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Towards Sustainable Roundabouts: An Evaluation of Driver Behavior, Emissions, and Safety

Derek Roach
droach@student.umass.edu

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Towards Sustainable Roundabouts: An Evaluation of Driver Behavior, Emissions, and Safety

A Thesis Presented

By

DEREK ROACH

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by

Derek Roach

Approved as to style and content by:

Eleni Christofa, Chairperson

Michael A. Knodler, Member

Richard N. Palmer

Richard N. Palmer, Department Head
Civil and Environmental Engineering Department

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ABSTRACT

TOWARDS SUSTAINABLE ROUNDABOUTS: AN EVALUATION OF DRIVER BEHAVIOR, EMISSIONS, AND SAFETY

DECEMBER 2014

DEREK ROACH

B.S.C.E., UNIVERSITY OF MASSACHUSETTS AMHERST

M.S.C.E., UNIVERSITY OF MASSACHUSETTS AMHERST

Directed by: Professor Eleni Christofa

Roundabouts have been gaining acceptance by city planners and traffic engineers alike. The number of roundabouts in the U.S. has risen to roughly 3,700 over the last 20 years. Due to this rise in use, there has been a need to better understand the characteristics roundabouts have and how they affect the performance of transportation networks. Sustainability-related advantages of roundabouts are of particular interest.

Field data were collected for the purpose of determining the critical gap at a double single-lane roundabout and whether that value is substantially different than other types of intersections like stop-controlled intersections. Critical gap values are used in micro-simulation software and the more accurate the input data are the more accurate the model behaves compared to reality.

VISSIM, a micro-simulation software was used to develop models for two roundabouts, a single–lane roundabout and a double single-lane roundabout. The single-lane roundabouts was previously a signalized intersection and the double single-lane roundabout used to be two stop-controlled intersections. Models of both the current conditions and the previous conditions of these two locations were developed for both the morning and evening peak periods of demand.

Due to lack of data for the previous condition entry volumes, the current volumes were used for the previous condition models. These eight models were used for a before and after comparison of emission levels to determine what types of intersections are most sustainable in terms of emissions. In addition, the after models were used for a safety evaluation of the two roundabouts.

The after condition models of the two locations were used to produce vehicle trajectory files that can be interpreted by the Surrogate Safety Assessment Model (SSAM), a conflict estimation software developed by the Federal Highway Administration. This was done to determine if SSAM is an adequate tool for estimating the total number, type, and location of conflicts that occur at both a single-lane roundabout and a double single-lane roundabout. To validate findings the SSAM data were compared to a safety analysis conducted on video data collected at each site.

Another field study was conducted that utilized the Intelligence to Drive (i2D) device that plugs into a vehicle's on-board diagnostic port. This device can produce a vehicle's speed profile and estimate the level of emissions produced while the car is running. The combination of this device with video data were used to attempt determining the relationship between pedestrian activity and the level of emissions at roundabouts.

This research showed that the critical gap at a roundabout is significantly different than the default values used in micro-simulation. The stop sign controlled intersections, which were the before condition of the double roundabout produced higher emissions than the double roundabout. The signalized intersection, which was the before condition for the single-lane roundabout, produced considerably fewer emissions than the single-lane roundabout. SSAM was shown to be a reliable tool for estimating the total number, type, and location of conflicts that occur at both locations. The relationship between pedestrians and high emission levels at roundabouts was difficult to determine due to the small number of data that were collected. However, based on the speed profiles it was shown that the presence of pedestrians at roundabouts could potentially lead to more aggressive deceleration rates causing them to produce higher levels of emissions.

Future research should include: 1) continuing all the studies presented above for a variety of roundabouts with various geometric and traffic conditions to determine if the observed patterns hold true, and 2) collecting more data with the i2D device to determine a clear relationship between the presence of pedestrians at roundabouts and the associated emission levels.

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CHAPTER 1

INTRODUCTION

Innovation is necessary in order for society to move forward. Striving for progression has led to serious global consequences. The footprint left by mankind is still constantly expanding but the difference is that people are aware and make efforts to grow in such ways that leave the Earth intact for future generations. This type of growth has been christened sustainable, a relatively new field of study that is gaining acceptance and respect throughout the world.

Particularly, in the field of transportation engineering this term has become the new buzz word. Large amounts of government funding are being handed out for projects focused on sustainability, meaning thousands of studies are being conducted in order to discover new innovative ways to design, construct, operate, and manage transportation systems in a more efficient, equitable, and environmentally friendly manner.

One such innovation is the roundabout. Introduced to the United States (U.S.) in 1990, the first roundabout was located in Summerlin, a residential suburb of Las Vegas, Nevada (*1*). Since that time, roundabouts have been gaining acceptance by city planners and traffic engineers alike, even though many drivers are still struggling to properly maneuver through this new type of intersection. Despite problems with societal acceptability, the number of roundabouts in the U.S. has risen to roughly 3,700. Due to this rise in use, there has also been a rise in the number of studies performed on roundabouts so that they can be better understood and implemented. More recently, these studies have focused on whether roundabouts have sustainability-related advantages, such as improved air quality due to decreased emissions or improved safety which leads to economic savings, when compared with other types of intersections.

Problem Statement

There is a need to evaluate roundabouts with different characteristics, such as intersection demand level, traffic demand patterns (e.g., turning movement ratios), geometric characteristics (e.g., entrance angle, exit angle), and pedestrian volumes, to name a few, to further understand roundabouts. Each roundabout has different characteristics and it is difficult to compare results from one study to another. A detailed study of these parameters is needed in order to discover the operational, as it pertains to driver behavior, safety, and environmental performance of roundabouts. This will provide insights as of how the levels of vehicle and pedestrian demand as well as the type of roundabout (single-lane vs. double single-lane) affect driver behavior, safety, and the environmental performance of this alternative intersection design.

Driver behavior, emissions, and safety are three major aspects of roundabouts that are of great importance. Understanding driver behavior is an important step in explaining safety and emission trends at roundabouts. Sustainability is a term that is being advocated in all aspects of life. Both safety and air quality are key aspects of sustainability. Improved emission levels are beneficial to the health of the planet and its inhabitants. As for safety improvements, they are always highly sought after due to the relatively high crash rates associated with driving versus other forms of transportation and the high costs imposed to society when traffic accidents occur.

As for assessing driver behavior at roundabouts, little has been done to determine gap availability or gap acceptance. Having accurate gap availability, and acceptance data helps calibrate micro-simulation models to more accurately represent real-world conditions. Accurate micro-simulation models ensure better roundabout design and implementation.

Furthermore, a need exists to evaluate the effect of pedestrian crossing volumes on vehicular emissions at roundabouts. Previous studies have focused on comparing emission levels at roundabouts to emission levels at signalized or stop-controlled intersections but the effect that pedestrian volumes may have on those results is mostly unexplored. Pedestrians crossing a roundabout force vehicles entering or exiting to stop, which can cause traffic to back up into the roundabout causing gridlock at the intersection. Delays and idling vehicles greatly affect the emissions at an intersection but the most influential aspect is the acceleration-deceleration cycles that a vehicle goes through. If pedestrian volumes affect the number of stops that vehicles experience at roundabouts then the extent of that affect should be explored in detail.

