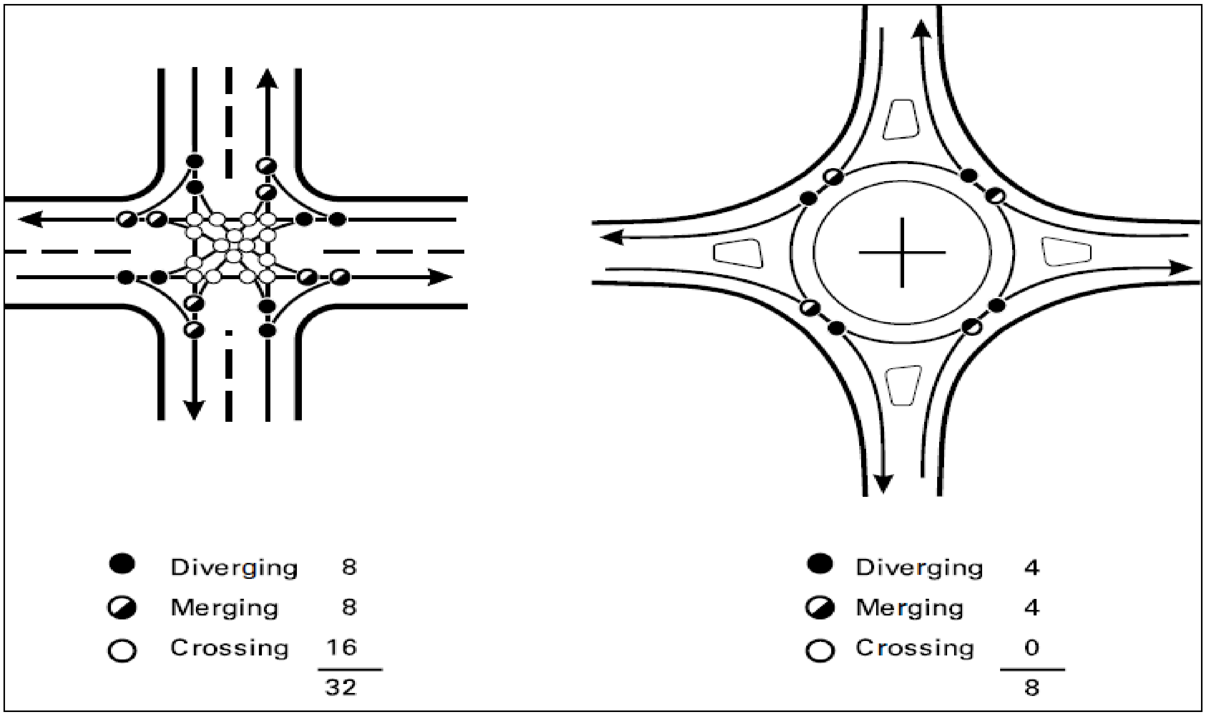

Figure 1-1 Comparison of Conflict Points at a Roundabout and Conventional Intersection (Kansas DOT, 2014)

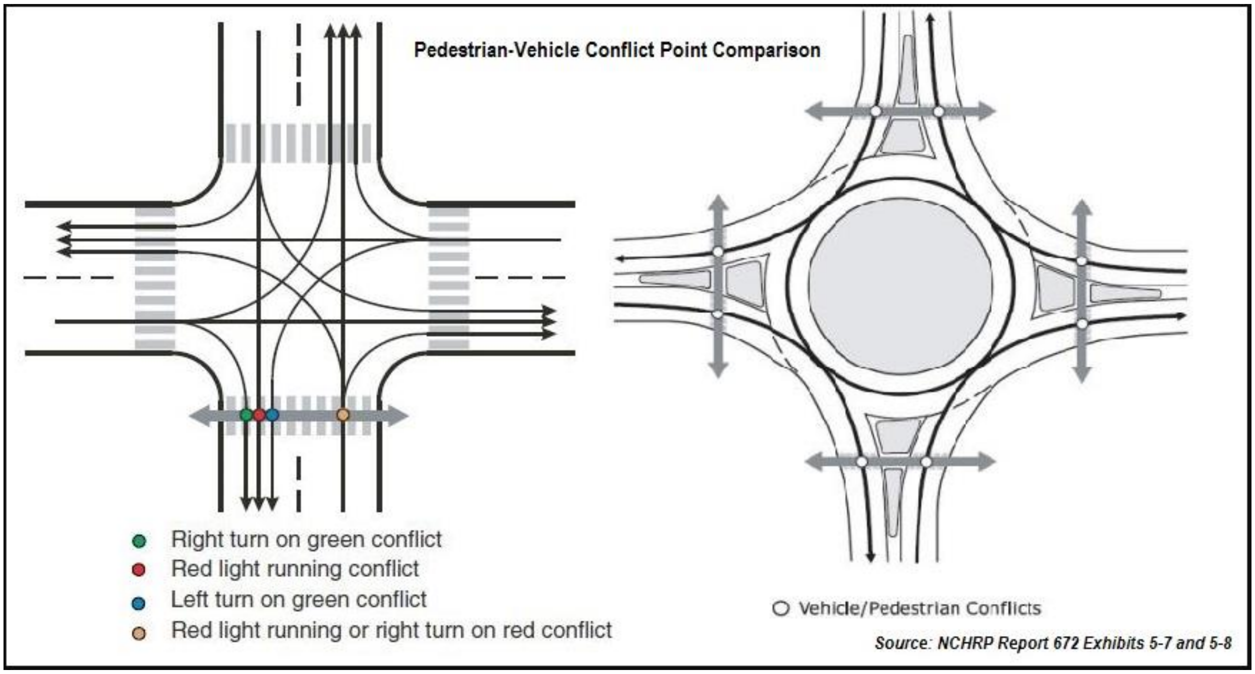

Figure 1-2 Comparison of Pedestrian-Vehicle Conflict Point at a Roundabout and Conventional Intersection (Kansas DOT, 2014)

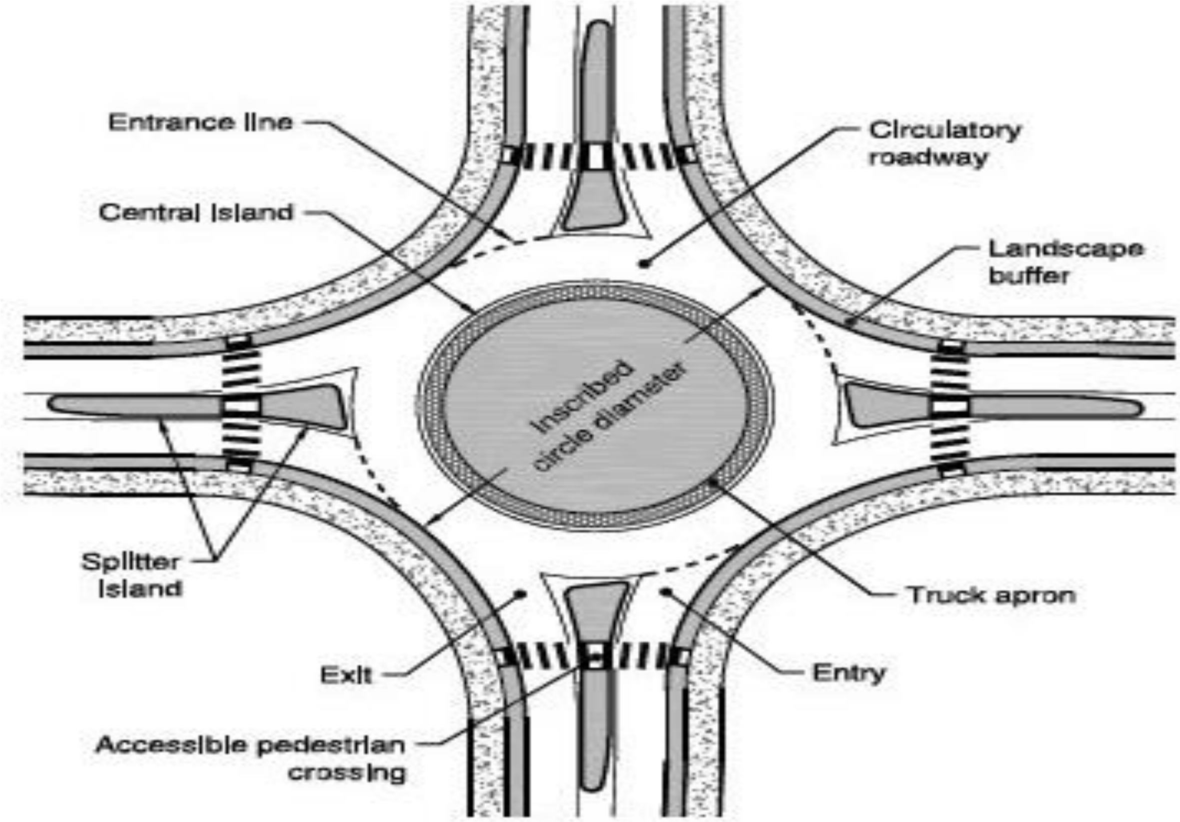

Figure 1-3 Basic Features of a Roundabout (FHWA, 2010)

1.2 Statement of Problem

Hudaart (1983) explains that the capacity of a roundabout is principally limited if traffic flows are unbalanced. This is mostly the case if one entry has a very heavy flow and the entry directly before it on the roundabout has a light flow so that the heavy flow proceeds virtually uninterrupted. This produces continuous circulating traffic which therefore prevents traffic entry on preceding approaches. Gaps can be created in the circulating traffic flow by using traffic signals and thus balance the capacity of the roundabout.

High traffic volume at roundabout causes navigation issues and increases the chance of collisions between vehicles because of different driver's behaviors when they are being controlled by traffic guide signs. Since roundabouts are designed to increase traffic capacity and reduce conflicts at intersection, high traffic volume at roundabout impedes the objective or use of roundabout to minimize delay and reducing conflict, it is thereby imperative to study features that can be incorporated into roundabouts to maintain the aim of constructing a roundabout at an intersection such as installing traffic signals. This research examines the effects of geometric features and traffic parameters on the average approach delay of a two-lane roundabout and how the use of traffic signals may mitigate those effects.

1.3 Objectives of the Study

The main aim of this research is to establish criteria for installing traffic control signals at a roundabout. To accomplish this objective, several tasks were carried out as listed below:

- Conduct a literature review.
- Choose a study area and obtain data through field study.
- Create models using VISSIM 9.0.
- Calibrate and validate model created.
- Obtain results from the simulation of different cases and scenarios considered.
- Analyzing results to create the criteria.

1.4 Scope of the Study

This research uses delay as a measure of effectiveness to analyze the capacity of an unsignalised two-lane roundabout through computer software (VISSIM). It considers the traffic parameters such as the volume of vehicle, and pedestrian volumes and geometric features such as the number of lanes, the width of the circle to establish criteria for installing traffic signals at two-lane roundabouts if an intersection with unbalanced traffic flow experiences excessive delay. The analysis is applicable to two-lane roundabouts with a constraint on increasing the number of lanes because of right-of-way issues. The research used a two-lane roundabout in Michigan as a case study with the ratio of P.M peak-hour traffic volume of the main street to the P.M peak hour traffic volume side street of 2:1. The vehicle composition of the model is 98% passenger cars and 2% heavy good vehicle (HGV). The LOS F (HCM, 2016) for unsignalized intersections was used as the threshold to determine when the entering flow experiences excessive delay which necessitates the use of traffic signals to create gaps between the circulating flows. The study does not discuss details of signal timings.

2 LITERATURE REVIEW

2.1 Traffic Signal Control at a Roundabout

Hallworth (1992) classified traffic signal controls into three namely means of control, time of operation and approach control. He described means of control at a signalized roundabout as "how the signal system controls entering and exiting vehicles which can be direct control and indirect control." Direct control affects internal and external approaches while indirect control only impacts the external approaches. Time of operation focuses on the period of time a signal or meter operates which can also be of two types, namely full-time and half-time. Full time means control operated permanently and doesn't stop work at any time of the day while part-time means signals are activated by detectors or time of the day. Approach control describes the number of approaches controlled with a signal or meter which can either be full control or partial control. Full control means all approaches of the roundabout are controlled by traffic signal while part control simply means not all the approaches of the roundabout are controlled by traffic signals.

Abdelfatah and Minhans 2014, provided guidelines for selecting the appropriate type of control for some at-grade intersection. A case study of a four-leg two-lane roundabout was considered and the traffic distribution on the approaches was used to establish the cases considered. Synchro and Sidra were used for performance evaluation of this study. From his observations, he concluded that under all traffic condition, the performance of roundabout was better the conventional signalized intersection, also at a roundabout where the percentage of the left turns is less than 20% and the traffic volume is about 3500 veh/hr.

Yang et al. 2004, proposed a new method of traffic signal control at modern roundabouts because of the safety issues and traffic congestion caused by weaving and merging vehicles. This research eliminates conflict points and weaving sections at a roundabout with varying approach traffic flow by introducing a second stop line in the geometric design as shown in figure 2-1. The traffic signal was installed to create a queue for left turns flow before the second stop line within the circulatory lanes. The case study for this research was a roundabout in Xiamen, China. The delay and capacity analysis of the proposed traffic signal operation showed that the capacity of the roundabout increased by 72.1% and the average vehicle delay reduced by 20seconds. In this study, consideration of pedestrians and cyclists were not included in the design and configuration of the traffic signal.

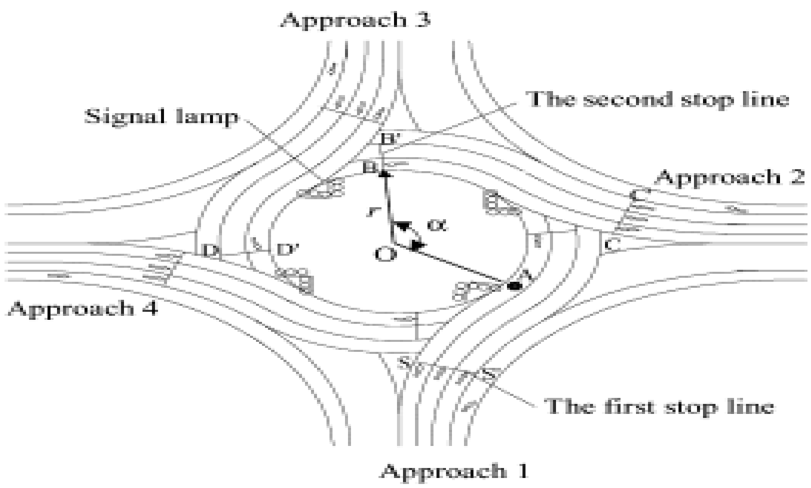

Figure 2-1 Geometric Design of a Roundabout with Improved Traffic Signal Settings (Yang et al. 2004)

2.2 Performance and Operational Analysis of Signalized Roundabouts

Stevens (2005) provided guidelines for installing or metering a roundabout based on three criteria namely; means of control, time of operation and approach control as explained by Hallworth (1992). These guidelines were developed from past reviews of signalized roundabouts in the United States, Europe, and Australia and from web surveys and professional judgment. These were developed because of unbalanced flow and high circulatory speeds at the roundabout.

Stevens consider few locations for the research as shown in the table below, Table 2-1 also describes the outcomes of the study and surveys. This research was limited because it did not vividly describe various impacts geometric features or traffic parameter have on determining whether to install traffic signals at a roundabout.

Table 2-1 Roundabouts Criteria (Stevens, 2005)

Roundabout or Criteria	System Signal	Geometry	Volume Design /Actual [vph]	ADT Design/ Actual	Location of Signals	Queue Lengths	Other
Clearwater	Traffic Meter	Oval 150/180m	3,655/NA	39,500/ 58000	150 to 250 from entry		
Park Square, UK	Signal	200m across	NA/6500		At entry		12 injuries per year, 3:1 ratio of approaches during peak hour
Granville Square, UK	Signal	Oval 70/30m	NA/3500-4000		At entry		
Moore Street, UK	Part-time		NA/3,300-1800 u-turn		25m from entry		
Newbridge, Scotland	Signal	60m diameter		NA/60,000	At entry	1.5km(max)	30mph

Akcelik (2004,2005,2011b) also studied the capacity, performance, and timing of roundabout metering signals. In his researches he evaluated the performance , capacities [delay, queue length, stop rate] and timing of one-lane, two-lane and three-lane roundabouts in different geographical region i.e Australia, UK and USA, because of the use of traffic metering signals to create gaps in a circulating stream so also the eliminate the issue of excessive delay on approaches with higher traffic volume at peak hour and to maintain balanced flow of traffic He described the two approaches of metering a roundabout which included the metered approach and controlling approach. The metered approach is used for approaches stopped by red signals while the controlling approach is used with a queue detector. He used the SIDRA intersection software package for his evaluation. Default values for typical design parameter for metering a roundabout in Australia were used in the model. In a case study of Mickleham and Broadmeadows Road roundabout in Melbourne, Australia, Akcelik (2005) compared roundabout with and without metering signals in terms of average delay, operating cost, fuel consumption, and emission. The results from his research show that using metering signals reduces the average delay, total stops and fuel consumption as described in Table 2-2. Akçelik (2011) analyzed entering platoon flow rates. He concludes that shorter cycle times produce better intersection performance compared with longer cycle times used in practice. These studies did not consider the operation or impacts of other traffic inputs such as pedestrians on the capacity and delay of a roundabout.

Table 2-2 Analysis of Capacity and Performance of a Roundabout (Akcelik, 2005)

		Demand Flow	**Average Delay**	**Worst Approach Delay**	**95% Back of Queue**	**Total Stops**	**CO_2**	**Operating Cost**
Option	Description	[Veh/h]	[sec]	[sec/veh]	[veh]	[veh/y]	[kg/y]	[$/y]
1	No Metering Signals	1,034,400	44.6	82.8	62	1,870,248	327,984	371,179
2	With Metering Signals	1.034,400	37.1	52.4	37	1,479,019	311,885	343,190
	Difference	0	-8	-30	-25	-391,229	-16,099	-27,989
	Percentage Difference [%]	0	16.9	36.7	40	20.9	-4.9	-7.5

Azhar and Svante (2011) studied signal controls of roundabouts because of increased use of roundabouts in urban areas. To avoid excessive delay at roundabout caused by pedestrian, cyclists or bus priority, the use of traffic signals was suggested. The objective of the research was to evaluate and compare various signal-controlled roundabout using VISSIM 5 and TRANSYT 13 to optimize coordinated signal timing. Three scenarios were analyzed which are signal control of crosswalk, complete signal control on one or two legs and fully signalized roundabouts. The signal control of crosswalk is further classified to Type A1 (Off Signal) when the crosswalk is located close to the roundabout and Type A2 (On Signal), when located far from the roundabout. The complete signal control is divided into two part which is when the “signalized crosswalks can be passed by pedestrians in one step” and “signalized crosswalks can be passed by pedestrians in two steps”. Figure 2-2 summarizes the results and they concluded that scenario A1 should be avoided because of capacity and safety, crosswalk can be placed 22m meters away from roundabouts, use of gating will yield more capacity if there is a need for crosswalk than no gating option and a fully signalized roundabout can be considered if there is high pedestrian volume in all approaches. In this research, a constant value of pedestrian volume was used in all approach which does not really show the effects of varying pedestrian hourly volume.

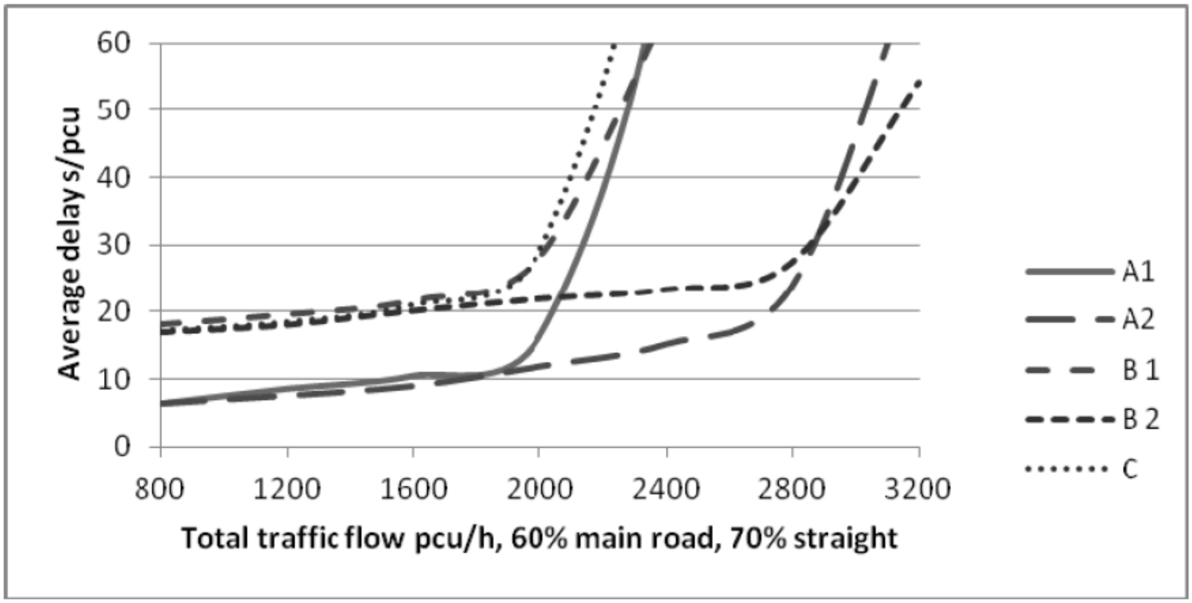

Figure 2-2 Relationship between Traffic Volume and Average Delay Time for Signal-Controlled Main Approach for all Types of Signal Control (Azhar and Svante, 2011)

Natalizio (2005) addressed the issue of excessive delays at roundabouts using metering signals. He provided some principles based on the results obtained from a conceptual analysis by Alcelik and Associate (2001), the principles he outlined are specifically for a single lane roundabout with heavy flow for two legs only. He considered the capacity and performance measures of roundabouts in Australia using Sidra. Figure 2-3 shows his observations. He observed that the most effective operational settings of a part-time metering signals are when the queue detector setback distance is 60metres, Minimum blank time 20sceonds and Minimum Red-time

20seconds because the minor minimum red time have a lesser impact on the capacity and performance of the metered approach than higher minimum blank times and larger queue detector setback distances. Metering a single lane roundabout is required when the total volume of the delayed approached and the circulation flow is between 1300 and 1400 vph. In this study, only single-lane roundabout was considered, the capacity of a single lane roundabout cannot expressly illustrate the capacity of a multilane roundabout, it will be necessary to consider more instances which include varying geometric features such as multilane roundabouts and traffic parameters.

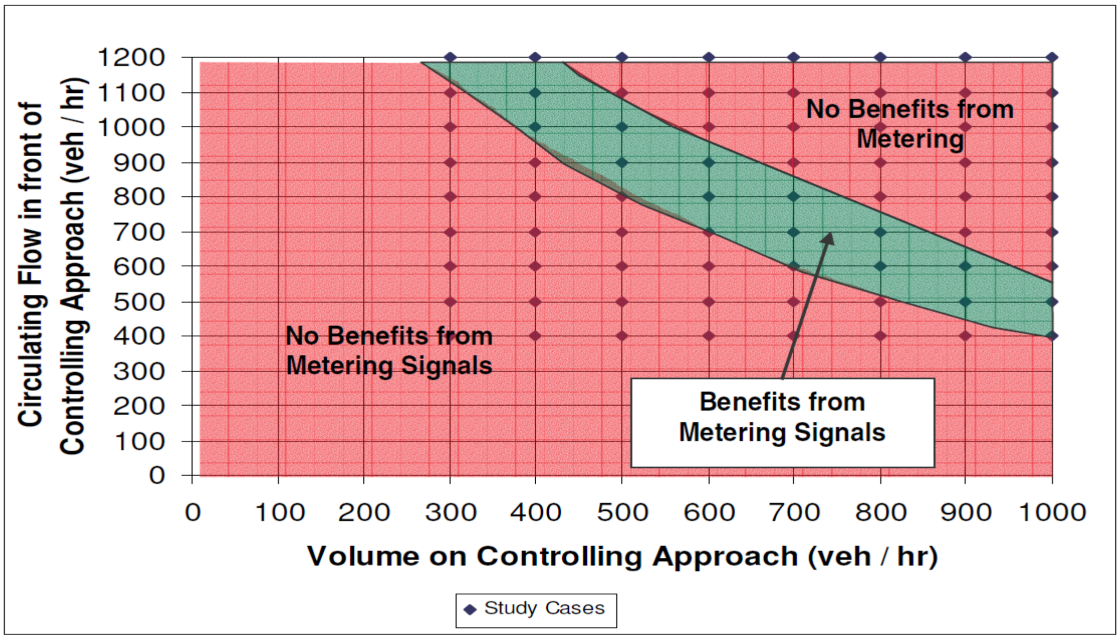

Figure 2-3 Benefit of Metering Signals (Natalizio, 2005)

Gasulla et al. (2016a) also studied the capacity and operational improvements of metering Roundabouts in Spain. This research was focused on the "analyzing operational and capacity improvements on suburban roundabouts with metering signals using traffic microsimulation for Spanish local Conditions", this capacity was estimated from Highway Capacity Manual for LOS F and also average delay. A single lane roundabout with an 80m diameter in Valencia (Spain) with 5legs was selected as the case study. VisVAP module in VISSIM 5.3 was used to create the traffic microsimulation model, in this model priority rules were included to observe driver behavior. Priority rules such as the headway and reduced speed areas were inputted in the module. The study was carried out during peak hour [7:30am-9:30 am] on Labor Day, manual and video recording was done for every 5minutte to observe vehicular flow. The average delay of the conflicting approach was plotted against the entering flow rate as shown in figure 2-4. From the results, he concluded that follow up headway must be variable, he also observed that metering a roundabout significantly increased capacity and reduced delays at every entrance flow. In this research interaction between various road users such as cyclist and pedestrians were not considered in their evaluation.

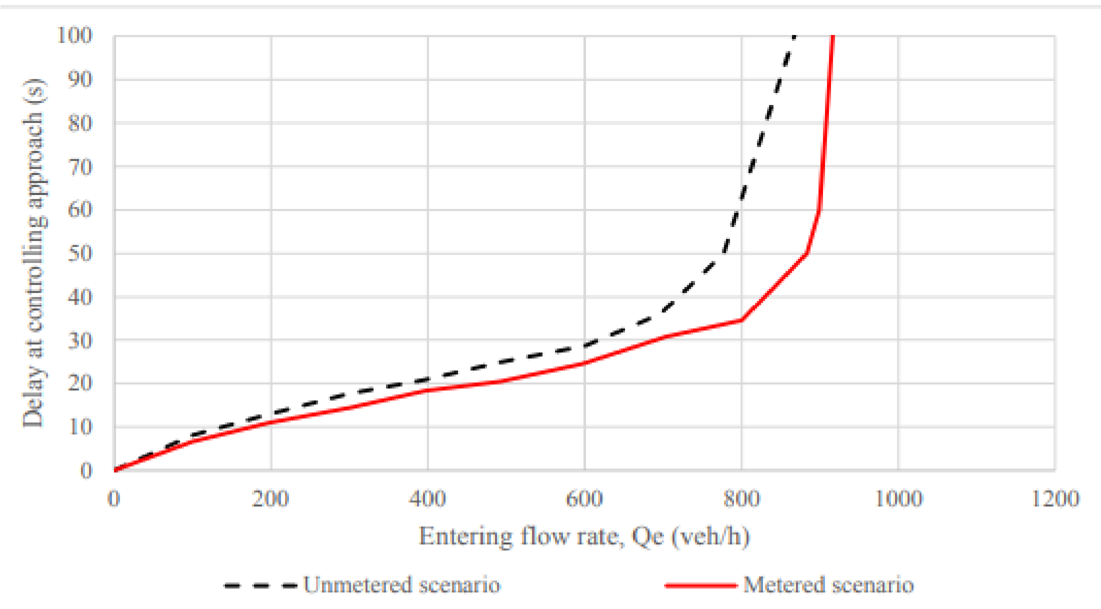

Figure 2-4 Delay against Entering flow rate (Gasulla et al. 2016a)

2.2.1 Level of Service [LOS]

Level of service (LOS) is a quality measure describing operational conditions within a traffic stream, generally in terms of such service measures as speed and travel time, freedom to maneuver, traffic interruptions, and comfort and convenience (HCM, 2016). Level of service is classified in HCM into six levels, A to F, where A represents best performance and F is the worst case. It is a function of flow rate and the associated control delay. Table 2-3 describes the level of service for both unsignalized intersections and roundabouts.

Table 2-3 Level of Service for Unsignalized Intersections (HCM, 2016)

Level of service	Average Control Delay [secs/veh]
A	0-10
B	>10-15
C	>15-25
D	>25-35
E	>35-50
F	>50

2.2.2 Definition of Delays

Delay is a measure of additional time to the total travel of a vehicle moving from origin to destination which could be due to the acceleration or deceleration rate, bottleneck, and traffic control devices. There are different types of delay as described below (Tom and Bombay, 2014):

- The stopped time delay is described as the time a vehicle is stopped in a queue while waiting to pass through the intersection. It commences when the vehicle is fully stopped and stops at the time of acceleration of the driver.
- Approach delay is the combination of stopped-time delay and the time loss due to deceleration from the approach speed to a stop and the time loss due to re-acceleration back to the design or desired speed.

- The travel time delay is the additional time to a driver's expected travel time through an intersection or from a given origin to a destination.
- Time-in-queue-delay is the total time spent for a vehicle joining an intersection queue to its discharge across the stop line on departure.
- Control delay is the delay due to the type of traffic control device used at that intersection either a traffic signal or a stop-sign. It is the sum of the time-in-queue delay plus the acceleration-deceleration delay component.

2.3 Benefits of A Signalized Roundabouts

Tracz and Chodur (2012) studied the performance and safety of roundabouts with traffic signals. In this respect, the design, benefits, and constraints of using a signalized roundabout in an urban area were outlined. A multilane roundabout with four legs located in Krakow was considered. One of the problems stated is that operation of a roundabout with two-phase signal setting always cause the collision with pedestrians and left turn. Due to overloading of the circulating volume within the circle when using a two-phase signal system, multiphase traffic signal setting was considered, also a comparison with unsignalized roundabouts. The results show that multiphase traffic signal settings can eliminate overloading of the center island but causes longer delay to entering flow. They concluded that a signalized roundabout is beneficial when there is high traffic volume with high left turn movement.

Roundabouts help improve pedestrian safety. Stone et al. (2002) considered the effects of roundabouts on pedestrian safety. This work evaluates the impacts modern roundabout have on pedestrian compared to the conventional intersection. This evaluation was approached in three ways: statically analysis, simulation, and a case study of Hillsborough-Horne Street intersection at North Carolina State University in Raleigh. The results from this analysis show that roundabout improves pedestrian safety at an intersection by reducing speed, conflict areas and providing pedestrian refuge area.

Ben-Edigbe et al (2012), studied the extent of delay and level of service at signalized roundabouts. Their research is aimed at determining "quality of highway service at a signalized roundabout" through delay studies. Manual computation of delay and queue as stated by Highway Capacity Manual [HCM] was used in a comparing result with delay and capacity output obtained from ARCADY and delay and queue length from TRANSYT. It was concluded that signalized roundabout is advantageous when traffic flow is high and have safety issues and when approach delay is high because it helps to balance the delay at different legs.

2.4 Geometric Design of a Roundabout

The circulating speed in a roundabout is a function of the radius of the roundabout. The radius of the inscribed roundabout is measured from the center of the circle to the center of the inner circulating lane. The speed curve relationship is computed as below (FHWA. 2010b);

$$V = \sqrt{15R(e + f)} \qquad \text{……(1)}$$

Where V = design speed(mph)

R =Radius(ft)

e = Superelevation

f = Side friction factor (obtained from figure 2-5)

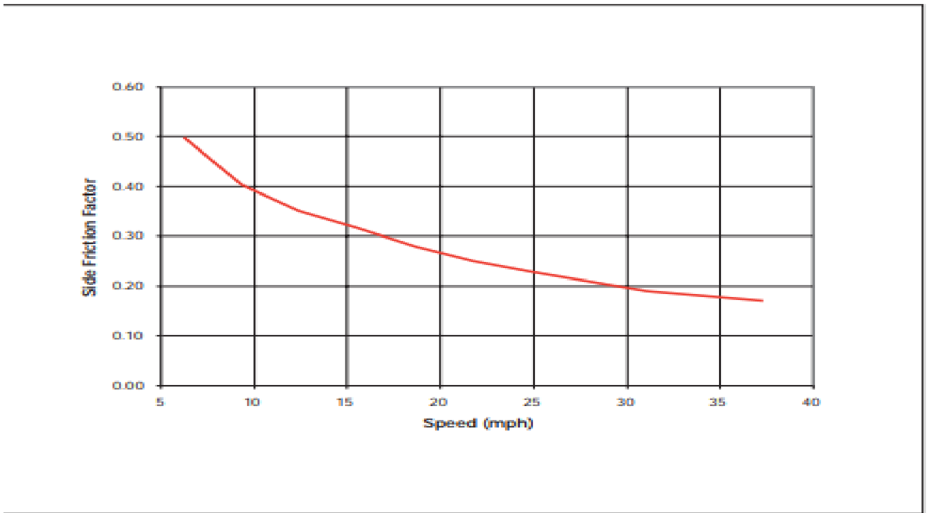

Figure 2-5 Side Friction Factors at Various Speeds (FHWA, 2010b)

3 METHODOLOGY

3.1 Study Area

A study area was selected based on reviews of various roundabouts in Michigan. There are over 80 multilane and single-lane roundabouts in Michigan. A two-lanes roundabout was considered for our research analysis. The case study for this research was a two-lane roundabout at 68th Ave./Randall St., Coopersville, Ottawa, MI (43.05976, -85.9567). It is a two-lane signalized roundabout with four approaches as shown in the figure below and the width of the center island is about 121ft. the approach speed for the main street is 45mph and side street is 35mph.