Safety aspects of roundabouts are well documented. The fact that the number of points of conflict decrease from 32 to 8 when intersections are converted from signalized or sign-controlled intersections to roundabouts indicates a considerable increase in safety when the latter is used. Recently, surrogate safety measures, such as estimated time-to-collision, conflict angle, and vehicle speed and acceleration differentials, have been developed and used to assess the safety of transportation networks using conflicts as a measure of effectiveness besides just number of crashes or crash frequency. Conflicts are events that occur when drivers have to make an evasive action in order to avoid a crash or drivers that are demonstrating dangerous and aggressive behavior such as following vehicles too closely or accepting a gap that is potentially insufficient. Excessive deceleration and acceleration, available gaps, and headways are parameters that correlate to the number of conflicts that occur at a particular intersection. Evaluating before and after conditions of recently converted roundabouts using this method of safety surrogate measures will identify number of conflicts at roundabouts and the potential severity of those conflicts. The Federal Highway Administration (FHWA) developed the Surrogate Safety Assessment Model (SSAM) that is designed to read trajectory files obtained from micro-simulation models such as VISSIM (*2*) and estimate the total number of conflicts using surrogate metrics such as minimum time-to-collision, minimum post-encroachment, initial deceleration rate, maximum deceleration rate, maximum speed, and maximum speed differential.

Scope of Research

The objective of the proposed research has three components: 1) gap acceptance study, 2) emission estimation, and 3) safety assessment at roundabouts.

Research Goals

The broad goal of this research is to better understand roundabouts functionality in relation to driver behavior, vehicular emissions, and safety. The following goals were determined in order to properly address this research need:

- Determine gap availability and acceptance characteristics at two types of roundabouts: a) single-lane and b) double single-lane.
- Determine if roundabouts produce lower emission levels than signalized and stop-controlled intersections for the same demand and turning ratio scenarios.
- Explore the effect of emissions at roundabouts due to pedestrians and the intensity of that effect as a function of the pedestrian demand level.
- Determine if roundabouts are safer than the above mentioned signalized and yield-controlled intersection designs with respect to safety surrogate measures for the same demand and turning ratio scenarios.

The goals listed above are explained in further detail in Chapter 3.

CHAPTER 2

LITERATURE REVIEW

The following sections present a review of the literature on driver behavior, emissions, and safety at roundabouts, in particular, driver behavior, air pollutant levels, and safety related benefits. In most cases, if delay decreases more trips can be made with less time spent on the road. This correlates to increases in economic activity. Air pollutants are harmful to the environment and hence human health. Reducing emissions caused by traffic operations would be beneficial to the natural environment and the health of those in it. Safety is a primary concern in transportation and roundabouts have demonstrated decreases in total crashes and frequency of crashes in past studies. The literature review that follows has categorized existing studies into three groups based on their focus: driver behavior, emissions, and safety.

Operations of Roundabouts

Delay and queue length are two performance measures of roundabouts that have been widely studied in the United States and around the world. Equally as important is determining how driver behavior affects delay and queue lengths at roundabouts. Two driver behavior metrics that should be examined are gap availability and gap acceptance at roundabouts. The following sections expand upon the research that has already been completed pertaining to gap availability and gap acceptance studies.

Driver Behavior: Gap Availability and Acceptance

Gap availability delves into examining all the gaps that are present at an intersection. This metric can help explain why drivers choose to accept particular gaps over others. Areas with few large gaps would be expected to have gap acceptance values that are relatively low. Polus et al. (*3*) conducted a study on gap availability at two single-lane roundabouts in Maryland. The study concluded that all drivers will always accept gaps of 8.2 seconds or greater. Gaps of 8.2 seconds and larger should be excluded from the data set when determining the critical gap to ensure the results are not skewed. The study also examined gap acceptance. The critical gaps at the two site locations they tested were 3.85 and 3.91 seconds. According to the authors these values are substantially lower than the values recommended by the 2000 Highway Capacity Manual (HCM 2000). Similarly, the follow up times, or headways, recorded were 1.9 and 2.1 seconds. Follow up times are the time distance between two consecutive vehicles measured from the front of the leading vehicle to the front of the following vehicle. Again the authors state these values are considerably lower than the HCM 2000 recommended values of 2.6 and 3.1 seconds respectively.

Gap availability at seven single-lane roundabouts in California was assessed by Xu and Tian (*4*). The average gap at the test sites was 4.8 seconds with a standard deviation of 1.1 seconds. Gap availability at three two-lane roundabouts was also assessed in this study and the average gap was found to be 4.7 seconds for vehicles entering from the left lane and 4.4 seconds for those entering from the right lane. The critical gap at the test sites was also determined. At single-lane roundabouts the critical gap ranged from 4.5 to 5.3 seconds and at two-lane roundabouts from 4.0 to 5.1 seconds.

Abrams et al. (*5*) evaluated the roundabout located on the campus of the University of Massachusetts Amherst for both spatial and temporal gaps accepted by drivers. Spatial gaps represent the physical distance and temporal gaps the time distance between two subsequent vehicles. The results showed that the average accepted spatial gap was 42 feet and the average temporal gap was 2.2 seconds. These values are much smaller than those determined from previous studies, which stated the temporal gaps were closer to 4 seconds. Vasconcelos et al. (*6*) determined that critical gaps at roundabouts in Portugal vary between 3.2 and 3.7 seconds.

Table 1: Summary of Gap Acceptance Studies

Study	**Type of Roundabout**	**Headway**	**Critical Gap (sec)**
Polus (*3*)	• single-lane roundabouts		3.85 and 3.91
Xu and Tian (*4*)	• single-lane roundabouts		Average: 4.8 Single-lane: 4.5 to 5.3 Double-lane: 4.0 to 5.1
Abrams (*5*)	• single-lane roundabouts • two-lane roundabouts	2.2 sec 42 feet	
Vasconcelos (*6*)	• 6 single-lane roundabouts • one has two lanes at the entry and three in the circle • the remaining are standard two-lane roundabouts		Average: 3.2-3.7

All the studies indicate that there is high variability in gap acceptance values (they range from 3.2 seconds to 5.3. seconds) at different locations and types of roundabouts (i.e., single-lane, two-lane roundabouts, and turbo roundabouts); see Table 1. Due to this high variability, local values of gap acceptance need to be obtained and used in micro-simulation models so that these models are more representative of reality.

Pedestrians at Roundabouts

Few studies have considered the pedestrian effect on vehicle operations at roundabouts. One study by Rouphail et al. (*7*) focused on quantifying pedestrian gap acceptance behavior for both sighted and blind pedestrians near roundabouts. That data were then used to develop and calibrate a micro-simulation model of a roundabout. Using this model, the researchers quantified the impact of pedestrian crossing behavior on vehicle operations and the motorized traffic impact on pedestrian delay. The results indicated that pedestrian delay increased nonlinearly as vehicle volume increased. The delay for blind pedestrians was significantly larger than that of sighted pedestrians.

Another study by Schroeder et al. (*8*) focused on vision impaired pedestrian signalization options for crosswalks at both single and two-lane roundabouts. Utilizing micro-simulation models a variety of pedestrian treatments were assessed. The results suggest that the impact of pedestrian signals at roundabouts increases as the vehicle volumes approach capacity but the resulting vehicle delay and queueing can be mitigated through alternative signal configurations.

A third study by Ashmead et al. (*9*) assessed delay at roundabouts for pedestrians with sensory or mobility impairments. The findings showed that blind pedestrians waited three times longer to cross the urban two-lane roundabout than non-impaired pedestrians. In addition, about 6% of the blind pedestrian crossing maneuvers were deemed dangerous enough to require intervention. There have been no studies that have investigated the effect of pedestrian demand on vehicular stops or emissions at roundabouts.