Figure 3-1 68th Ave./Randall St., Coopersville, Ottawa, MI

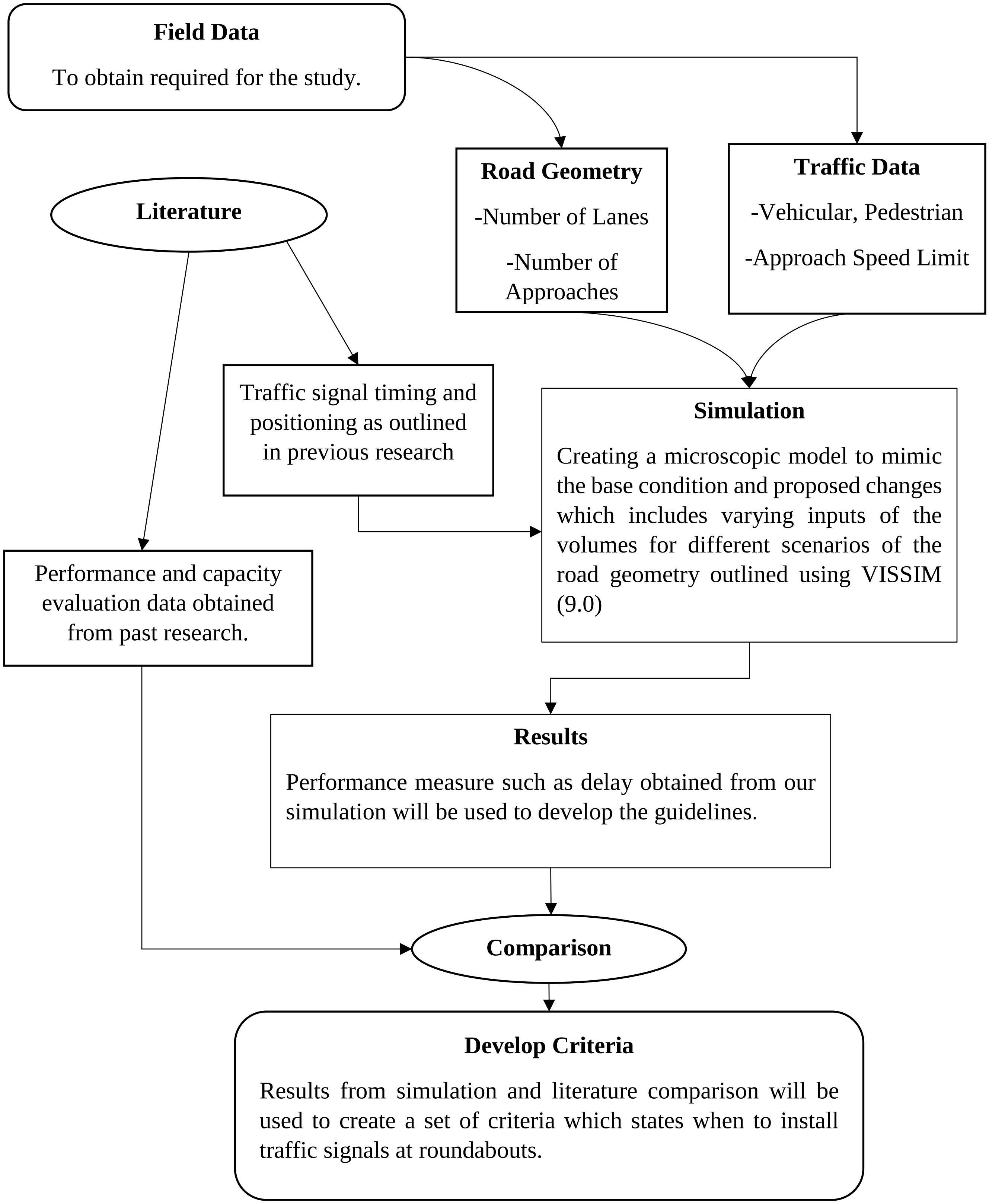

Figure 3-2 Methodology Flow Chart

3.2 Field Study

A field study was conducted to get familiarized with unsignalized roundabouts for better understanding and judgment on how it operates and help in developing the criteria. The study area characteristics (such as road geometry and traffic counts) for our simulation were obtained with the use of count pads and video camera. Figure 3-3 shows the count pad used. The traffic volumes were collected for a weekday (Thursday) PM peaks hour (5:30 PM – 6:30 PM). There were three observers using different count pads to record the turning volumes of vehicles at different approaches, the first and second observer collected data for Westbound (WB) and Southbound (SB) approach respectively while the third observer collected data for both Northbound (NB) and Eastbound (EB) approaches. A camera mounted on a tripod was position on the island at the roundabout to record traffic at the eastbound approach. In this research, various components of roadway were observed carefully for calibration of the model created.

Approach delay study was also conducted for this intersection using a stopwatch. The travel times of vehicles from about 150m away from the stop line of different legs were obtained for the off-peak hour (3:05 PM – 3:55 PM) and the peak hour (4:45 PM – 5:25 PM). The travel time for the eastbound approach was obtained from video recording using the time stamp on the exported video, the set-up is as shown in figure 3-5 and figure 3-4 indicates the point of observation of the vehicle travel times. The average delay was then computed using equation 2:

$$\text{Average Approach Delay} = \frac{\sum\left[\mathbf{x_j} - \frac{\sum \mathbf{x_i}}{\mathbf{n_i}}\right]}{\mathbf{n_j}} \quad \text{.........(2)}$$

Where x_i = average travel times for off peak hour

x_j = travel times for PM peak hour

n_i – number of samples for off peak hour

n_j = number of samples for PM peak hour

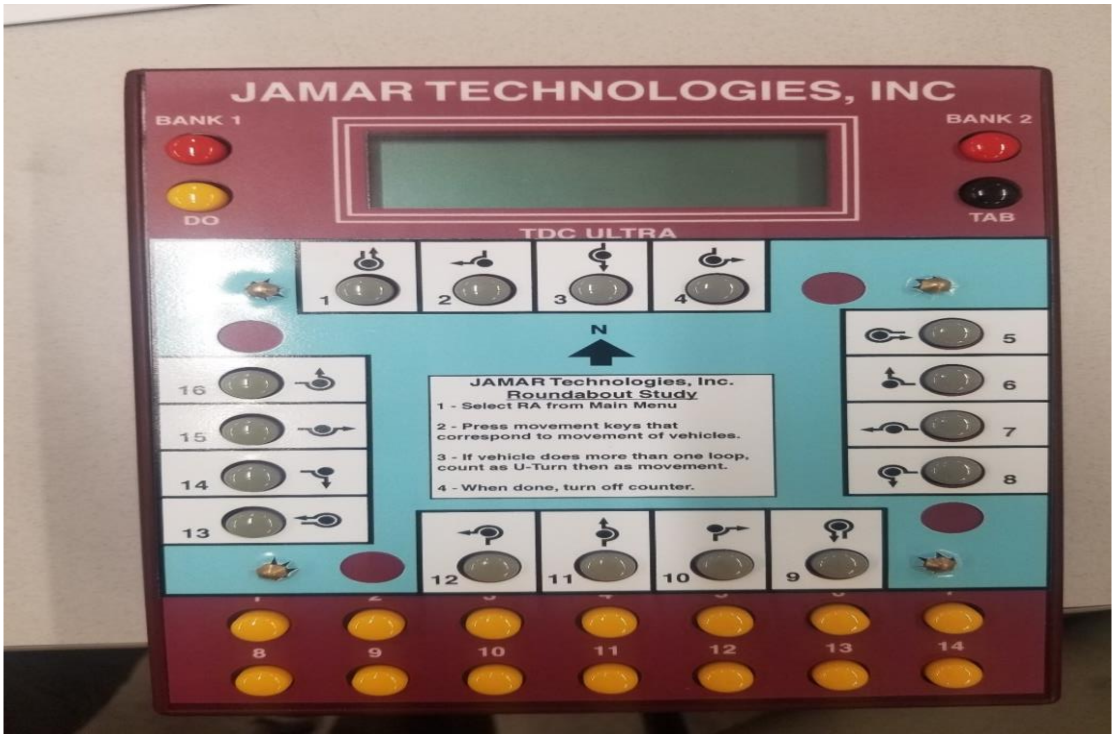

Figure 3-3 Count Pad Used for Traffic Count

Figure 3-4 One Observer Observing Travel Time of Vehicle

Figure 3-5 A Camera Mounted on a Tripod to Observe Vehicle Travel Time

3.3 Simulation

Based on the selected study area's traffic volume and road geometry, microscopic models were created in VISSIM 9.0 to observe various parameters such as delay and delay in queue. Through simulations, the delays, and delay in queue results were obtained and used to compare the variation in delays for the various cases and scenarios considered in this research.

The simulations run for an hour (i.e. 3600 seconds). Data were obtained every 20 seconds interval of the simulation generating 180 values for the total simulation duration. The travel times were used to observe the delay and the delay in queue was obtained by establishing data collection points for every approach of the intersection. The average of the results from the simulation was computed using equation 3:

$$\text{Average Approach Delay or Delay in Queue} = \frac{\sum x_{i-j}}{n} \quad \ldots\ldots(3)$$

x_{i-j} = average delay for time period i to j

n = total number of observed values

A threshold of 50 seconds as stated in HCM 2010 for level of service F was used as the limit for average approach delay. The simulation was categorized into different cases based on the geometric design and the traffic features as described below;

3.3.1 Case 1: Base Scenario with Increasing Traffic Volume

This comprises of the base condition model for the selected study area and generated other scenarios by increasing the traffic volume for the various approach of the roundabout. The speed, headway and priority rules remain the same for all the scenarios. The vehicle composition of the model is 98% passenger cars and 2% heavy good vehicle (HGV)

3.3.2 Case 2: Relationship between Circulating Speed and Radius of the Roundabout

In developing this case, the geometric features were altered by reducing the speed of the circulating traffic and width of the roundabout by using the speed-curve relationship to determine the speed within the circle with respect to the radius of the circle as outlined in equation 1. The super elevation (e) of 0.08 (maximum acceptable value in Michigan) was used and the side friction was obtained using the figure 2-5. The diameter was computed using equation 4. Table 3-1 describes the diameter of the roundabouts with respect to the circulating speed used to consider various instances for this case.

Inscribed Diameter

$$D = 2(R + 1.5W) \quad (4)$$

Where D = Inscribed Diameter (ft)

R = radius of the Circle (ft)

W = width of the lane (ft)

Table 3-1 Circulating Speed and Corresponding Width

Diameter of Inscribed Circle[ft]	Speed[mph]
110	15
145	15
145	25
240	30

3.3.3 Case 3: Varying Pedestrian Volume and Varying Traffic Volume

Varying pedestrian volume with varying vehicle volumes were incorporated into the model to observe the effect pedestrian have on the vehicular delay for the various approach. The crosswalk is placed 20ft away from the yield line. Consistent with field observations of no pedestrians, the simulation for base scenario did not include pedestrians. However, to forecast the impact of pedestrians, the pedestrian volume in subsequent simulations scenarios was varied from 60pers/hr to 400pers/hr. It was assumed the pedestrians are evenly distributed around the roundabout i.e pedestrians move from the NE position to SE, SW, NW or vice versa as shown in figure 3-6. The pedestrian speed ranges from 0.97m/s to 1.62m/s for man and 0.71m/s – 1.19m/s for woman.

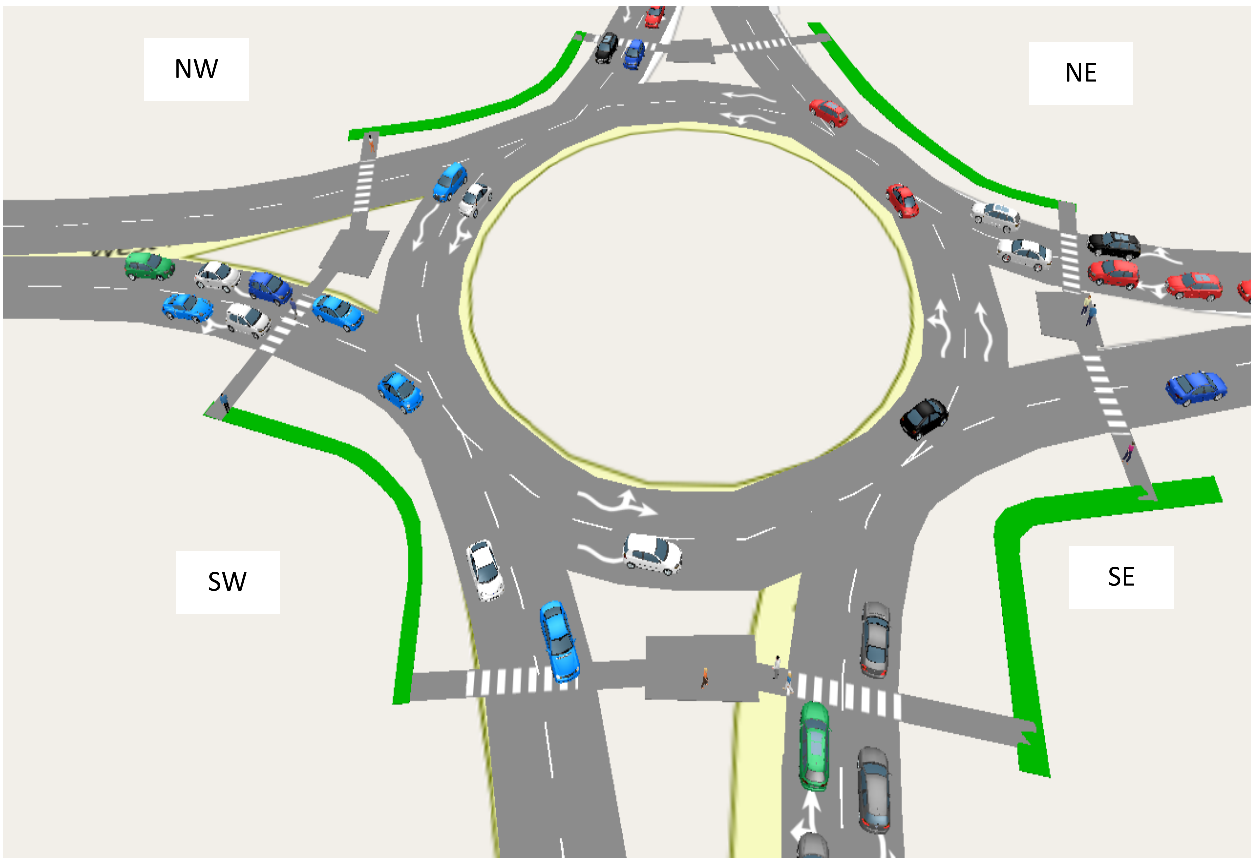

Figure 3-6 Interaction Between Vehicles and Pedestrians at a Roundabout

3.3.4 Case 4: Using Traffic Signals at a Two-Lane Roundabout

In the case, the traffic signal was used for controlling the entering flow at the roundabout instead of stopping lines used in case 1. A ring barrier controller was used in VISSIM to configure the traffic timing. Detectors were used with the traffic signals. Figure 3-7 and 3-8 below show the configuration of the traffic signal. The traffic timing was obtained from typical design and control parameters for roundabout metering Signals (Alcelik, 2005). The minimum green time for the Main Street and Side Street ranges from 20-50seconds, the yellow time for the main and side street is 3seconds and 4seconds respectively and all-red time for all street is 1second. The detectors setback distance is 7.5m for the Side Street and 60m for the main street as shown in figure 3-9.