Safety at Roundabouts

Although a myriad of research related to roundabouts exists, the material most related to this current research study addresses the safety of roundabouts as well as the methods of assessing safety at roundabouts. The safety benefits of roundabouts have been extensively investigated. Studies have evaluated different aspects of safety. The focus has been mainly on vehicular safety but there are studies that look at bicyclist and pedestrian safety as well. Most of these studies determine the total number of crashes or crash frequencies to assess safety, but recently an influx of surrogate safety measure (i.e, measures that can be used as proxies for determining safety risks) studies are surfacing. These studies assess intersection safety based on conflicts produced by SSAM. The sections that follow detail the studies to date pertaining to the safety topics discussed above.

Pedestrian Safety

Pedestrian safety is a critical aspect of the overall safety at an intersection. Due to the vulnerability of pedestrians and the high risk of serious injury if an accident does occur, pedestrians are the focus of a number of safety studies at roundabouts. One study completed a meta-analysis that showed that roundabouts are safer for pedestrians than traditional intersections and have no negative effect on cyclist safety (*10*). Another study observed what factors affect pedestrian crossing behavior and concluded that the presence of pedestrian crossings, the location of those crossings, signage, pedestrian islands, number of traffic lanes, vehicular speed, and traffic volumes all affect pedestrians' willingness to cross at roundabouts (*11*). A third study evaluated driver yielding behavior toward pedestrians at roundabouts and found that drivers exiting the roundabout are less likely to yield to pedestrians than when entering the roundabout and that as speed increases the likelihood of a driver yielding decreases (*12*).

Bicyclist Safety

Two studies have investigated cyclist safety at roundabouts all of which have reported that cyclist safety deteriorates when a signalized intersection or other intersection types are converted to roundabouts (*13,15*). In addition to the number of accidents, their severity increases as well (*13*). This finding was confirmed not only for mixed-traffic roundabouts but for roundabouts that have bicycle facilities such as bicycle lanes, separated cycle paths, and grade separated cycle paths as well (*14*). Other studies have reported potential explanations about these increases. Potential causes include bicyclists staying close to the curb while traveling through the roundabout, essentially turning a one-lane roadway into a two-lane roadway (*16*) or more generally cyclists' unsafe behavior when traveling through roundabouts (*17*).

Vehicle Safety

One of the first studies on vehicle safety at roundabouts in North America was performed by Montonen (*18*), who conducted a crash study using data from roundabouts both on national and municipal roads. The results showed that on national and municipal roads with roundabouts the accident rate was 26% and 23% while the injury accident rate was 4% and 4% respectively. Vehicle safety at roundabouts has been the focus of several other studies which all conclude that when intersections are converted to roundabouts the safety benefits are tangible (*19,20*).

Other studies have investigated particular aspects of roundabout design and their correlation with safety. An example is a study that focused on how sight distance and crash rates are related at roundabouts (*21*). This study discovered that increasing intersection sight distance, upstream approach sight distance, circulating approach sight distance, and circulation sight distance leads to increases in total and entry rear-end crash rates at a roundabout. Miranda-Moreno et al. (*22*) evaluated factors that increase crash severity at roundabouts and determined that factors such as a large number of involved vehicles, accidents occurring within the intersection, vehicle rollovers, the involvement of buses, and accidents occurring in the dark on unlit roads in snowy conditions all increased the severity of crashes at roundabouts. Factors such as accidents involving only cars, cars and animals, and snow-covered roadways were found to reduce the likelihood of severe injuries.

Applications of SSAM

The Surrogate Safety Assessment Model (SSAM) (*23*) is a software application that is capable of evaluating trajectory files obtained from micro-simulation models to estimate the number of conflicts in a simulated network. This allows for a new way to determine how safe a particular design is compared to alternative designs. Before the existence of this software application, safety evaluations could only be performed with data collection from real-world sites, which is expensive and does not allow for evaluation of alternative designs unless the changes are actually implemented. However, now simulation software can be utilized to evaluate the safety impacts of various designs using surrogate measures of safety. Events where drivers make evasive maneuvers, are forced to drive close to other users, or are excessively aggressive are all dangerous and affect the level of safety (*24*,*25*,*26*).

Multiple studies have focused on assessing the reliability of SSAM for different types of roadway networks, e.g., freeway merges (*27*) and signalized intersections (*28,29*). The Mean Absolute Percentage Error (MAPE) values for total, rear-end, and lane change conflicts were 33.4%, 33.5%, and 35.8% respectively at freeway merge areas (*27*). The MAPE was comparing the number of conflicts before model calibration to after model calibration. For signalized intersections the MAPE for the two studies found in the literature ranged from 18-24%, 15-20%, 29-31%, 38-81% at signalized intersections for total, rear-end, crossing, and lane change conflicts respectively (*28,29*).

Other studies have concentrated on how different driving behaviors affect the estimated conflicts by SSAM (*30*, *31*). Driving behaviors such as following or tailgating, weaving in and out of traffic, speeding or driving too fast for certain geometric or weather conditions, or the combination of close following, weaving through traffic and speeding practiced all at the same time produced 2.36, 6.16, 7.02, and 10.36 times the number on conflicts compared to non-aggressive driving behavior. A sensitivity analysis on 21 driver behavior parameters in VISSIM showed that all 21 parameters had a significant effect on the number of conflicts estimated by SSAM.

SSAM was used by Stevanovic et al. (*32*) to develop a relationship between intersection safety and efficiency. The study concluded that most of the safety improvements came at the expense of worsening intersection efficiency indicating the inevitability that efficiency will be lost when improving safety. Zhou et al. (*33*) completed a different type of study that evaluated the relationship between the speed limit and conflicts obtained through SSAM. The results indicated that safety performance improved when the speed limit was reduced.

SSAM and Roundabouts

The literature on the use of SSAM to perform safety evaluations at roundabouts is very limited. One of the existing studies has focused on assessing the impact of slip lanes for right turning vehicles at roundabouts using SSAM (*34*). This study confirmed that conflicts in the merge area were more prevalent than in the approach area and that the installation of a free-flow slip lane exit reduced overall conflict occurrence. Another study (*35*) used AIMSUN, a micro-simulation software, and SSAM to evaluate three different urban intersection designs: 1) a 4-leg intersection, 2) a 4-leg staggered intersection, and 3) a single-lane roundabout and compared the results to field observations at four different intersections: two priority controlled intersections, and two roundabouts. The author concluded that the best results are achieved when the models are properly calibrated, though a systematic underestimation of number of conflicts will still be present. SSAM is a relatively new software tool that has many potential applications but more research needs to be conducted for determining its accuracy and whether it is applicable for use at roundabouts.

Emissions at Roundabouts

Roundabouts have been shown to decrease queue length, vehicle delay, and number of stops compared to signal or stop-sign controlled intersections. The question is whether or not these improvements are correlated to a decrease in emissions at roundabouts. Studies using field measurements, analytical models, and micro-simulation models have been recently conducted to assess whether roundabouts decrease emissions and under what circumstances such a statement would be accurate.

Field Measurements

Field data produce results that best represent what is actually happening in the real world. Unfortunately, field data is expensive and tedious to gather. With regards to emissions, second-by-second field data could not even be tracked until recent technological advancements became available. On board devices with such capabilities were not available to Paul Hoglund in 1994 (*36*). Instead data from a Swedish field study was used to estimate vehicular emissions for the before and after conditions of a signalized intersection in Stockholm that was converted to a roundabout. This study provided a relationship between average speeds of vehicles and level of

HC emissions. Hoglund used this data to predict emission levels based on vehicular speeds that were observed. Decreases in hydrocarbons (HC) ranged from 0.014 to 0.057 g/veh depending on the direction of traffic that was observed. Only one direction of traffic saw a 0.008 g/veh increase in HC. Carbon monoxide (CO) emissions decreased ranging from 0.513 to 1.253 g/veh and again for only one direction of traffic emissions they slightly increased. Three directions of traffic experienced an increase in Nitrogen Oxides (NO_x) while the other three did not. The magnitude of these differences was relatively low with the largest being a 0.019 g/veh increase in NO_x.

A much more recent study conducted by Hallmark et al. (*37*) collected field data along two corridors using a Portable Emissions Monitoring System (PEMS) that was attached to a 2005 Dodge Caravan. The first corridor consisted of two 4-way stop-controlled intersections, one signalized intersection, and a roundabout and the second corridor was the same but had one less stop-controlled intersection. At the first corridor, carbon dioxide ($CO2$) emissions were the highest at the 4-way stop-controlled intersection and lowest at the signalized one. At the 4-way stop-controlled intersection CO_2 emissions were 9-12% higher than at the roundabout and at the signalized intersection CO_2 emissions were 5-25% lower than at the roundabout. CO emissions were the highest at the roundabout and the lowest at one of the 4-way stop-controlled intersections. At the 4-way stop-controlled intersection CO emissions were 39-46% lower than at the roundabout. The signalized intersection CO emissions were 22-43% lower than at the roundabout. HC emissions were in the highest concentration at the 4-way stop-controlled intersection. The signalized intersection had HC emissions that were 23-30% lower than the roundabout and 15-24% lower than one of the stop-controlled intersections. Strangely, NO_x was the highest (52% higher than that at the roundabout) for one of the stop-controlled intersections and lowest for the rest of the stop-controlled intersections. Similar results were obtained from the second corridor that was studied.

Analytical Models

In 2001 Andras Varhelyi utilized car following methods to estimate vehicle emissions for a before and after comparison of several yield controlled intersections and one signalized intersection that were converted to roundabouts (*38*). The signalized intersection experienced a decrease in CO emissions of 29% and in NO_x emissions of 21% when converted to a roundabout. As for the yield controlled intersections, CO increased by an average of 4%, NO_x by 6%, and fuel consumption by 3% when converted to roundabouts.

Vehicle Specific Power (VSP) is an indicator of engine power demand that can be used to approximate emissions based on a vehicle's speed and acceleration and the gradient of the roadway. A study in 2006 by Margarida et al. (*39*) used VSP to estimate emissions and evaluate three different congestion specific speed profiles at single-lane roundabouts in urban corridors. The first speed profile represented drivers that only had to slow down through the intersection, the second drivers that had to stop once, and the third drivers that had to stop multiple times before exiting the roundabout. Conflicting volume levels were also investigated in this design and it was discovered that as conflicting volumes increase so do emissions of CO, NO_x, and HC. Similarly, at low conflicting volumes an increase in those emissions was experienced. The author suggests that this is due to the fact that at low and high conflicting volumes, drivers spend more time in the acceleration mode, which has been found to produce the highest concentration of emissions (*40*, *41*). This experiment was expanded in 2012 by the same reseach group to analyze multilane roundabout emissions as a function of the driver speed profile and the level of left and right lane volumes (*42*). As expected, the high congestion scenarios produced higher levels of emissions than the low congestion ones for all the single-lane roundabouts that were examined. During high levels of traffic congestion vehicles in the left lane emitted 11% more pollutants than the ones in the right lane when the volumes for the two lanes were equal. This was not the case when the right lane had a larger volume than the left one. The right lane produced appropriately 100% more emissions than the left lane in this case.

In a study conducted in 2013, Vasconcelos et al. (*43*) evaluated emissions at a new type of roundabout called a turbo roundabout in Portugal. The turbo roundabout is a new innovation implemented at multi-lane roundabouts that helps control lane movements by adding raised medians between lanes within the roundabout in order to reduce crash risk. Using VSP to estimate emissions, the new turbo roundabout was compared to two-lane roundabouts and single-lane roundabouts. Interestingly, single-lane roundabouts had the highest levels of CO, CO_2, NO_x, and HC compared to both the two-lane and the turbo roundabouts. The turbo roundabout, produced more CO_2 and NO_x emissions than a two-lane roundabout, but less CO and HC. The author concluded that two-lane roundabouts are potentially beneficial when trying to reduce CO_2 and NO_x but turbo roundabouts should be used if one wishes to reduce CO and HC levels.

Simulation Studies

While simulation studies are time-consuming, they are often the only feasible way to perform multiple scenarios with different inputs. For these reasons many more simulation studies have been conducted on roundabouts over the years than studies that develop analytical models or perform field tests.

One simulation study in 2001 modeled 25 signalized intersections in Burlington, Vermont as roundabouts using the software SIDRA (*44*). The author estimated a 250,000 yearly reduction in fuel use, when signalized intersections were converted to roundabouts; that amounts to 61,000 tons of CO_2 saved per year. In another study in 2005 SIDRA was used to model roundabouts in Maryland and Delaware (*45*). Since SIDRA uses average default values for certain inputs such as gap acceptance, the study looked at two sets of simulations. The first set used the default SIDRA values for gap acceptance and the second used measured gap acceptance values at the tested roundabouts. In all cases the levels of CO, CO_2, NO_x, and HC decreased when the measured values of gap acceptance were incorporated into the model instead of the default ones. This reinforces the fact that micro-simulation models need to be carefully calibrated with real-world data.

A study in Kansas in 2007 focused on modeling the before and after conditions of six stop-controlled intersections that had been converted to roundabouts. The models were developed in SIDRA (*46*). CO, CO_2, NO_x, and HC emissions decreased from 21-42%, 16-59%, 20-48%, and 17-65% respectively after the signalized intersections were converted to roundabouts. The following year Thieken (*47*) compiled a report assessing emission levels at four separate roundabouts: 1) U.S. 33 and S.R. 161/Post Road Interchange, Dublin, Ohio, 2) Sawmill Parkway Extension, Delaware County, Ohio, 3) Hilliard Triangle Project, Hilliard, Ohio, and 4) Avery Road South Corridor Study, Dublin, Ohio). The four studies were performed using both aaSIDRA and RODEL for delay estimation. The emission estimates from RODEL were significantly smaller than the estimates produced by aaSIDRA but in three of the four studies both roundabout models produced lower values than those of the respective signalized intersections.

Hu et al. (*48*) analyzed two two-lane roundabouts in Bellingham, Washington. SIDRA INTERSECTION 5.1 was utilized for modeling the before and after conditions. One of the roundabouts was compared to a hypothetical stop-controlled intersection and the other to a hypothetical signalized intersection. The percent changes in fuel consumption, CO, CO_2, NO_x, and HC from a stop-controlled intersection to a roundabout were -23%, -15%, -23%, -23%, and 0% respectively. Similarly the percent changes of the same metrics when comparing the roundabout to a signalized intersection were -34%, -45%, -34%, -44%, -40% respectively.

SIDRA and RODEL are not the only micro-simulation programs that can output emissions. INTERGRATION is a micro-simulation software that outputs emissions and has been used in more recent studies. A study by Jackson and Rakha (*49*) examined fuel consumption, CO_2, CO, NO_x, and HC emissions at signalized and stop-controlled intersections and roundabouts using INTERGRATION. When volumes dropped below 500 veh/hr/approach, and the left turn demand was greater than 50% of the approach traffic demand, the two-way stop-controlled intersections resulted in the lowest fuel consumption and CO_2 emissions compared to the other intersection designs. When demand was greater than 500 veh/hr/approach and left turn demand was larger than 50% of the total approach demand the signalized intersection presented the lowest CO_2 emissions. Otherwise fuel consumption and CO_2 were the lowest at the roundabouts. HC and CO were the lowest at the roundabout for all conditions except when the left turn demand was very low or high. NO_x was the lowest at the signalized intersections when the volume exceeded 500 veh/hr/approach and at the two-way stop-controlled intersection when the volume was lower than 500 veh/hr/approach. All other configurations led to NO_x being the lowest at the roundabout.