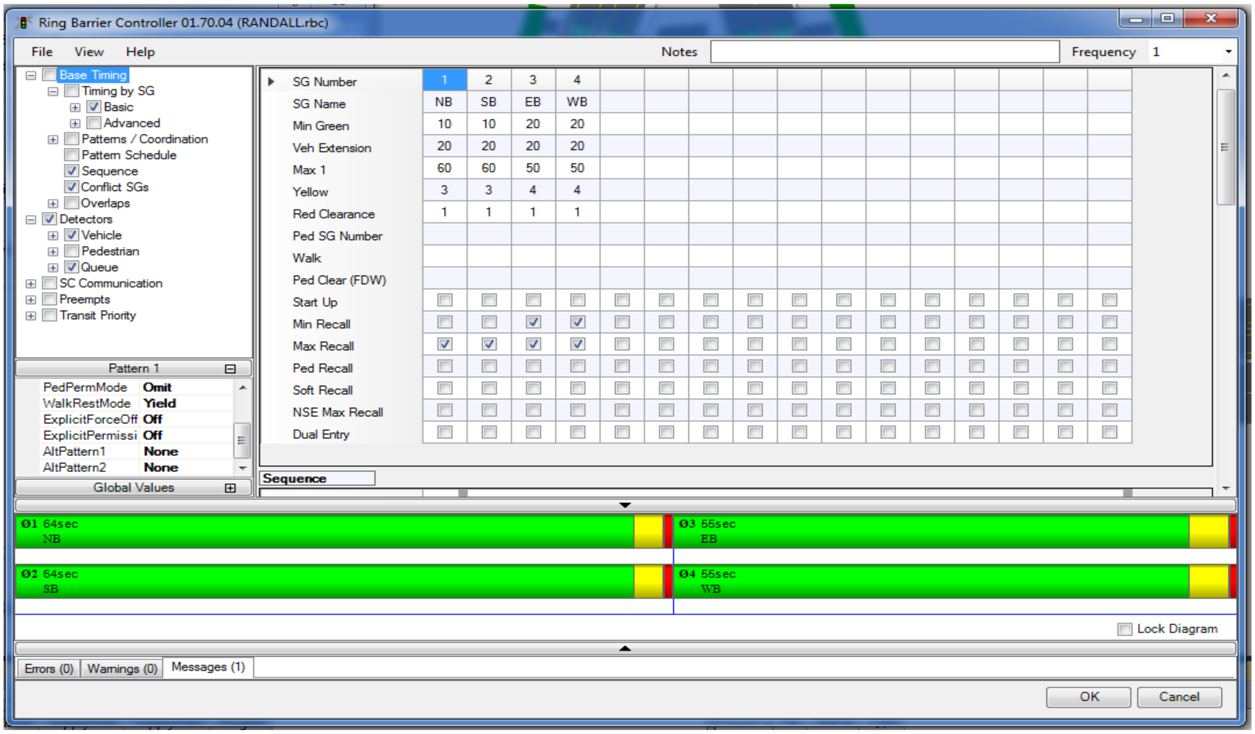

Figure 3-7 Traffic Signal Timing Using Ring Barrier Controller

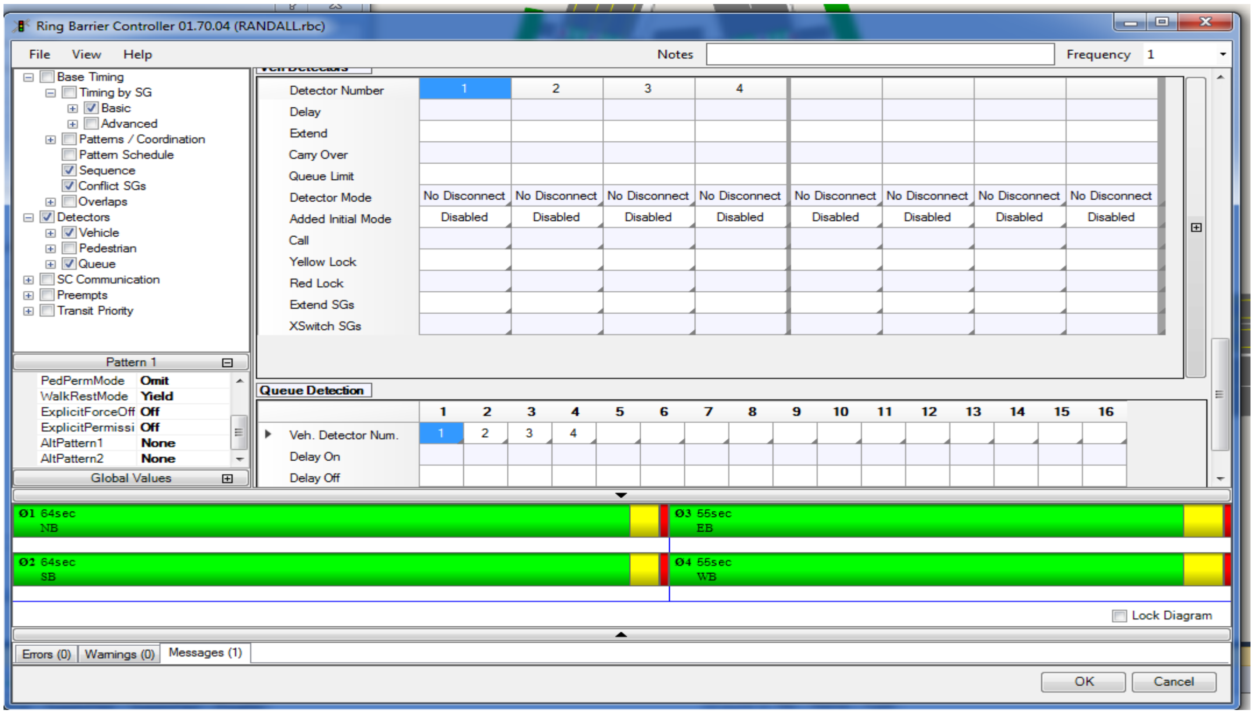

Figure 3-8 Traffic Signal Configuration

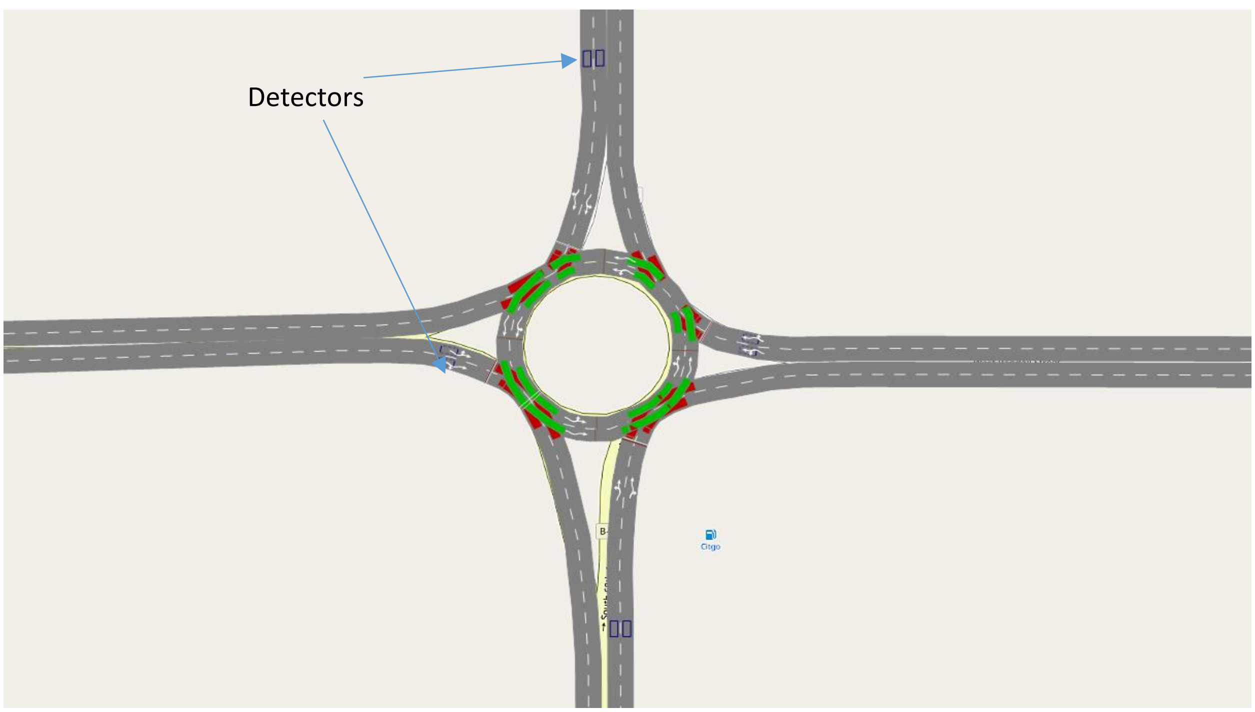

Figure 3-9 Location of the Detector in the Model Created

3.3.5 Case 5: Incorporating Slip Lanes to a Two-Lane Roundabout

Case 5 considers the impact of the geometric features on the approach delay by introducing a slip lane to the approach experiencing more delay and considered for all approaches as shown in figure 3-10 and 3-11 respectively. The traffic inputs and characteristics remain the same as in case 1. Extra scenarios (11 – 14) were considered by increasing the traffic volumes of various approaches by 100vhp.

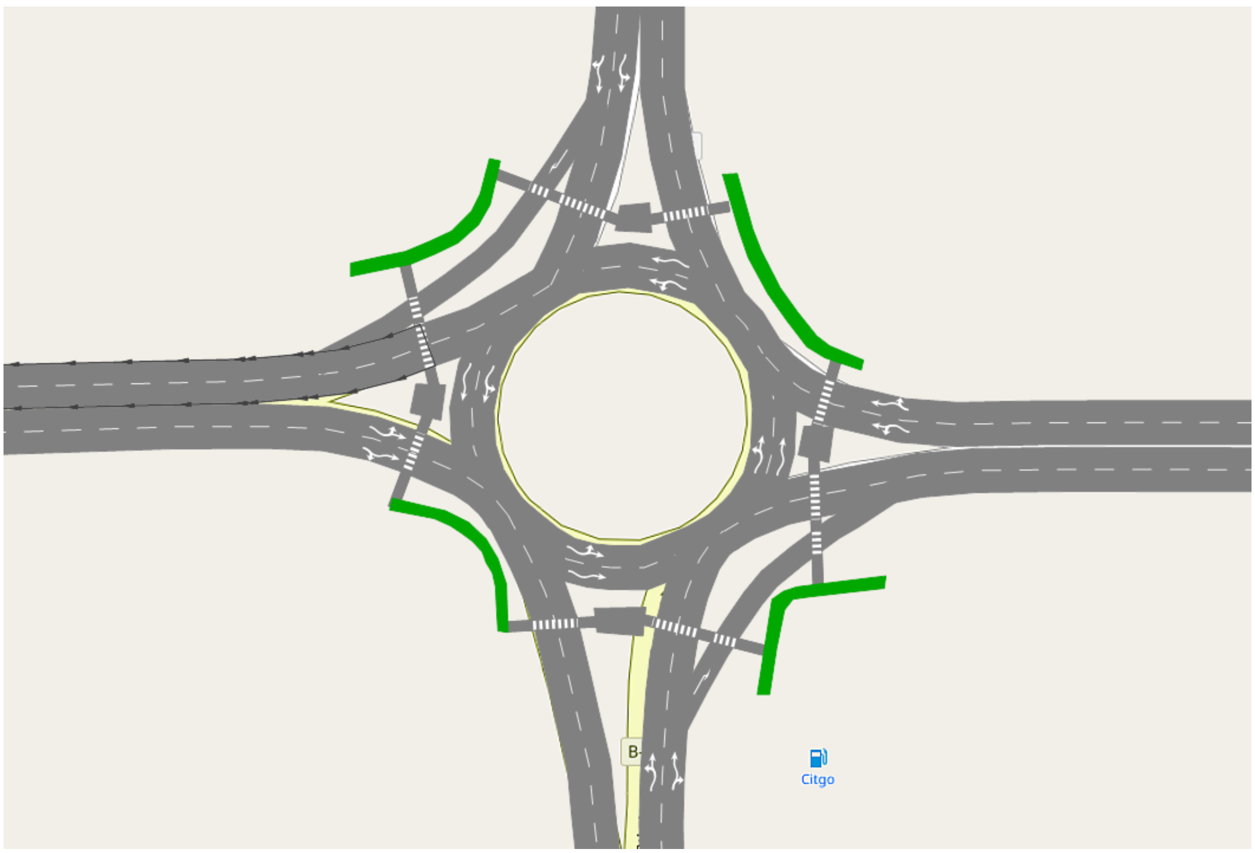

Figure 3-10 Adding Slip Lane to the Main Street

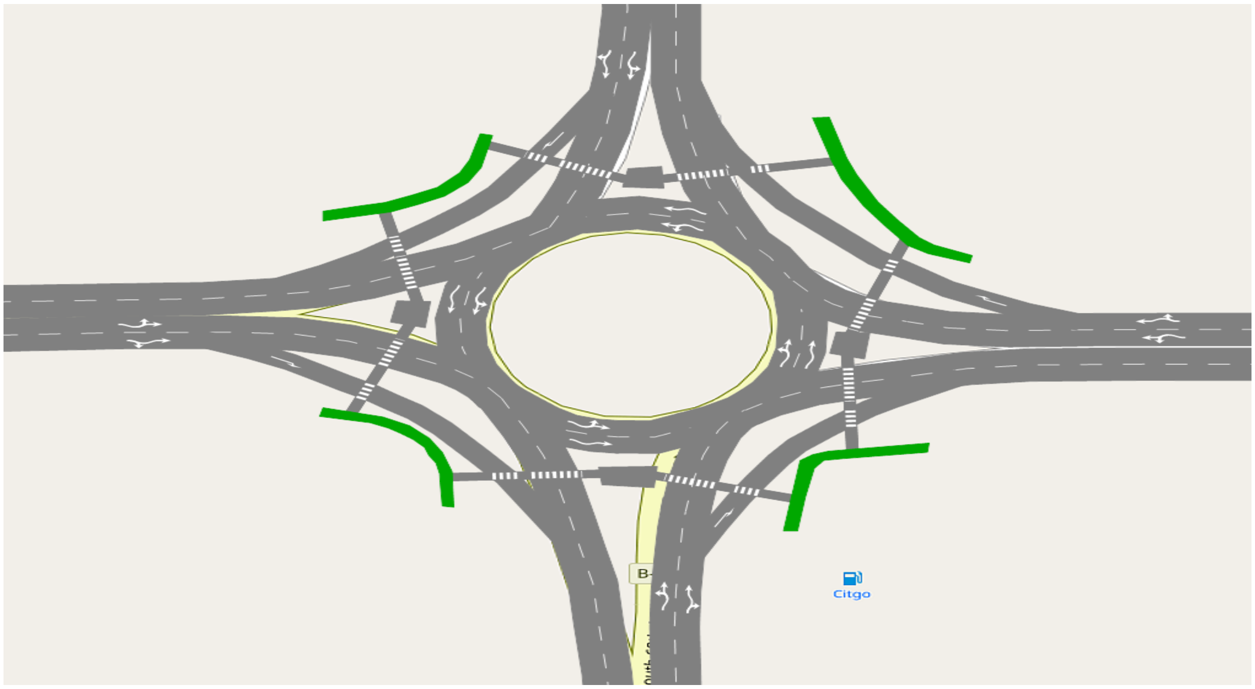

Figure 3-11 Adding Slip Lane to All Approaches

3.4 Calibrating and Validating the Model

3.4.1 Calibration

While creating the model in VISSIM, some parameters were introduced so as to adjust the model to mimic the exact base condition such as conflicts markers, desired speed, reduced speed zones, stop line and the vehicle route decision. The conflict markers help set priority for vehicles entering the circle, diverging or merging. The stop line is set for each approach to allow entering vehicles yield to the circulating traffic in the circle. The following inputs were used in VISSIM to calibrate the model based on the characteristics of the study area.

- Desired speed for Main street = 70km/h Side street= 60km/h
- Circulating speed = 40km/h
- Minimum headway gap: 3.0seconds

The green and red region indicates the conflict zones, the green indicated that priority is given to vehicle moving in the circle as shown in figure 3-12. The region highlighted with yellow shows the reduced speed zones.

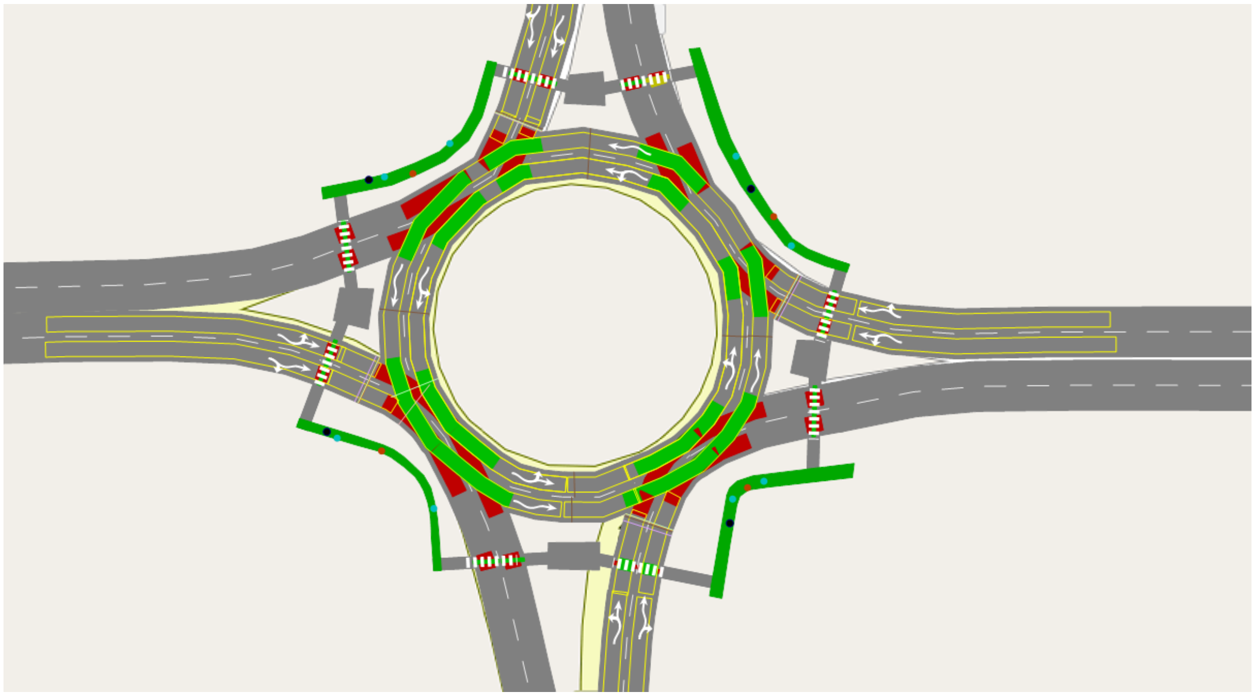

Figure 3-12 Priority Rules and Reduced Speed Zones

3.4.2 Data Validation

The delay results from the simulation were validated using the observed values obtained from the field delay studies. The t-test was used to statistically check whether there is a significant difference between the means of the data obtained from the field and the model outputs. The following hypotheses were tested under the 95 percent confidence level:

Null hypothesis H_o: $\mu_{sim} = \mu_{field}$

Alternative hypothesis H_a: $\mu_{sim} \neq \mu_{field}$

μ_{sim} is the mean of the observed values from the simulation model while μ_{field} represents the mean of the values obtained from the field study. We reject the null hypothesis if the p-value is less than 0.05 and favor H_a and fail to reject the null hypothesis if the p-value is greater than 0.05.

4 RESULTS AND DISCUSSION

4.1 Field Study Results

A traffic count study was carried out to obtain the actual turning volumes of traffic at P.M peak hour for the study area. No pedestrians or cyclists were observed during the period of this traffic study. Table 4-1 and 4-2 show the traffic count data obtained from the field study. The total P.M peak hour traffic volume for this intersection was 1,075vph. The ratio of the total volumes of the main street to the side street was 2:1 - the main street had more hourly traffic volume than the side street.

Table 4-1 Traffic Volume for Randall Street

INTERVAL		**MAIN STREET[VPH]**							
		SB				**NB**			
START	**END**	**RIGHT**	**THRU**	**LEFT**	**U-TURN**	**RIGHT**	**THRU**	**LEFT**	**U-TURN**
17:30	17:45	11	33	10	1	67	54	46	4
17:45	18:00	12	28	1	0	53	32	41	1
18:00	18:15	11	41	4	1	50	28	42	0
18:15	18:30	5	20	5	0	52	30	36	0
TOTAL		39	122	20	2	222	144	165	5
TOTAL PER APPROACH[VPH]		**183**				**536**			
TOTAL MAIN STREET[VPH]		**719**							

Table 4-2 Traffic Volume for 68th Street

INTERVAL		SIDE STREET[VPH]							
		WB				EB			
START	END	RIGHT	THRU	LEFT	U-TURN	RIGHT	THRU	LEFT	U-TURN
17:30	**17:45**	8	25	36	0	14	11	4	0
17:45	**18:00**	9	18	29	0	4	10	1	0
18:00	**18:15**	2	21	36	0	13	11	3	0
18:15	**18:30**	6	27	36	0	16	12	4	0
TOTAL		25	91	137	0	47	44	12	0
TOTAL PER APPROACH[VPH]		**253**				**103**			
TOTAL SIDE STREET[VPH]		**356**							

Table 4-3 summaries the average vehicle delay per approach obtained from the field study using equation 2. The observed values show that the vehicles traveling northbound(NB) approach experiences more delay than other approaches. Generally, the main street experiences higher vehicular delay than the side street and the average approach delay for this roundabout is about 8seconds.

Table 4-3 Delay Results from Field Study

Approach	Average Delay[secs]
WB	6.08
EB	6.22
SB	7.87
NB	9.30
AVERAGE	7.39

4.2 Simulation Results

4.2.1 Case 1: Base Scenario with Increasing Traffic Volumes

The base condition was modeled first. Then, seven other scenarios were modeled by increasing the traffic volumes of the base scenario for each of the approaches by 50vhp. Table 4-4 summarizes the increments in traffic volumes for the scenarios created and the total hourly traffic volume for the roundabout. After obtaining the results for scenarios 1 to 7, the average delay threshold of 50seconds was used to further break down the traffic volumes to obtain a closer average approach delay value for the scenarios considered. Additional scenarios where created as described in table 4-5.

Table 4-4 Traffic Volume Distribution for Each Scenarios

Scenarios	Traffic Volumes[vph]				Total Entering Flow[vph]
	SB	NB	WB	EB	
BASE	183	536	253	103	1075
S1	233	586	303	153	1275
S2	283	636	353	203	1475
S3	333	686	403	253	1675
S4	383	736	453	303	1875
S5	433	786	503	353	2075
S6	483	836	553	403	2275
S7	533	886	603	453	2475

Table 4-5 Traffic Volume for Extra Scenarios

Scenarios	Description	Traffic Counts[vph]				TOTAL[vph]
		SB	NB	WB	EB	
S8	**S4+25**	408	761	478	328	1975
S9	**S5+10**	443	796	513	363	2085
S10	**S5+20**	453	806	523	373	2095

Average approach or control delay is the delay upstream of the intersection and comprises of additional time to vehicle travel time due to acceleration and deceleration while approaching a roundabout and additional time due to stop or queued vehicles at that approach. The delay in queue is the additional time due to queued vehicles at a certain approach. Table 4-6 shows the average delay and delay in queue results per approach (i.e northbound (NB), southbound (SB), eastbound (EB) and westbound (WB)). The minimum and maximum values of the average approach delay and delay in queue were also calculated. It was observed that the average approach delay constituted the largest portion of the delay in queue at the roundabout.

Table 4-6 Result for Base Condition

APPROACH	AVERAGE DELAY[SECS]			AVERAGE DELAY IN QUEUE[SECS]		
	AVE	MIN	MAX	AVE	MIN	MAX
WB	7.2	0.0	16.8	3.9	0.0	13.4
EB	5.9	0.0	20.2	4.1	0.0	18.3
NB	10.4	3.2	29.0	7.9	0.0	27.9
SB	7.1	5.9	21.0	4.2	1.5	9.4
AVE	7.6			5.0		

4.2.2 Validating the Model

Figure 4-1 graphically show the differences between the average approach delays obtained from the field study and model created. It could be observed that there are no substantial differences between the set of data.

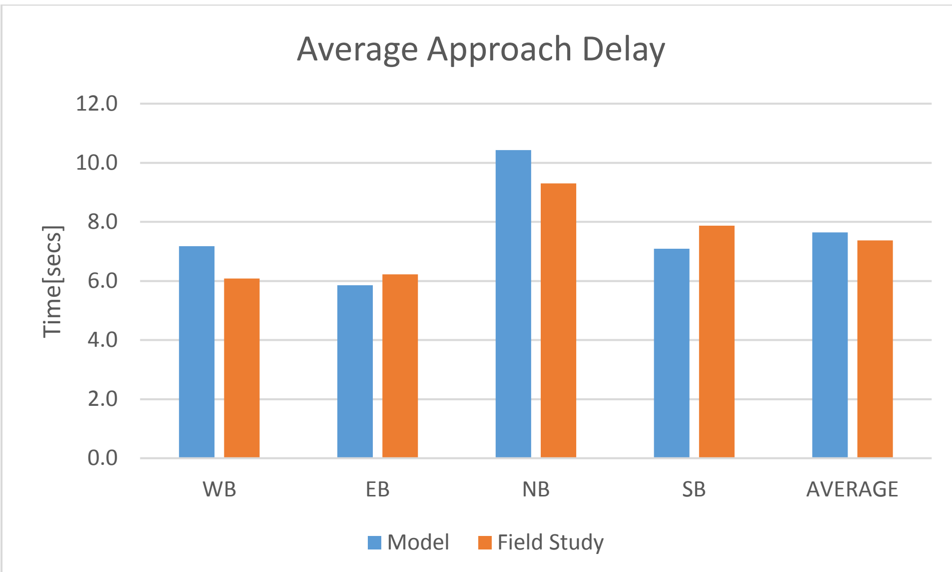

Figure 4-1 Comparison of the Result from Model and Field Study

Using t-test to examine the similarities between the average values observed from the simulation model and field study considering a 95% level of confidence, the obtained p-values for the eastbound, westbound, northbound and southbound are 0.78, 0.24, 0.34 and 0.68, respectively. The p-value when considering all the approaches delays together is 0.41 The results of the t-test for all approaches and the combination of the approaches are presented in tables 4-7 to 4-11. All p-values are greater than 0.05 so we fail to reject the null hypothesis as described earlier in the methodology. Therefore, the averages obtained are statistically similar.

Table 4-7 T-Test: Two samples Assuming Unequal Variances for Eastbound Approach

	Simulation Model	Field Study
Mean	5.86	6.22
Variance	5.02	15.61
Observations	87	10
Hypothesized Mean Difference	0	
df	10	
t Stat	-0.29	
P(T<=t) two-tail	0.78	
t Critical two-tail	2.23	

Table 4-8 T-Test: Two samples Assuming Unequal Variances for Westbound Approach

	Simulation Model	Field Study
Mean	7.18	6.08
Variance	3.89	18.81
Observations	142	23
Hypothesized Mean Difference	0	
df	23	
t Stat	1.19	
P(T<=t) two-tail	0.24	
t Critical two-tail	2.07	

Table 4-9 T-Test: Two samples Assuming Unequal Variances for Northbound Approach

	Simulation Model	Field Study
Mean	10.43	9.30
Variance	20.06	26.63
Observations	176	22
Hypothesized Mean Difference	0	
df	25	
t Stat	0.98	
P(T<=t) two-tail	0.34	
t Critical two-tail	2.06	

Table 4-10 T-Test: Two samples Assuming Unequal Variances for Southbound Approach

	Simulation Model	Field Study
Mean	7.09	7.87
Variance	3.30	46.26
Observations	121	14
Hypothesized Mean Difference	0	
df	13	
t Stat	-0.42	
P(T<=t) two-tail	0.68	
t Critical two-tail	2.16	

Table 4-11 T-Test: Two samples Assuming Unequal Variances Considering All Approaches

	Simulation Model	Field Study
Mean	8.03	7.49
Variance	12.42	27.22
Observations	526	69
Hypothesized Mean Difference	0	
df	76	
t Stat	0.83	
P(T<=t) two-tail	0.41	
t Critical two-tail	1.99	

The simulation model could not process the entire traffic volume for the northbound (NB) approach for some of the scenarios because of the traffic volume inputted is more than it could process within the time frame given, it reduced the total traffic volumes for the scenarios affected. Table 4-12 shows the summary of the traffic volume not simulated and the new traffic volume for each scenario.

Table 4-12 Number of Cars Not Simulated per Scenario

	NB[vhp]			TOTAL[vph]
Scenarios	**Nos. of Cars Not Simulated**	**Inputted Volume**	**Nos. of Cars Simulated**	
BASE	0	536	536	1075
S1	0	586	586	1275
S2	0	636	636	1475
S3	0	686	686	1675
S4	0	736	736	1875
S5	12	786	774	2063
S6	74	836	762	2201
S7	143	886	743	2332
S8	0	761	761	1975
S9	18	796	778	2067
S10	32	806	774	2063

Tables 4-13 shows the average delay per approach and average approach delay for the various scenarios considered by increasing the traffic volumes of the base scenario in case 1. The average delay for the side street and the main street were also computed. The results obtained show that increase in the traffic volumes increases the average approach delay for each of the scenarios.

Table 4-13 Summary of the Approach Delay for Various Scenarios

SCENARIO	WB [vph]	EB [vph]	NB [vph]	SB [vph]	AVERAGE APPROACH DELAY[vph]	AVERAGE MAIN STREET[vph]	AVERAGE SIDE STREET[vph]
BASE	7.2	5.9	10.4	7.1	7.6	8.8	6.5
S1	8.2	6.5	11.9	7.5	8.5	9.7	7.4
S2	8.8	6.7	14.8	8.4	9.7	11.6	7.7
S3	10.0	7.5	19.5	9.4	11.6	14.5	8.8
S4	13.2	8.9	49.4	11.6	20.8	30.5	11.1
S5	14.8	10.4	137.0	14.7	44.2	75.8	12.6
S6	21.5	13.8	207.3	45.8	72.1	126.5	17.6
S7	38.1	16.7	230.1	138.3	105.8	184.2	27.4
S8	13.2	9.7	95.0	14.3	33.1	54.7	11.4
S9	16.0	11.3	158.7	22.0	52.0	90.3	13.7
S10	16.0	11.4	181.6	18.0	56.7	99.8	13.7

From figure 4-2, it could be observed that the roundabout experiences unbalanced flow, the main street experience more delay due to the higher traffic volume. We could also notice that the higher the total entering flow the higher the delay. Figure 4-3 shows the gradual increase in the average approach and the corresponding entering flow. Tracing out 50 seconds as the acceptable threshold for an unsignalized intersection for LOS of F, the corresponding total entering volume is 2,085veh/hr. This means when an unsignalized two-lane roundabout has a peak hour volume above 2,085veh/hr. We could also obtain the average approach delay at a four-leg two-lane roundabout by tracing out the total entering volume and obtain the corresponding value of the average delay.

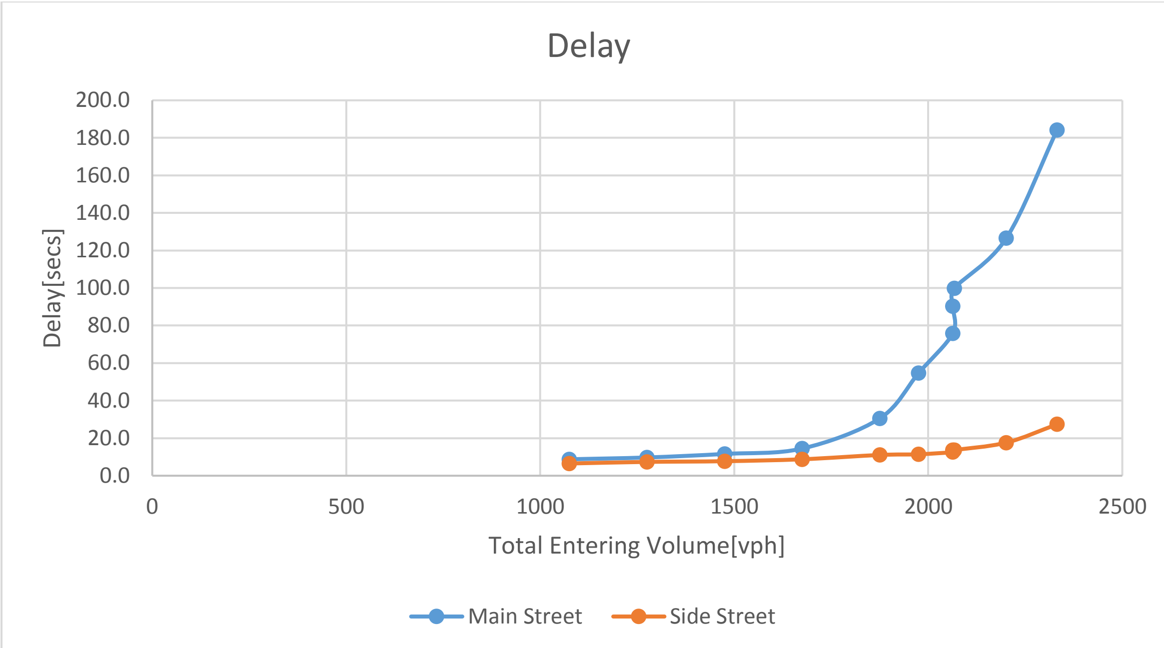

Figure 4-2 Comparing the Average Delay for Main and Side Street

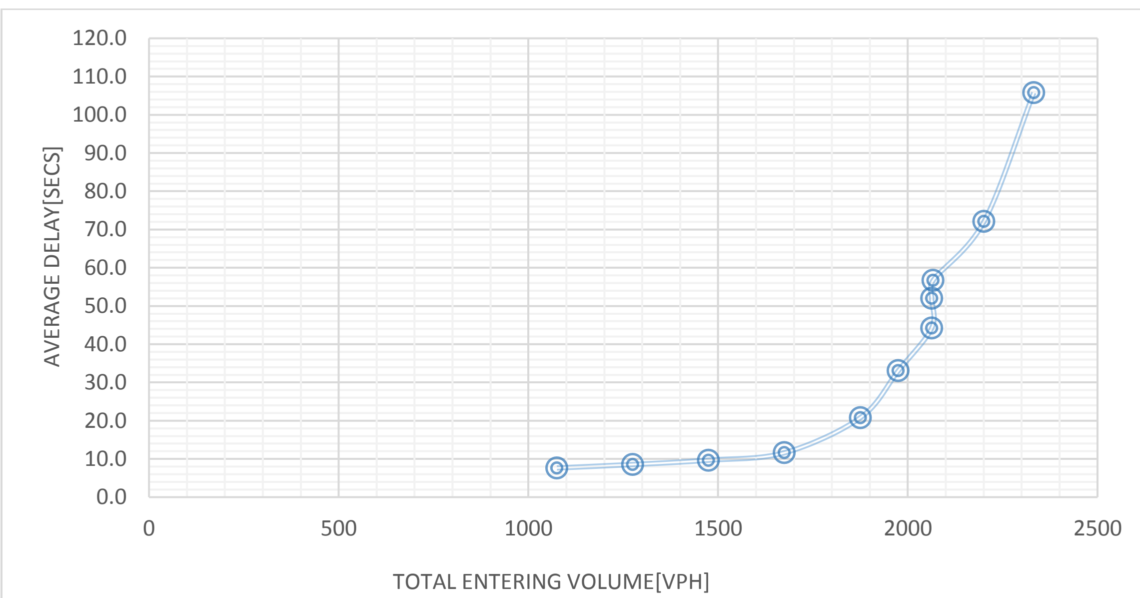

Figure 4-3 Graph of Average Delay against Total Entering Volume

4.2.3 Case 2: Relationship between Circulating Speed and Radius of the Roundabout

The circulating speed was reduced to observe the effect on the approach delay. The same traffic volumes for each scenario was used, and table 4-14 shows the number of vehicles not processed for the northbound approach in case 2 scenarios and the actual total traffic volumes were obtained.

Table 4-14 Cars not Simulated per Scenario for Case 2

	NB[vph]			TOTAL [vph]
SCENARIOS	**Nos. of Cars Not Processed**	**Inputted Volume**	**Nos of Cars Simulated**	
Base	0	536	536	1075
S1	0	586	586	1275
S2	0	636	636	1475
S3	0	686	686	1675
S4	43	736	693	1832
S5	125	786	661	1950
S6	201	836	635	2074
S7	321	886	565	2154
S8	87	761	674	1888
S9	135	796	661	1950
S10	141	806	665	1954

From the results, as shown in table 4-15, we can observe that reducing the circulating speed increases the delay at the various approach of the intersection. Considering circulating speed of 15mph, the total entering volume to obtain a threshold of 50seconds it about 1,800vph compared to 25mph which is about 2,100vph as shown in figure 4-4.