The second study that used INTERGRATION was conducted by Ong et al. (*50*). This study modeled both a single and a two-lane roundabout and compared them with similar four and two-way stop-controlled and signalized intersections. The single roundabout performed the best besides the two-way stop-controlled intersection in fuel consumption, HC, CO, and CO_2 emissions. The two-way stop-controlled intersections observed the lowest NO_x emissions. The two-lane roundabouts produced the lowest values of fuel consumption, HC, CO, and CO_2.

The final study that will be discussed used the Virginia Tech Microscopic Energy and Emission Model (VT-Micro) and the Comprehensive Modal Emissions Model (CMEM) to compare emissions at roundabout against signalized and stop-controlled intersections (*51*). VT-Micro and CMEM are emission models that were used to estimate the level of emissions produced based on processing vehicle trajectories obtained from micro-simulation software. The VT-Micro model showed that compared to stop-controlled intersections, roundabouts produce 155%, 203%, 38%, and 10% higher HC, CO, NO_x, and CO_2 respectively. A similar trend was seen in the CMEM model, which estimated 344%, 456%, 95%, and 9% higher values of HC, CO, NO_x, and CO_2 respectively at roundabouts compared to the estimates obtained for stop-controlled intersections.

Summary of Literature Review

The literature review detailed in this chapter covers a variety of aspects of roundabouts and their users. Driver behavior at roundabouts has been significantly documented in many places throughout the country but it is clear that this behavior is vastly varied depending on the geographic location. In addition, no study to date has assessed gap availability and acceptance characteristics at double roundabouts.

Many studies have tried to quantify the environmental benefits of roundabouts by assessing emissions at roundabouts compared to signalized and stop-controlled intersections. The results of these studies have been inconsistent and no definite conclusions have been reached. This may be in part due to the wide variety of micro-simulation programs and emission models that have been used in these studies. Most importantly, there has been no effort of assessing the effect of pedestrian crossing volumes at roundabouts on the level of vehicular emissions.

Finally, safety at roundabouts has been assessed in many studies based on crash rate and severity reductions but little research has been done to assess roundabout safety based on surrogate measures of safety. Only one study has used SSAM to assess safety at a single-lane roundabout and no assessment of a double roundabout has been conducted.

CHAPTER 3

STUDY DESIGN

The study design is composed of the research objectives, research tasks, and research contributions.

Research Objectives

To address the goals of this research, it was pertinent to develop research objectives. The motivation behind these objectives is explained in further detail later in this chapter. The four research objectives were:

- *Determine gap acceptance behavior at a double roundabout.*
- *Compare the levels of NOx and CO emissions at roundabouts to respective emission levels at signalized intersections and stop-controlled intersections that have the same demand and turning ratios.*
- *Perform a surrogate safety analysis to determine if SSAM is an accurate tool for estimating conflicts at single-lane and double roundabouts.*
- *Explore the effect pedestrian crossing volumes have on emissions at roundabouts.*

The following sections provide background information on the motivation of the objectives listed above.

Research Objective 1

- *Determine gap acceptance behavior at a double roundabout.*

The collection of gap acceptance data through a field study is a critical step in properly calibrating micro-simulation models. Without proper calibration the results of the simulation cannot be used to determine anything useful about the real-world situation. Many simulation programs and studies used national averages for characteristics such as gap acceptance but these values can lead to significant biases in the results and subsequent conclusions. Therefore, it is important to ensure the values used in the models match those of reality.

Research Objective 2

- *Compare the levels of NO_x and CO emissions at roundabouts to respective emission levels at signalized intersections and stop-controlled intersections that have the same demand and turning ratios.*

As discussed in the previous chapter, much controversy still remains regarding whether roundabouts produce fewer emissions than other more traditional intersection designs. Many different simulation software have been used to assess the performance of roundabouts with respect to air pollutant emissions. The results seem to vary considerably from study to study and no single conclusion can be agreed upon. Field and simulation studies were used to assess and compare emission levels at roundabouts to signalized and stop-controlled intersections.

Research Objective 3

- *Perform a surrogate safety analysis to determine if SSAM is an accurate tool for estimating conflicts at single-lane and double roundabouts.*

Previous research studies that dealt with roundabout safety mostly examined total crashes and crash frequencies with the use of field data. In addition, of the previous research efforts that utilized SSAM only one study assessed safety at a roundabout. An interesting research opportunity exists to determine if SSAM is a viable tool for estimating conflicts at roundabouts in order to determine its level of safety.

Research Objective 4

- *Explore the effect pedestrian crossing volumes have on emissions at roundabouts.*

Emissions at roundabouts have been studied extensively over the last decade but as previously stated little data exist as on how pedestrian crossing volumes affect emission levels. Roundabouts present a unique problem in terms of pedestrians' crossings. If pedestrian volumes are high, vehicles attempting to exit or enter the roundabout could be forced to stop to allow for pedestrian crossings. If the volumes are very high, queues can develop that prevent traffic from exiting and entering or circulating the roundabout. This could lead to even higher emission levels. There is a need to quantify the relationship between pedestrian crossing volumes and vehicular emissions at roundabouts to ensure proper evaluation and design of roundabouts in the future.

A series of tasks, detailed below, were followed to complete the aforementioned research objectives.

Task 1: Literature Review

A comprehensive literature review was conducted. This provided an in-depth understanding of issues related to driver behavior, safety, and air pollutant emissions at roundabouts. It also ensured that all the strengths and weaknesses of the previous research studies were identified. The literature review preformed was presented in Chapter 2.

Task 2: Critical Gap Field Study

Gap availability, acceptance, and queueing data were collected from 7:30 AM to 8:30 AM (i.e., the morning peak period) and from 4:30 PM to 5:30 PM (i.e., the evening peak period) at a double roundabout located on Route 116 and Bay Road in Amherst, MA (Figure 1); from now on referred to as Atkins Corner double single-lane roundabout. The purpose of collecting gap availability and acceptance data were to determine the critical gap at the intersection.

Figure 1: Double Single-Lane Roundabout at Route 116 and Bay Road, Amherst, MA
https://www.google.com/maps

The data were collected with the use of a program, Gap Acceptance Processing System (GAPS), developed at UMass and adjusted specifically for this project using Microsoft Access. Only one person is required to operate this program in the field and it does not require anything more than a typical laptop to run. Proper procedures for collecting data were explained and followed by all persons involved in the data collection process. The “Gap Acceptance Study Packet” (*52*) details the steps involved in completing a gap acceptance study.

Most of the data analysis was automated using the GAPS program in Microsoft Access and Microsoft Excel. After the vehicle data were entered into the GAPS program a basic analysis was run which outputs data in a form that can be imported to a spreadsheet in Microsoft Excel. This spreadsheet was programmed to take the input and run detailed analysis to determine gap acceptance behavior at the roundabout. The output is both tabular and graphic.

Task 3: Calibration and Validation of VISSIM Models

In order to perform more extensive tests for assessing emission levels at roundabouts micro-simulation was used. Four different models were developed in VISSIM. The first represents the before conditions of the pre-timed signalized intersection on the UMass campus that is now a roundabout (Figure 2). The second represents the before conditions of the two stop-controlled intersections that are now a double single-lane roundabout in South Amherst Massachusetts (Figure 1); from now on referred to as UMass campus single-lane roundabout. The other two models consist of the two after conditions of the locations mentioned above. The models were calibrated and validated for the after conditions using data collected through cameras at both locations.