Table 4-15 Summary of Average Delay per Approach and Total Traffic Volumes for Case 2

SCENARIOS	WB [vph]	EB [vph]	NB [vph]	SB [vph]	AVERAGE APPROACH DELAY[secs]	TOTAL VOLUME [vhp]
Base	7.4	5.8	12.6	7.4	8.3	1075
S1	8.2	6.2	16.2	8.0	9.7	1275
S2	9.4	6.9	25.1	8.7	12.5	1475
S3	9.7	7.8	92.7	9.4	29.9	1675
S4	11.6	9.4	215.5	10.9	61.9	1832
S5	13.9	10.1	264.6	15.9	76.1	1950
S6	20.3	13.4	301.4	31.6	91.7	2074
S7	30.2	20.0	283.5	111.3	111.3	2154
S8	12.0	9.3	252.7	13.1	71.8	1888
S9	14.9	12.4	267.3	16.2	77.7	1950
S10	15.2	12.7	274.1	25.3	81.8	1954

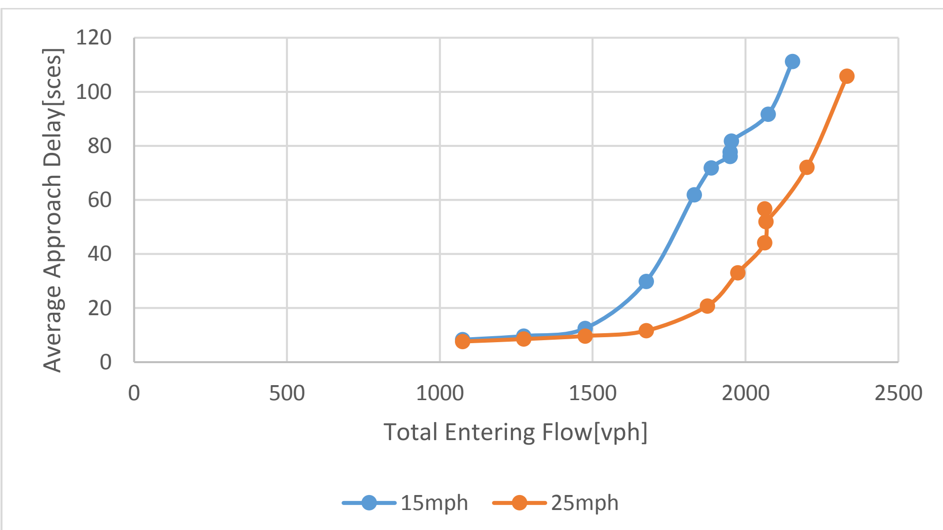

Figure 4-4 Comparing Results for Using 15mph and 25mph With Constant Radius

Four extra scenarios were considered for these instances by increasing the traffic volumes of scenario 7 by 100vhp per approach as described in the table 4-16 so as to obtain a threshold of 50seconds for scenarios in case 3.

Table 4-16 Traffic Volumes for Additional Scenarios

Scenarios	SB[vph]	NB[vph]	WB[vph]	EB[vph]	TOTAL TRAFFIC VOLUME[vph]
S11	633	986	703	553	2875
S12	733	1086	803	653	3275
S13	833	1186	903	753	3675
S14	933	1286	1003	853	4075

Table 4-17 and 4-18 show the results of varying the circulating speed and varying the diameter of the circle i.e using a circulating speed of 15mph and 30mph. The average approach delay, delays per approach and the total traffic volume are presented. The values for a circulating speed of 25mph were obtained from case 1. It was observed that the higher the circulating speed the higher the capacity of the roundabout. The volumes to obtain a threshold of 50seconds for 15mph, 25mph and 30mph are about 1,700, 2,100 and 2,750, respectively as shown in figure 4-5.

Table 4-17 Average Approach Delay 15mph with the Corresponding Radius

SCENARIOS	WB [vph]	EB [vph]	NB [vph]	SB [vph]	AVERAGE APPROACH DELAY[secs]	TOTAL VOLUME [vhp]
Base	5.3	2.4	5.1	6.5	4.8	1075
S1	5.8	2.6	6.9	6.5	5.5	1275
S2	6.3	2.6	9.5	7.6	6.5	1475
S3	7.0	3.1	23.7	8.1	10.5	1675
S4	8.5	3.7	79.6	10.3	25.5	1875
S5	9.6	4.3	232.8	11.2	64.5	1993
S6	12.6	5.5	270.8	29.5	79.6	2112
S7	25.0	9.2	290.7	53.4	94.6	2235
S8	8.4	3.8	163.9	10.9	46.8	1961
S9	11.8	4.8	212.8	12.3	60.5	2020
S10	13.4	6.1	221.5	15.0	64.0	2023

Table 4-18 Average Approach Delay 30mph with the Corresponding Radius

SCENARIOS	WB [vph]	EB [vph]	NB [vph]	SB [vph]	AVERAGE APPROACH DELAY[secs]	TOTAL VOLUME [vhp]
Base	5.9	4.8	7.6	4.2	5.6	1075
S1	6.6	5.1	8.2	4.3	6.0	1275
S2	6.7	5.1	9.5	4.7	6.5	1475
S3	7.2	5.4	10.8	4.9	7.1	1675
S4	7.6	5.7	12.2	5.1	7.7	1875
S5	8.5	6.1	17.6	5.9	9.5	2075
S6	10.4	6.8	31.3	6.7	13.8	2275
S7	9.9	6.8	31.6	6.9	13.8	2475
S8	8.1	5.8	14.6	5.6	8.5	1975
S9	9.3	6.5	22.1	6.9	11.2	2085
S10	9.3	6.3	18.8	6.4	10.2	2095
S11	19.5	11.2	190.9	17.3	59.7	2747
S12	48.8	21.5	214.5	81.5	91.6	3016
S13	252.8	96.6	222.7	261.9	208.5	3257
S14	309.6	261.1	231.7	317.2	279.9	3291

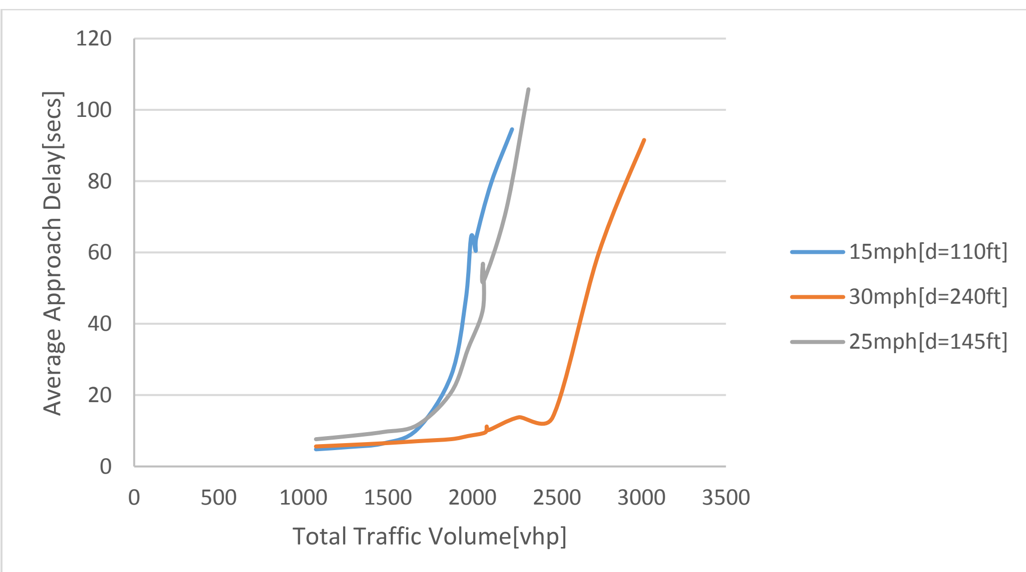

Figure 4-5 Comparing Circulating Speed with Change in Radius

4.2.4 Case 3: Varying Pedestrian Volume and Varying Traffic Volume

This case takes into consideration varying pedestrian volume and varying traffic volumes. Four instances were considered as shown in the table 4-19 (assuming they are evenly distributed around the roundabouts for all direction).

Table 4-19 Pedestrian Volumes

	PEDESTRIAN VOLUME[pers/h]				
INSTANCES	**NW**	**NE**	**SW**	**SE**	**TOTAL**
1	15	15	15	15	60
2	25	25	25	25	100
3	50	50	50	50	200
4	75	75	75	75	300
5	100	100	100	100	400

Tables 4-20 to 4-24 summary the results of the average delay per approach obtained for different instances of the simulation model for case 3. The Pedestrians at a roundabout increase the delay for various approaches of the roundabout as shown in figure 4-6. The lower the pedestrian's volume the lower the average approach delays as shown and vice versa. This condition is when car yield to pedestrians using the crosswalk i.e pedestrians are not controlled by traffic signals. The volumes to obtain a threshold of 50 seconds is between 1,700 to 1,900veh/hr for pedestrian's volume between 60pers/hr to 400pers/hr. The pedestrian speed ranges from 0.97m/s to 1.62m/s for man and 0.71m/s – 1.19m/s for woman

Table 4-20 Average Approach Delay For Instance 1

SCENARIOS	WB [vph]	EB [vph]	NB [vph]	SB [vph]	AVERAGE APPROACH DELAY[secs]	TOTAL VOLUME [vhp]
BASE	8.1	6.6	12.3	7.6	8.7	1075
S1	9.0	7.1	13.6	8.5	9.6	1275
S2	9.9	7.8	19.3	9.5	11.7	1475
S3	11.1	9.2	39.8	9.8	17.5	1675
S4	13.4	11.1	167.7	11.8	51.0	1865
S5	18.6	13.1	220.0	18.3	67.5	2002
S6	29.0	18.3	253.0	26.8	81.8	2130
S7	49.9	29.5	268.4	102.6	112.6	2265
S8	15.3	12.9	222.6	19.9	67.7	1938
S9	19.5	14.4	222.6	19.9	69.1	2005
S10	20.2	14.5	243.2	21.5	74.8	1988

Table 4-21 Approach Delay for Instance 2

SCENARIOS	WB [vph]	EB [vph]	NB [vph]	SB [vph]	AVERAGE APPROACH DELAY[secs]	TOTAL VOLUME [vhp]
Base	8.0	6.8	11.9	8.0	8.7	1075
S1	9.4	7.3	13.8	8.4	9.7	1275
S2	9.8	8.1	21.0	9.8	12.2	1475
S3	11.4	8.7	50.4	11.0	20.3	1675
S4	14.4	10.3	148.3	12.1	46.3	1875
S5	18.8	13.3	231.2	21.5	71.2	1994
S6	25.1	17.9	254.7	38.2	84.0	2128
S7	50.9	25.0	269.5	122.2	116.9	2258
S8	14.3	12.0	221.0	14.8	65.5	1926
S9	18.0	14.6	116.5	15.9	41.2	1997
S10	19.5	15.1	239.2	24.2	74.5	1992

Table 4-22 Average Approach Delay for Instance 3

SCENARIOS	WB [vph]	EB [vph]	NB [vph]	SB [vph]	AVERAGE APPROACH DELAY[secs]	TOTAL VOLUME [vhp]
BASE	8.4	6.8	12.7	7.6	8.9	1075
S1	10.0	7.4	15.2	9.2	10.4	1275
S2	10.6	8.2	19.7	10.3	12.2	1475
S3	12.0	9.4	63.8	10.4	23.9	1675
S4	14.6	10.8	167.7	13.5	51.6	1864
S5	17.4	13.4	236.2	17.2	71.0	1986
S6	29.9	19.7	256.4	63.5	92.4	2126
S7	117.9	26.1	279.8	118.3	135.5	2249
S8	17.1	11.4	227.8	19.1	68.8	1921
S9	23.9	14.5	251.9	26.5	79.2	1978
S10	22.8	16.0	253.7	20.2	78.2	1979

Table 4-23 Average Approach Delay for Instance 4

SCENARIOS	WB [vph]	EB [vph]	NB [vph]	SB [vph]	AVERAGE APPROACH DELAY[secs]	TOTAL VOLUME [vhp]
BASE	8.1	6.6	12.3	7.6	8.7	1075
S1	9.0	7.1	13.6	8.5	9.6	1275
S2	9.9	7.8	19.3	9.5	11.7	1475
S3	11.1	9.2	39.8	9.8	17.5	1675
S4	13.4	11.1	167.7	11.8	51.0	1865
S5	18.6	13.1	220.0	18.3	67.5	2002
S6	29.0	18.3	253.0	26.8	81.8	2130
S7	49.9	29.5	268.4	102.6	112.6	2265
S8	15.3	12.9	222.6	19.9	67.7	1938
S9	19.5	14.4	222.6	19.9	69.1	2005
S10	20.2	14.5	243.2	21.5	74.8	1988

Table 4-24 Average Approach Delay for Instance 5

	WB [vph]	EB [vph]	NB [vph]	SB [vph]	AVERAGE	TOTAL VOLUME
BASE	8.6	7.2	14.1	8.3	9.5	1075
S1	10.3	8.0	16.8	9.7	11.2	1275
S2	11.1	8.7	26.0	10.4	14.0	1475
S3	13.5	10.1	110.0	11.0	36.1	1675
S4	18.0	11.8	219.0	15.0	66.0	1832
S5	21.3	13.6	254.8	21.6	77.8	1962
S6	46.0	19.8	270.6	76.9	103.3	2102
S7	140.1	29.5	298.4	147.7	153.9	2222
S8	19.8	12.0	235.4	17.1	71.1	1905
S9	23.8	14.4	259.2	29.5	81.7	1958
S10	28.3	16.3	269.3	86.9	100.2	1964

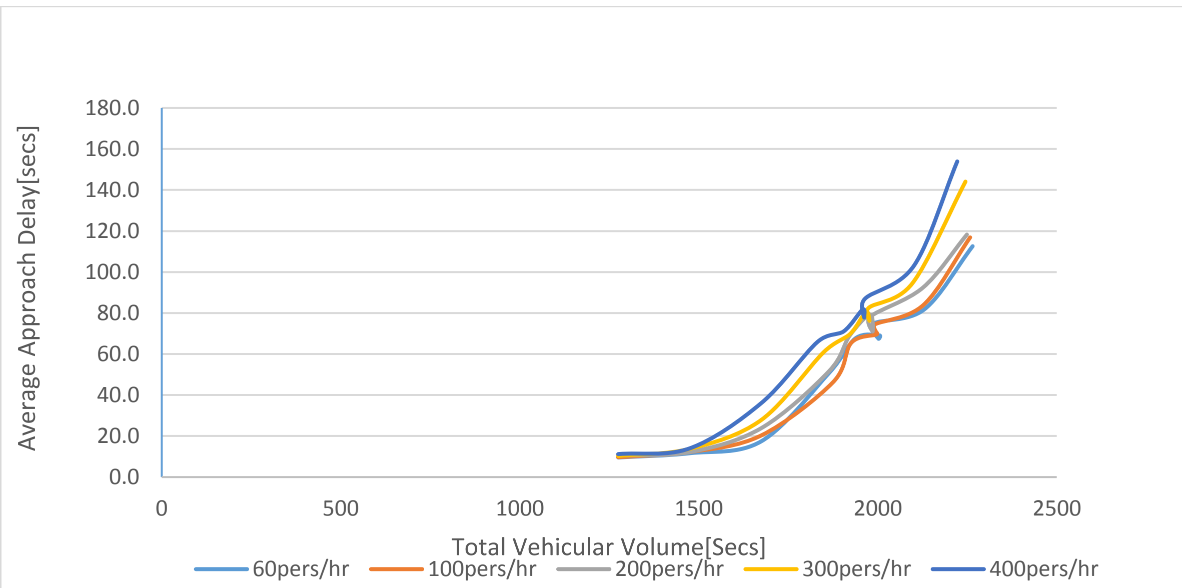

Figure 4-6 Comparing Results for all Instances

4.2.5 Case 4: Using Traffic Signals at a Two-Lane Roundabout

The use of a traffic signal at a roundabout can help balance the flow at an intersection as shown in the result of this case. Table 4-25 shows the number of vehicles not simulated for the northbound approach due to the limitation of time and the total traffic volumes for case 4. Table 4-26 presents the average delay per approach, average approach delay and the total traffic volumes for each of the scenarios considered in case 4.

Table 4-25 Number of Cars Not Simulated per Scenario for Case 4

	NB[vph]			
SCENARIOS	**Nos. of Cars Not Processed**	**Inputted Volume**	**Nos of Cars Simulated**	**Total Volume [vph]**
Base	0	536	536	1075
S1	0	586	586	1275
S2	0	636	636	1475
S3	0	686	686	1675
S4	0	736	736	1875
S5	0	786	786	2075
S6	0	836	836	2275
S7	37	886	849	2438
S8	0	761	761	1975
S9	0	796	796	2085
S10	0	806	806	2095

Table 4-26 Summary of Average Delay per Approach and Total Traffic Volumes for Case 4

SCENARIOS	**WB [vph]**	**EB [vph]**	**NB [vph]**	**SB [vph]**	**AVERAGE Approach Delay[vph]**	**Total Volume[vph]**
Base	10.7	15.3	15.4	16.0	14.4	1075
S1	14.0	15.1	16.3	11.8	14.3	1275
S2	16.5	13.4	17.9	12.7	15.1	1475
S3	17.5	17.4	20.0	14.4	17.3	1675
S4	21.0	19.7	25.1	15.0	20.2	1875
S5	23.2	24.5	32.0	17.4	24.3	2075
S6	27.3	33.6	49.8	21.5	33.0	2275
S7	32.5	35.0	156.3	24.9	62.2	2438
S8	21.1	19.7	27.9	17.7	21.6	1975
S9	22.2	24.6	31.5	18.1	24.1	2085
S10	23.1	23.6	36.9	17.1	25.2	2095

Figure 4-8 to 4-11 graphically present results for the base condition and scenarios 1 to 4. They show the region when the traffic signal is not beneficial to the traffic. Using a traffic signal at those volumes will be a waste of resources and causing more delay to the public. From figure 4-12, we could see the substantial decrease in delay because of the presence of traffic signal. It also helps to balance traffic distribution at this intersection. Figure 4-13 below shows the benefits of installing a traffic signal at a roundabout. From the graph, the points where traffic signals become beneficial is when the total entering flow is about 2.000vph.