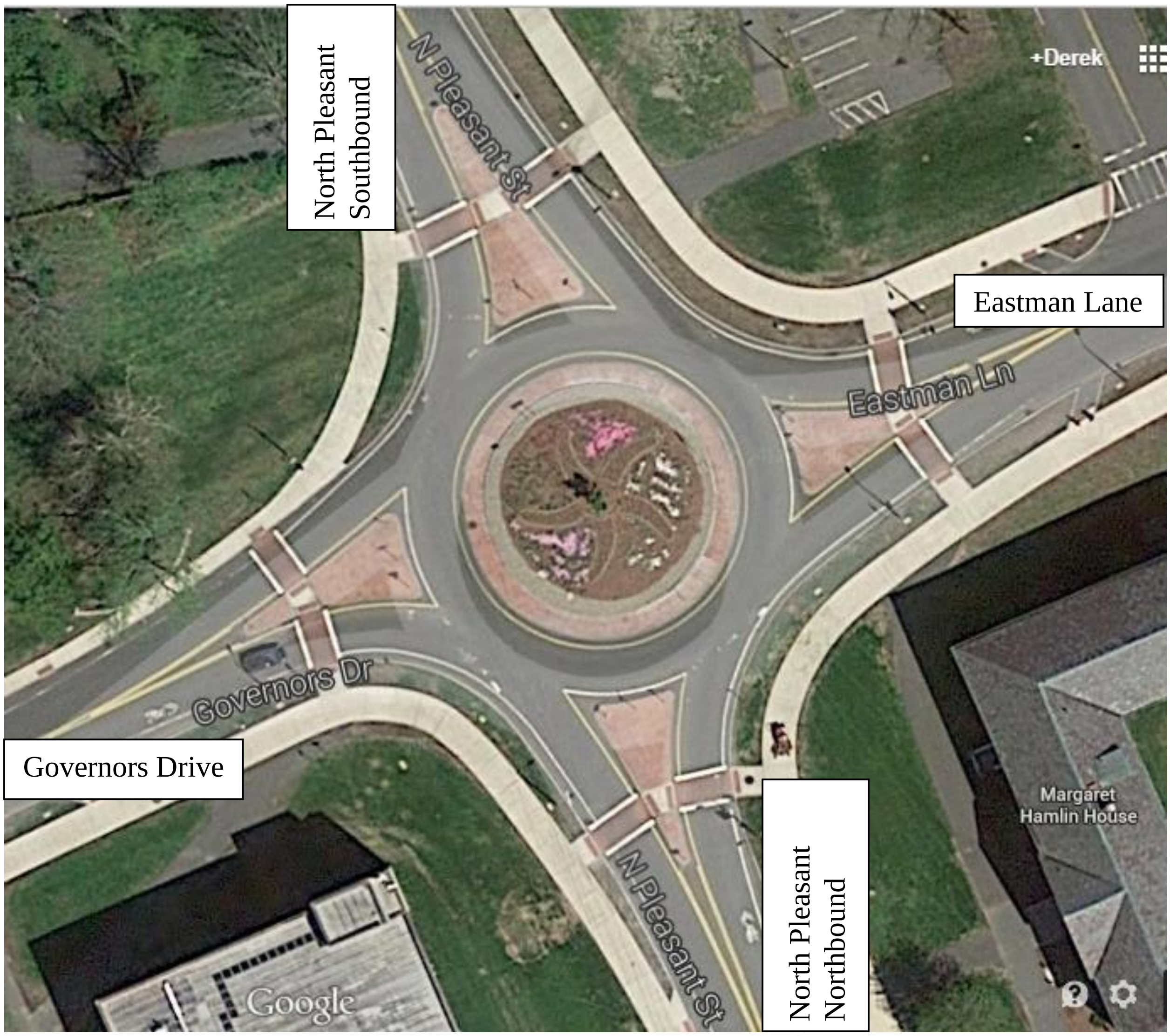

Figure 2: Single-lane Roundabout at N. Pleasant and Governors Dr. at the University of Massachusetts campus in Amherst, MA
https://www.google.com/maps

Task 4: Before and After Comparison of Emissions through Simulation

The fully calibrated and validated VISSIM models were used to estimate vehicle emissions including NO_x and CO. Multiple simulation runs were processed to account for stochasticity in the input parameters and their outputs were used to obtain average emission estimates. A detailed comparison of the before and after conditions was conducted to assess whether roundabouts do in fact decrease vehicle emissions compared to signalized and stop-controlled intersections.

Task 5: SSAM Analysis

SSAM developed by FHWA was used through simulation to estimate conflicts for the single-lane roundabout and double single-lane roundabout mentioned above. SSAM allows for the type of conflicts to be filtered by conflict type. Rear-end, lane change, and crossing conflicts are the three types of conflicts recorded by SSAM. The severity of these conflicts is represented by the value of time-to-collision (TTC) registered by SSAM from the VISSIM trajectory files. TTC values range from 1.5 seconds to 0 seconds decreasing by half second intervals. A TTC value of 0 seconds indicates a collision where a TTC value of 1.5 seconds indicates driver following behavior that is dangerous. The location of the conflicts on the network is another aspect of the SSAM software that is helpful in developing countermeasures. The SSAM results were compared to the safety analysis conducted on the video collected at those two locations.

Task 6: Comparison of Field and Simulation Safety Data

In addition to calibrating and validating the micro-simulation models, video recorded at each of the site locations was used to compare the model results from VISSIM and SSAM to the real-world results. Due to the limitations of only having video data the severity of video conflicts were not estimated. Only number of conflicts, type of conflict, and location of the conflict were determined from the video. This comparison was performed for investigating the reliability of SSAM to estimate conflicts at both a single-lane roundabout and a double single-lane roundabout.

Task 7: Impact of Pedestrians on Roundabout Emissions

A field study was conducted at the roundabout located on the campus of the University of Massachusetts (UMass) Amherst. Understanding the effect that pedestrian crossing volumes have on emissions was the objective. In order to achieve this objective driver subjects were asked to drive a vehicle equipped with the intelligence to Drive (i2D) device, which is an on board vehicle diagnostic technology that can be plugged in the OBD port of any vehicle. In addition to providing the trajectory of the vehicle it can also estimate emissions through an online model that uses the information from a vehicle's trip to calculate percent time spent in different driving modes, in which driving mode most energy is being consumed, and consequently total emissions.

Participants were asked to drive the equipped vehicle from the top of Eastman Lane down the hill straight through the roundabout and continue to parking services on the UMass Amherst campus. Figure 3 depicts the route drivers were asked to navigate. Drivers were instructed to drive as they would if they were in their own vehicle. Video data of each trip were collected using UbiPix, which is a smart-phone application. The video data were used to determine where and when pedestrians affected the vehicle operations and determine pedestrian demand volumes. The level of emissions was estimated and compared across participants. In addition, emission levels were studied as functions of pedestrian crossing volumes.