Figure 4-7 Comparing Base Condition with and Without Traffic Signals

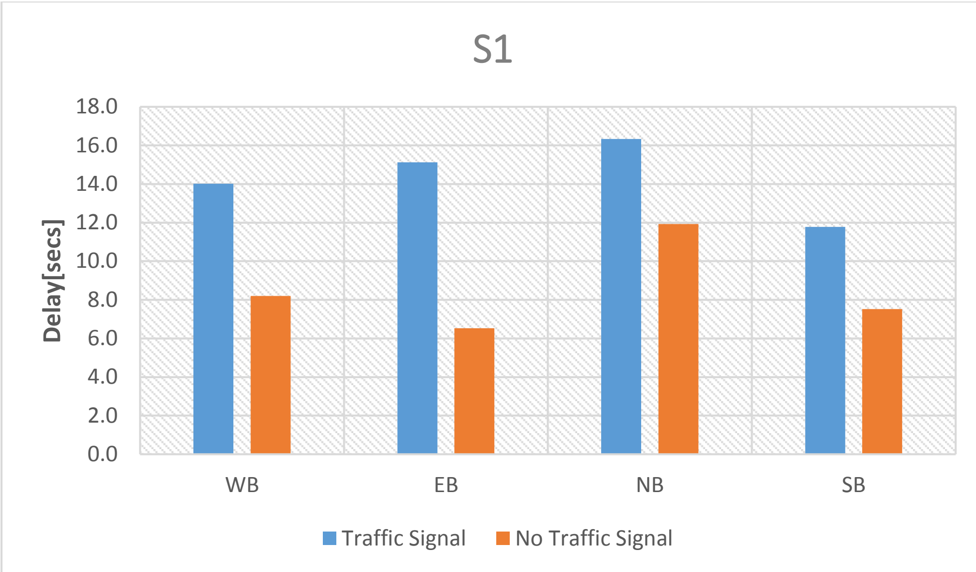

Figure 4-8 Comparing Scenario 1 With and Without Traffic Signals

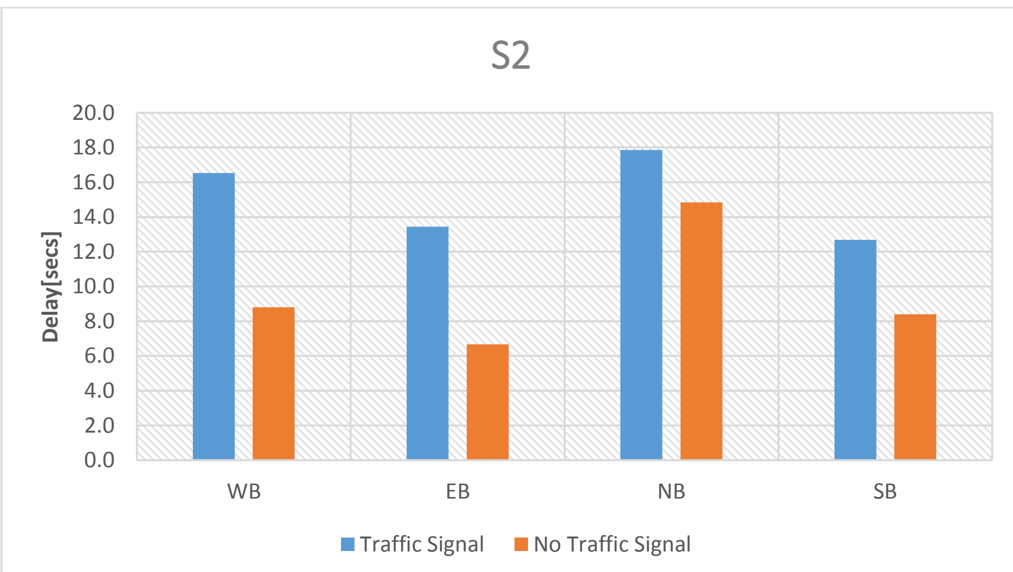

Figure 4-9 Comparing Scenario 2 With and Without Traffic signals

Figure 4-10 Comparing Scenario 3 With and Without Traffic signals

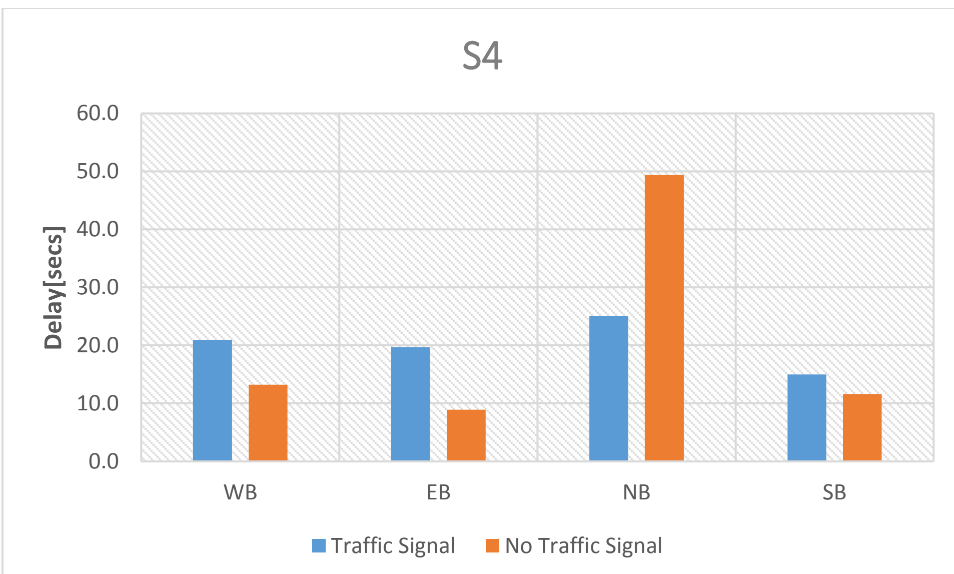

Figure 4-11 Comparing Scenario 4 With and Without Traffic signals

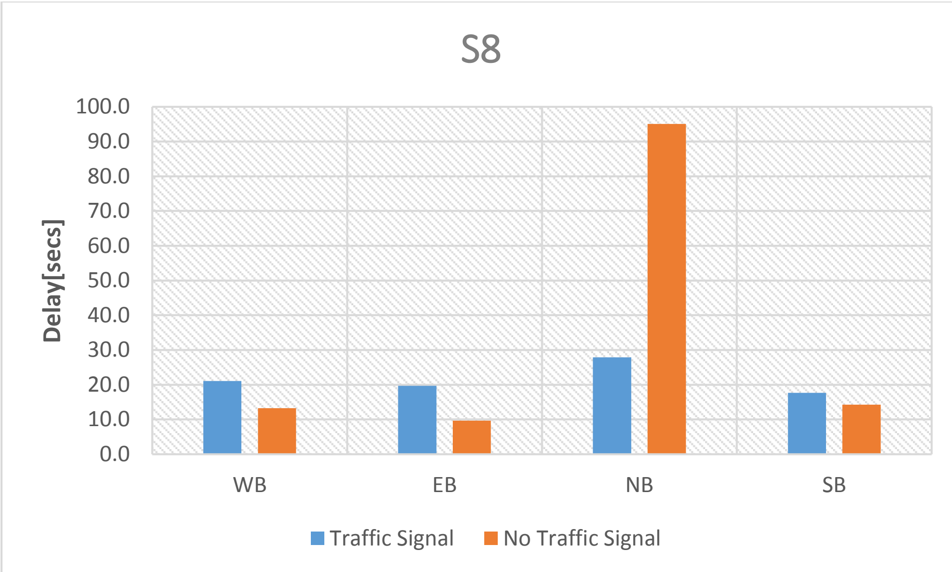

Figure 4-12 Comparing Scenario 8 with and Without Traffic signals

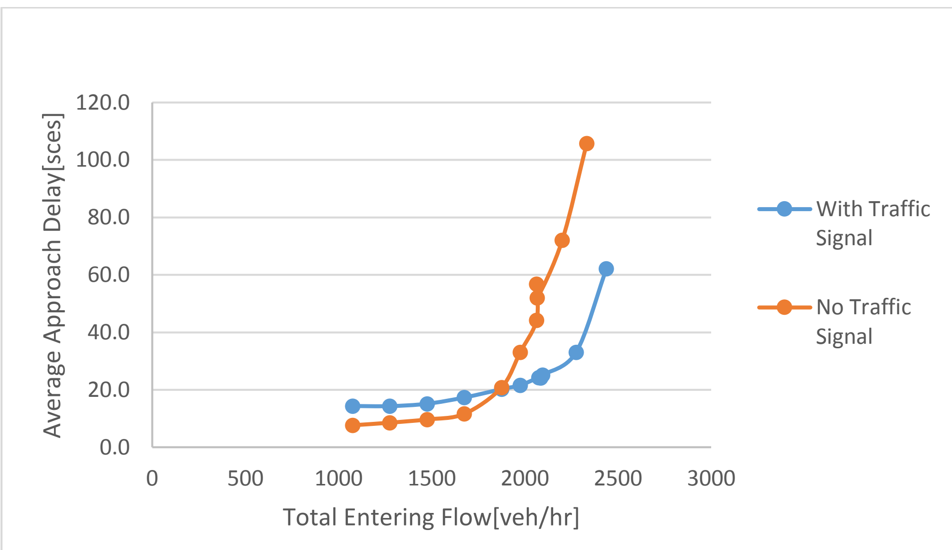

Figure 4-13 Comparing Average Approach Delay for Roundabout with and Without Traffic Signals

4.2.6 Case 5: Incorporating Slip Lanes to a Two-Lane Roundabout

Table 4-27 and 4-28 show the average delay per approach, average approach delay and the total traffic volumes for incorporating slip lanes into the geometry design of a roundabout for the main street only and incorporating slip lanes to all the approaches respectively. From the result, it was observed that the slip lanes reduce the delay at an intersection substantially and increase the capacity of the roundabouts though it might incur more space and cost of constructing. Figure 4-14 shows the volume to attain the threshold of 50seconds is 2,750veh/hr if slip lanes are introduced for the lane suffering excessive delay only and 3,450veh/hr and if the slip lane is introduced for all approaches.

Table 4-27 Adding Slip Lane on Main Street Only

SCENARIOS	WB [vph]	EB [vph]	NB [vph]	SB [vph]	AVERAGE Approach Delay[vph]	Total Volume[vph]
Base	6.8	5.7	6.6	1.4	5.1	1075
S1	7.7	5.8	6.7	1.9	5.5	1275
S2	8.1	6.2	7.2	2.4	6.0	1475
S3	8.9	7.1	7.0	2.5	6.4	1675
S4	9.7	7.7	7.6	3.0	7.0	1875
S5	11.9	8.5	8.5	3.4	8.1	2075
S6	15.6	11.9	9.1	3.9	10.1	2275
S7	23.4	14.7	9.3	4.5	13.0	2475
S8	11.1	8.5	7.9	3.3	7.7	1975
S9	14.5	8.9	8.2	3.8	8.8	2085
S10	12.9	9.0	8.7	3.9	8.6	2095
S11	218.6	25.1	15.2	7.8	66.7	2875
S12	367.0	184.5	32.0	15.6	149.8	3195
S13	409.1	374.6	80.8	41.7	226.5	3368
S14	419.9	446.7	93.0	55.6	253.8	3414

Table 4-28 Adding Slip Lane to All Approach

SCENARIOS	WB [vph]	EB [vph]	NB [vph]	SB [vph]	AVERAGE Approach Delay[vph]	Total Volume[vph]
Base	6.0	3.4	4.9	2.1	4.1	1075
S1	6.4	3.5	5.2	2.2	4.3	1275
S2	6.7	3.7	5.4	2.6	4.6	1475
S3	6.6	4.1	5.6	2.5	4.7	1675
S4	7.3	4.4	6.2	3.0	5.2	1875
S5	7.7	4.5	6.8	3.1	5.5	2075
S6	8.9	4.9	7.5	3.5	6.2	2275
S7	11.5	5.5	8.1	3.5	7.2	2475
S8	7.4	4.2	6.2	2.9	5.2	1975
S9	8.2	4.9	6.8	3.3	5.8	2085
S10	8.0	4.9	7.0	3.3	5.8	2095
S11	18.4	6.1	11.9	4.4	10.2	2875
S12	125.6	7.7	16.5	5.6	38.9	3275
S13	252.0	9.0	44.8	9.2	78.8	3670
S14	309.6	16.3	111.8	10.0	111.9	3843

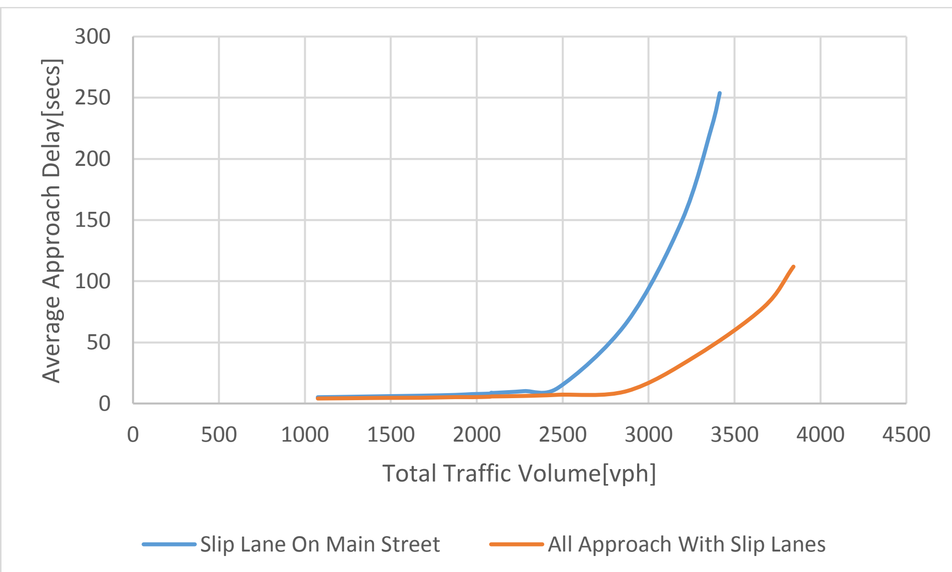

Figure 4-14 Delay Curve for Adding A Slip Lane on Main Street and/or Side Street

5 CONCLUSIONS AND RECOMMENDATIONS

Using the results obtained from the simulations of each of the cases considered, the following are the conclusions;

- First, the scenarios in case 1 show that the higher the traffic volume at a roundabout, the more the average vehicular delay. This is because the average vehicular delay for an approach depends on the volume of traffic entering the circle from different legs of the roundabouts.
- Secondly, the speed of the circulating flow is a function of the diameter of the circle, the larger the diameter of the circle the higher the speed of the circulating flow. Larger width increases the capacity of the roundabout as shown in case 2 results. Also, at a constant diameter, increasing the speed within the circle increases the capacity of the roundabout and reduces vehicular delay.
- Pedestrians at a roundabout reduce its' capacity as shown in the results obtained from case 3. The increase in total pedestrian volumes at a roundabout increases the average approach delay when the vehicles yield for pedestrians using the crosswalk.
- This research further found that installing traffic signals at a roundabout is beneficial because it enhances the capacity of a roundabout by reducing the average approach delay when the legs of the roundabout are experiencing unbalanced flow. A disadvantage of using traffic signal is that it increases average approach delay when the total traffic volume at that roundabout is substantially low. The traffic volume when traffic signals become beneficial is about 2000vph.
- Lastly, case 5 shows how incorporating slip lanes at a roundabout experiencing excessive delay help improve the capacity of the roundabout. The results showed that the average

approach delay could be reduced by 20 – 80 percent if slip lane is used at a roundabout. The constraints associated with this design is that occupies more space.

Conclusively, traffic signals can be considered when the total entering flow at a two-lane roundabout is about 2,000vph [if the pedestrian volumes are negligible]. If the total pedestrian volumes at the roundabout are about 400pers/h and the total vehicle volume is about 1,800vph, it is imperative to consider using a traffic signal. Slip lanes are advisable if there is a higher volume of the vehicle making a right turn. The volume to attain the threshold of 50seconds is 2750veh/hr if slip lanes are introduced to the lane suffering excessive delay only and 3450veh/hr and if the slip lane is introduced for all approaches. This paper has shown the impacts of traffic parameters and geometric features on the delay at a two-lane roundabout. Further works can include evaluating the impacts different categories of vehicles have on a roundabout, considering the varying ratio of the total traffic volume of the main street and total traffic volume of the side street and impacts of varying approach speeds on the average approach delay.

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Appendix A

Criteria for Installing Traffic Signal at Two-Lane Roundabouts

From the various cases considered in this research, the following criteria will help in capacity evaluation on whether to install a traffic signal at a two-lane roundabout experiencing unbalanced flow between the main street and side street approaches when considering addition lane is not a choice. Generally, the criteria are applicable for all the charts:

- The ratio of the street with more peak hour traffic volume to the least is 2:1.
- The approach speed for the main street is 45mph and the side street is 35mph.
- The vehicle composition of the model is 98% passenger cars and 2% heavy good vehicle[HGV]

Figure 0-1 shows the impacts of increasing traffic volumes on delay at a two-lane roundabout. It is applicable under the following conditions:

- The circulating flow speed at a two-lane roundabout with is 25mph.
- The inscribed diameter is 145ft.
- Zero pedestrian in consideration.

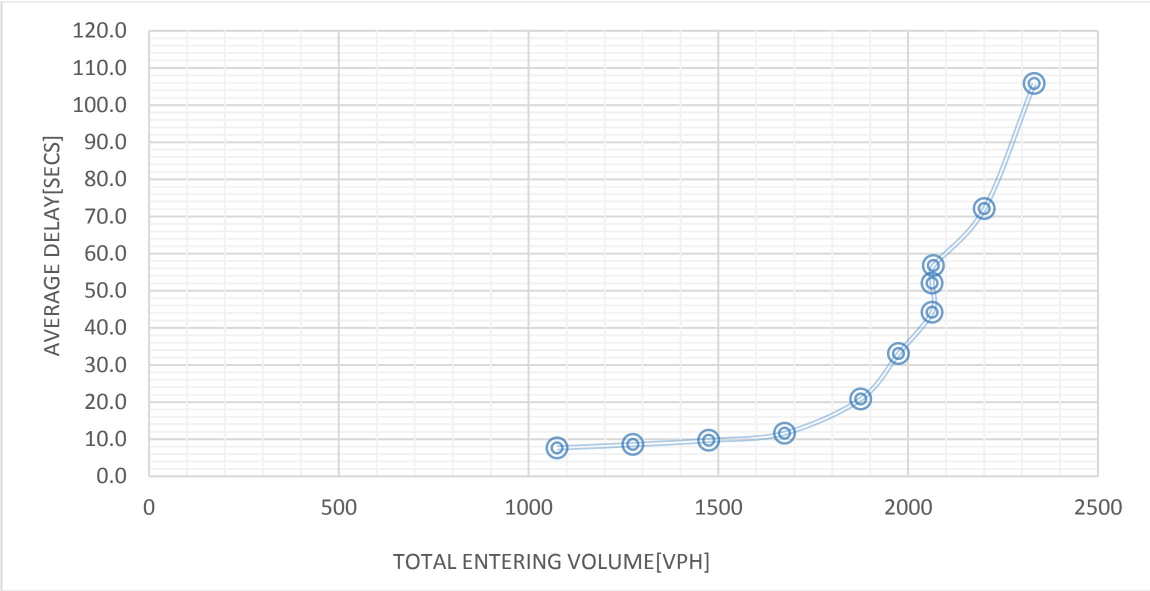

Figure 0-1 Impacts of Increasing Traffic Volumes on Delay at a Two-Lane Roundabout

Figure 0-2 shows the relationship between constant inscribed diameter and varying circulating speed. The following conditions satisfies using it:

- The circulating flow speed at a two-lane roundabout with is 25mph or 15mph
- The inscribed diameter is 145ft
- Zero pedestrian in consideration.

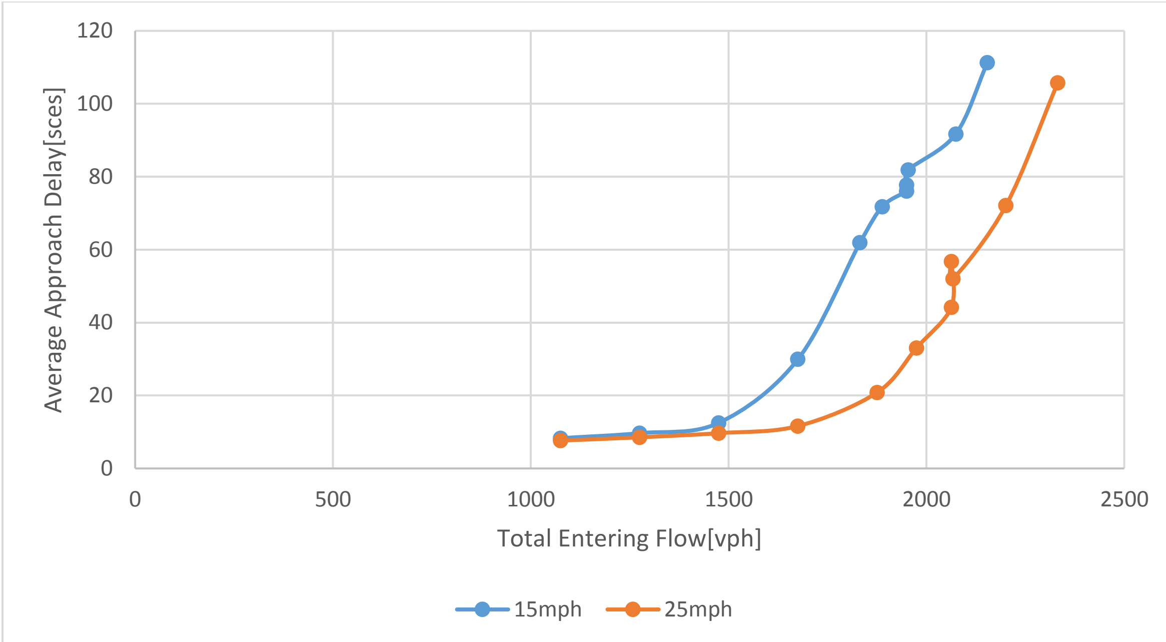

Figure 0-2 Relationship between Constant Inscribed Diameter and Varying Circulating Speed

Figure 0-3 shows the relationship between varying inscribed diameter and varying circulating speed. The following conditions satisfies using it:

- A circulating flow speed of 15mph and corresponding diameter of 110ft
- A circulating flow speed of 25mph and corresponding diameter of 145ft
- A circulating flow speed of 30mph and corresponding diameter of 240ft
- Zero pedestrian in consideration.

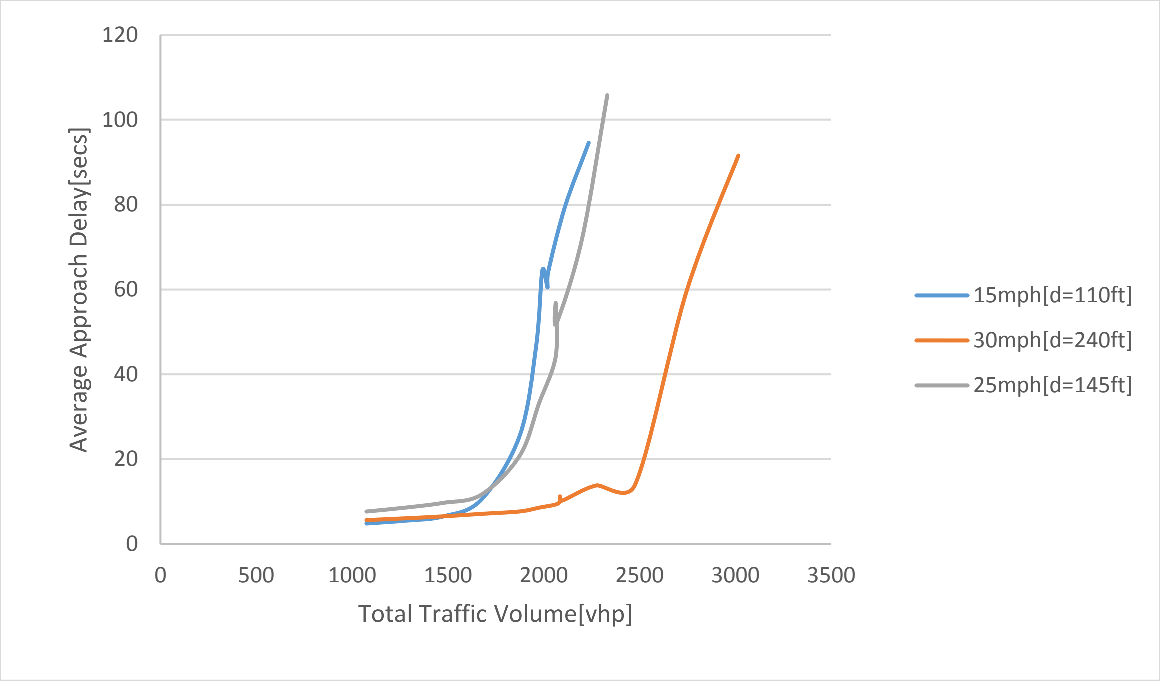

Figure 0-3 Relationship between Varying Inscribed Diameter and Varying Circulating Speed

Figure 0-4 shows various curve of varying pedestrian volumes and varying entering flow. It is applicable under the following conditions:

- Circulating flow speed is 25mph
- Inscribed diameter is 145ft
- Pedestrians speed
  - Man: 0.97m/s – 1.62m/s
  - Woman: 0.71m/s – 1.19m/s
- Pedestrians Volumes is between 60pers/hr – 400per/hr

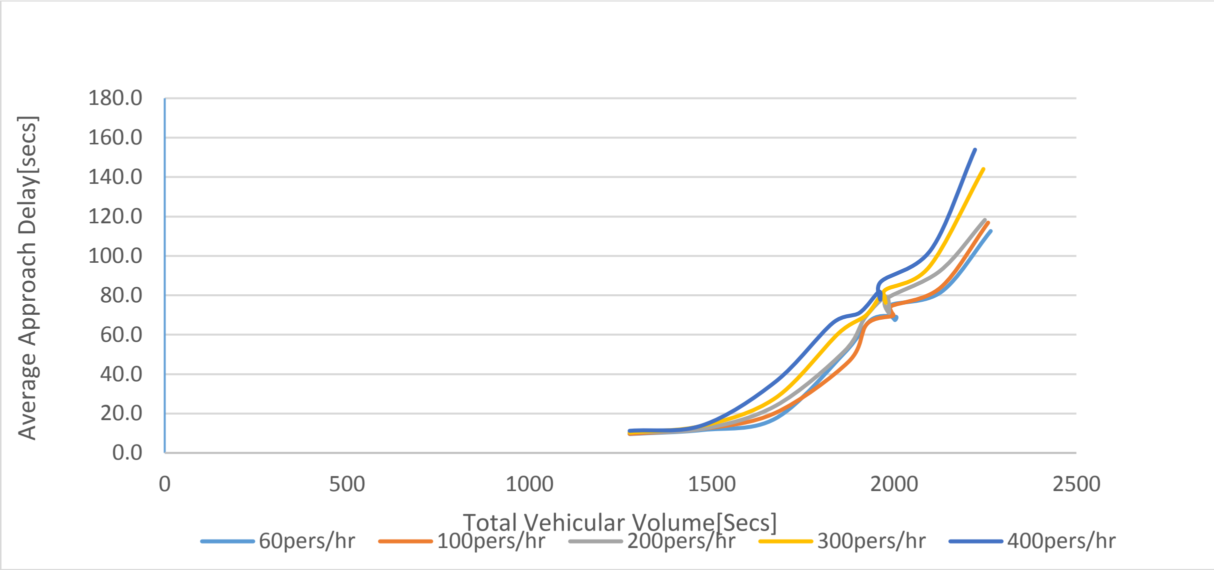

Figure 0-4 Varying Pedestrian Volumes and Varying Entering Flow

Figure 0-5 shows the profile of the benefit of traffic signal at a two-lane roundabout. It is applicable under the following conditions:

- Circulating flow speed is 25mph
- Inscribed diameter is 145ft
- No pedestrian in circulation

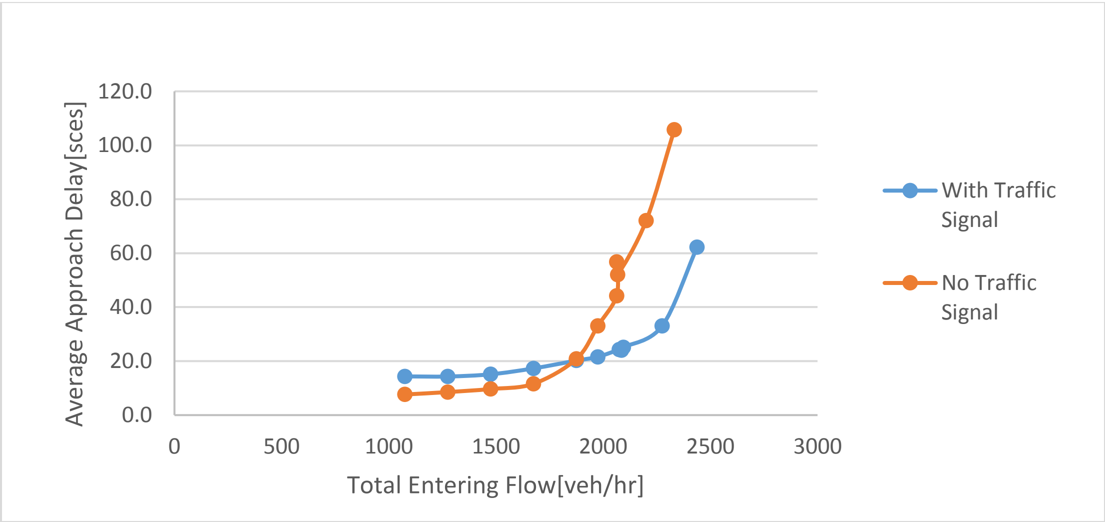

Figure 0-5 Profile of The Benefit of Traffic Signal at a Two-Lane Roundabout

Figure 0-6 shows the impact of adding slip lanes on delay to the approach with excessive delay only and for all approaches. It is applicable under the following conditions:

- Circulating flow speed is 25mph
- Inscribed diameter is 145ft
- No pedestrian in circulation

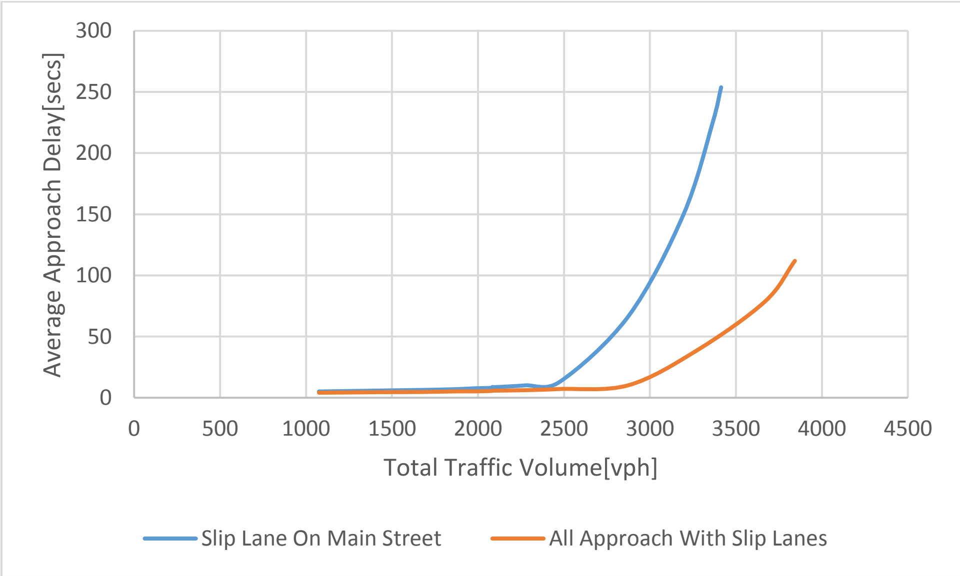

Figure 0-6 Impact of Adding Slip Lanes on Delay

Appendix B

Field Data

Travel times of sampled vehicles for various approaches are presented in the tables below;

Table 0-7 Off Peak Hour Approach Delay Study Sheet 1

Off Peak Period Approach Delay Study					
Location	68th Ave./Randall St., Coopersville, Ottawa				
Date	11/08/2018				
Time	Start	3:05PM	End		
Approach		Side Street		Main Street	
Street Name		68th Avenue		Randall Street	
Free-Flow Speed[FFS]		35 MPH		45 MPH	
		Travel Times(secs)			
	Sample Nos	WB	EB	SB	NB
	1	17	18	15	19
	2	15	20	26	14
	3	22	19	15	17
	4	13	20	18	16
	5	13	16	14	13
	6	13	20	18	12
	7	14	23	15	17
	8	18	19	17	11
	9	15	21	22	14
	10	11	17	16	11
	11	15	23	21	14
	12	17	25	16	20
	13	10	16	17	11
	14	17	22	18	15
	15	20	17	19	11
	16	18	19	14	12
	17	15	24		15
	18	17	26		17
	19	15			15
	20	15			17
	21	16			12
	22	13			14
	23	20			15
	24	19			14
	25	14			17

Table 0-8 Off Peak Hour Approach Delay Study Sheet 2

Off Peak Period Approach Delay Study					
Location	68th Ave./Randall St., Coopersville, Ottawa				
Date	11/08/2018				
Time	Start		End	3:55P.M	
Approach		Side Street		Main Street	
Street Name		68th Avenue		Randall Street	
Free-Flow Speed[FFS]		35MPH		45MPH	
		Travel Times(secs)			
	Sample Nos	WB	EB	SB	NB
	1	17			14
	2	14			15
	3	14			16
	4	13			23
	5	14			14
	6	17			17
	7	26			16
	8	20			16
	9	19			15
	10	18			13
	11	13			11
	12	18			14
	13	19			13
	14	16			18
	15	15			14
	16	29			12
	17				17
	18				17
	19				13
	20				15
	21				14
	22				18
	23				16
	24				15
	25				15

2

Table 0-9 P.M Peak Hour Approach Delay Study Sheet 1

1

P.M Peak Period Approach Delay Study					
Location	68th Ave./Randall St., Coopersville, Ottawa				
Date	11/08/2018				
Time	Start	4:45PM	End	5:25 PM	
Approach		Side Street		Main Street	
Street Name		68th Avenue		Randall Street	
Free-Flow Speed[FFS]		35 MPH		45 MPH	
		Travel Times(secs)			
	Sample Nos	WB	EB	SB	NB
	1	25	23	17	23
	2	19	25	30	28
	3	30	27	41	21
	4	25	19	19	20
	5	20	30	14	28
	6	22	33	21	30
	7	25	30	15	30
	8	20	25	34	33
	9	28	29	26	19
	10	18	22	18	30
	11	30	21	25	26
	12	25	35	17	17
	13	22	33	16	18
	14	25		30	20
	15	25		23	19
	16	33		16	35
	17	17		20	20
	18	19		17	19
	19	20		20	25
	20	20		19	21
	21	22		30	27
	22	21			32
	23	18			28
	24	17			25
	25	30			27