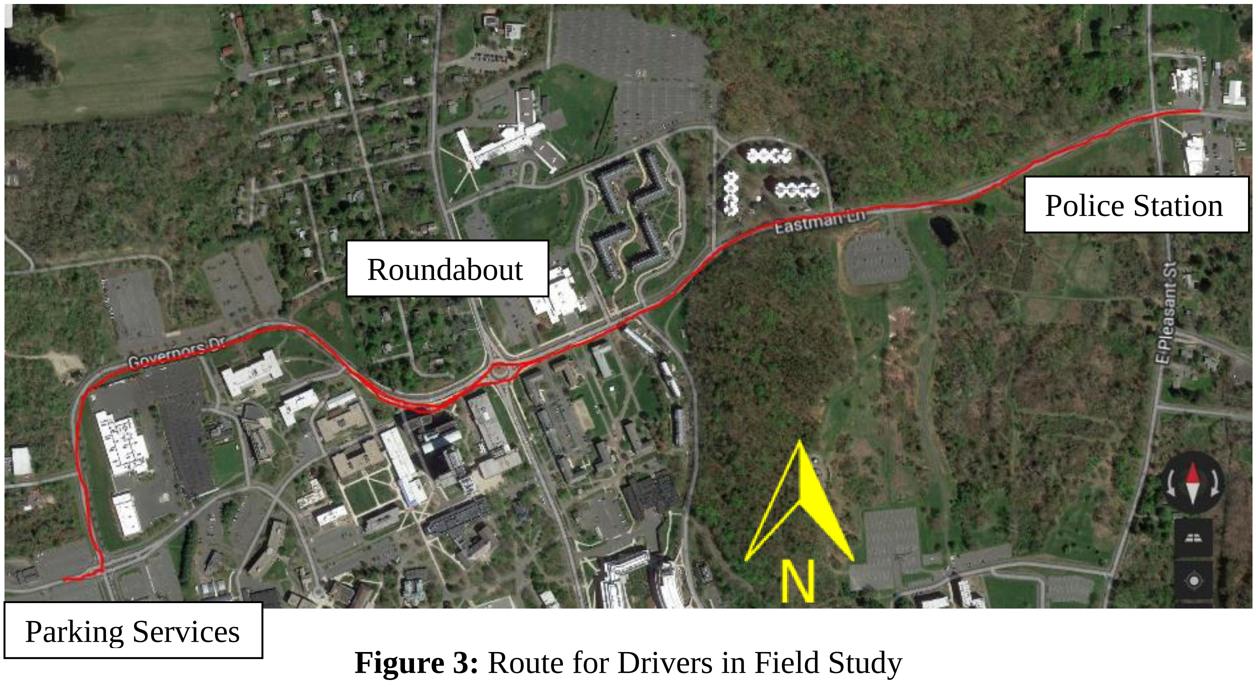

Figure 3: Route for Drivers in Field Study
https://www.google.com/maps

Task 8: Documentation of Findings

The research detailed above was documented in the form of a Master's Thesis that was submitted to the Graduate School of the University of Massachusetts Amherst. The "Guidelines of Master's Thesis and Doctoral Dissertations" were followed in completing this document.

Research Contributions

Overall this thesis contributes in four areas:

- Determine critical gap at a double single-lane roundabout.
- SSAM analysis and accuracy determination for two types of roundabouts: a) single-lane and b) double single-lane.
- Explore the relationship between pedestrian crossing volumes and vehicle emissions at roundabouts.

- Emission level comparison of roundabouts with signalized intersections and stop-controlled intersections.

CHAPTER 4

DRIVER BEHAVIOR AT ROUNDABOUTS

This chapter details the results obtained from the queue and gap study conducted at the double single-lane roundabout located in South Amherst Massachusetts. The roundabouts were converted from two stop-controlled intersections. The queue lengths were measured for comparison to the values collected when the intersections were two stop-controlled intersections.

Queue Study Results

Data were collected at a double single-lane roundabout in Amherst, Massachusetts. Before the roundabouts were constructed the site consisted of two stop-controlled intersections. Figure 4 shows the site during construction so both the previous condition and current conditions can be seen. Queuing data were recorded for both the morning and evening peak hour. To remain consistent with the before study data that were collected by Steven Tupper, a UMass Alum, the peak hours recorded for the after study were 7:30 AM to 8:30 AM and 4:30 PM to 5:30 PM and the day chosen for the data collection was Wednesday October 16th 2013. Though the study before recorded two hours of queuing data, the peak hours were as previously stated and therefore only the peak hour intervals were taken into account in the data collection in the after study. The previous data were collected from the Bay Road approach at the first intersection and the West Bay Road approach at the second intersection. These same locations were selected for the after study data collection. The results of the after study are explained in further detail in the following section.

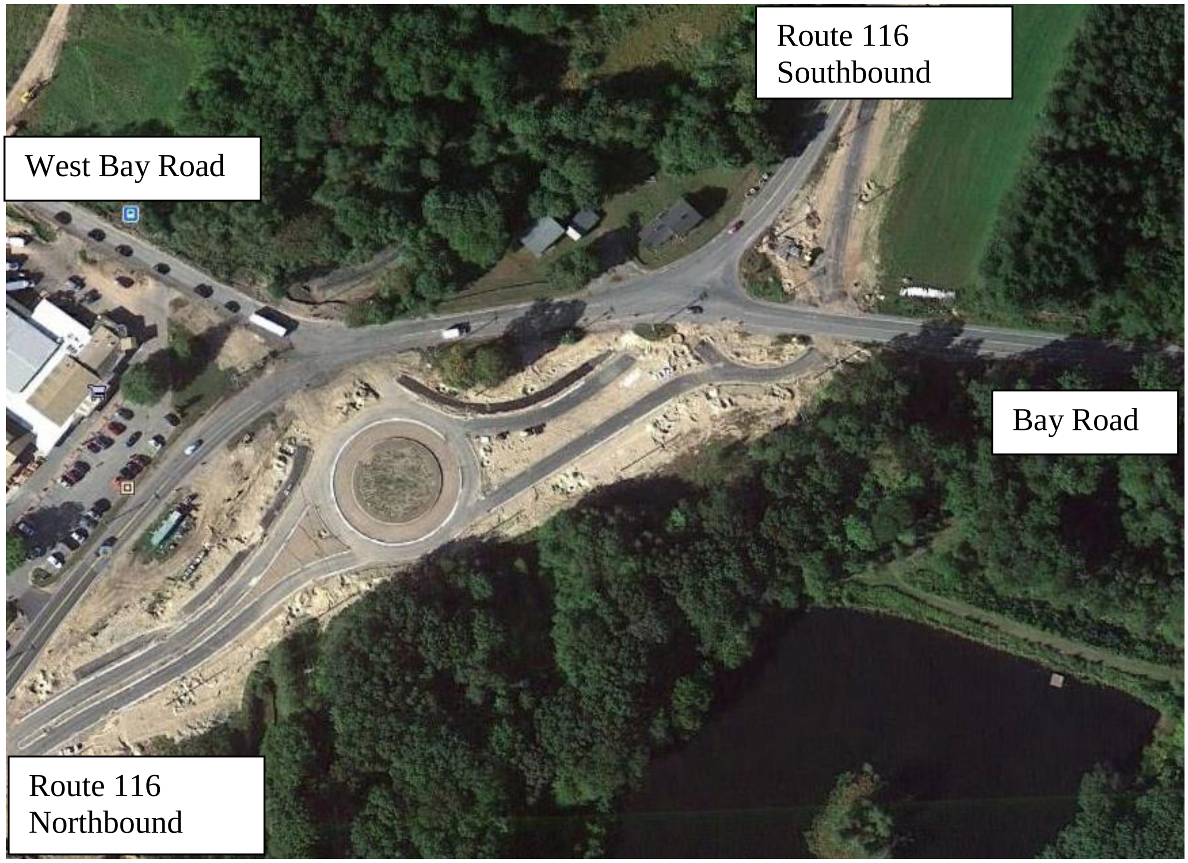

Figure 4: Before and After Conditions at the Double Single-Lane Roundabout Site
https://www.google.com/maps

Average and Maximum Queue Lengths

Tables 2 and 3 show average queue lengths and Tables 4 and 5 show maximum queue lengths for both the Bay Road and West Bay Road approaches. The average queue length decreased considerably from the before study to the after study. Each approach, during both peak hours, saw a decline in the average queue length equal to one vehicle as can be seen by the results in Tables 2 and 3. Similarly, the maximum queue lengths in the after study were generally lower than the before study results. Maximum queues reached only 7 vehicles and dissipated rapidly during the after study whereas the before study experienced queues that exceeded 11 vehicles as can be seen in Tables 4 and 5. The line of sight only allowed for the observer to count up to 11 vehicles so the real maximum queue length and average queue lengths for the before study on the West Bay Road approach, are underestimated. This underestimation is depicted in the Table 5 by the symbol $^+$ indicating that the maximum queue was longer than what could be measured and is reported in the table.

Table 2: After Study: Average Queue Length (Recorded Every Minute for Morning and Evening Peak Hour on both Approaches)

Approach	**Average Queue**	
	7:30 AM to 8:30 AM	**4:30 PM to 5:30 PM**
Bay Road	0.95	0.36
West Bay Road	0.03	1.11

Table 3: Before Study: Average Queue Length (Recorded Every Minute for Morning and Evening Peak Hour on both Approaches)

Approach	**Average Queue**	
	7:30 AM to 8:30 AM	**4:30 PM to 5:30 PM**
Bay Road	2.90	1.10
West Bay Road	2.20	3.60

Table 4: After Study: Maximum Queue Length (Recorded Every Minute for Morning and Evening Peak Hour on both Approaches)

Approach	**Maximum Queue**	
	7:30 AM to 8:30 AM	**4:30 PM to 5:30 PM**
Bay Road	7	7
West Bay Road	1	7

Table 5: Before Study: Maximum Queue Length (Recorded Every Minute for Morning and Evening Peak Hour on both Approaches)

Approach	**Maximum Queue**	
	7:30 AM to 8:30 AM	**4:30 PM to 5:30 PM**
Bay Road	11	6
West Bay Road	8	11^+

Gap Study Results

The gap data were collected at the same times on the same day as the queue study detailed above.

Raff Method

The Raft method is used most often to obtain a samples critical gap. The analysis is simple to understand and easy to manipulate, which is the reason it is the most commonly practiced method. The accepted and rejected gaps are binned into intervals of one second and the number of accepted and rejected gaps is counted. The data is then transformed into percent accepted and rejected gaps. Using this data the critical gap is found. The critical gap, as defined by the Raff method, is the gap value corresponding to when the driver has a 50 percent chance of accepting or rejecting that gap. Any gaps greater than 10 seconds were grouped together and all gaps less than 2 seconds were also grouped together. The reason for this grouping is that most gaps over 10 seconds will be accepted and most gaps under 2 seconds will be rejected. The critical gap data using the Raff method are shown in Tables 6 and 7 below.

Table 6 summarizes the value of the critical gap obtained by utilizing the Raff Method for the before and after study. Significant decreases in the magnitude of the critical gap can be seen. More significant decreases were experienced at the West Bay Road approach. Figures 1-4 show how the critical gap values were graphically obtained for the after study data for both approaches and both the morning and evening peak hours. The critical gap, t_c, was estimated to the nearest 0.5 seconds.

Table 6: Before Study: Summary of Critical Gap Using the Raff Method

Approach	**West Bay Road**		**Bay Road**	
	Morning	Evening	Morning	Evening
Critical Gap	6.5 s	6.0 s	6.5 s	6.0 s

Table 7: After Study: Summary of Critical Gap Using the Raff Method

Approach	**West Bay Road**		**Bay Road**	
	Morning	Evening	Morning	Evening
Critical Gap	2.5 s	2.5 s	4.0 s	4.5 s

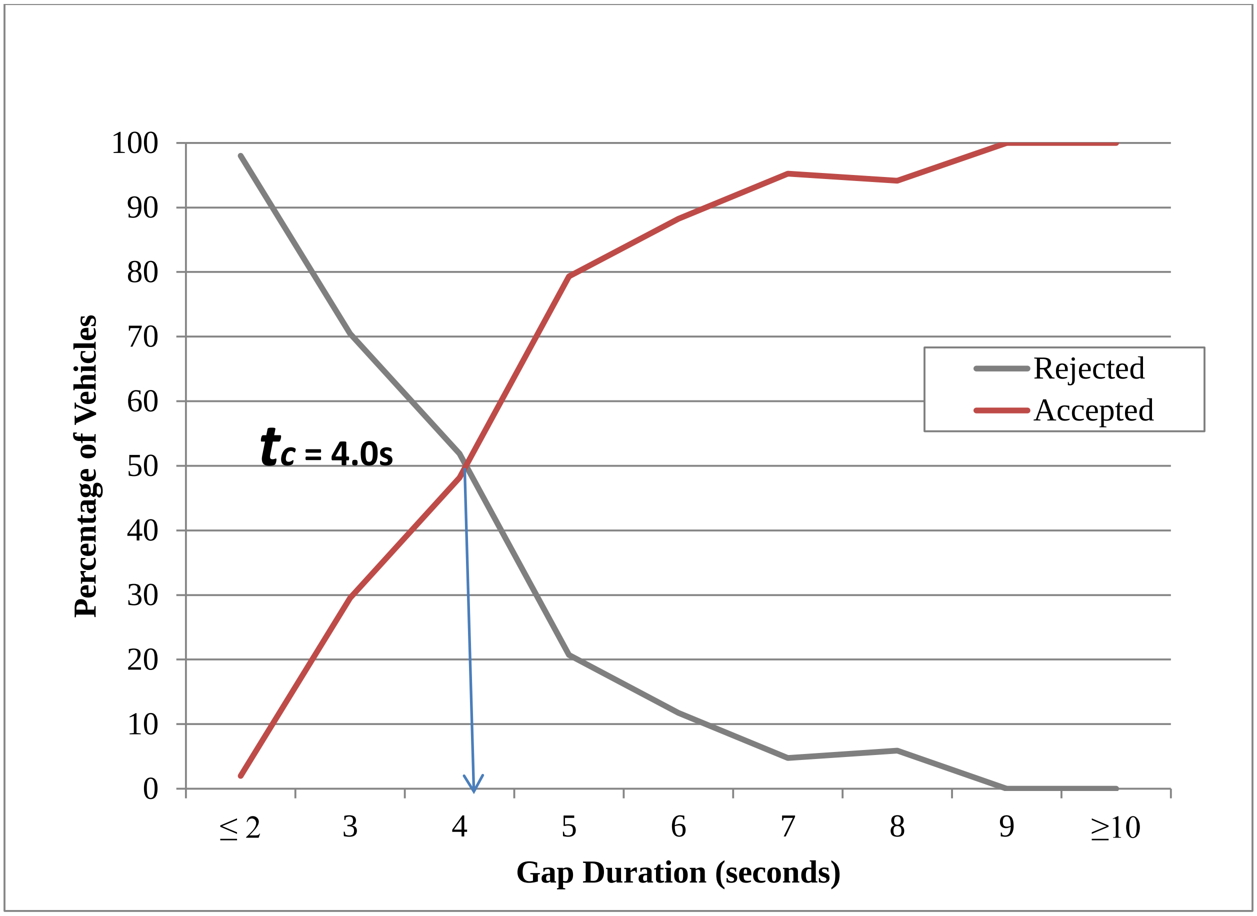

Figure 5: After Study: Critical Gap for the Bay Road Morning Peak Using the Raff Method

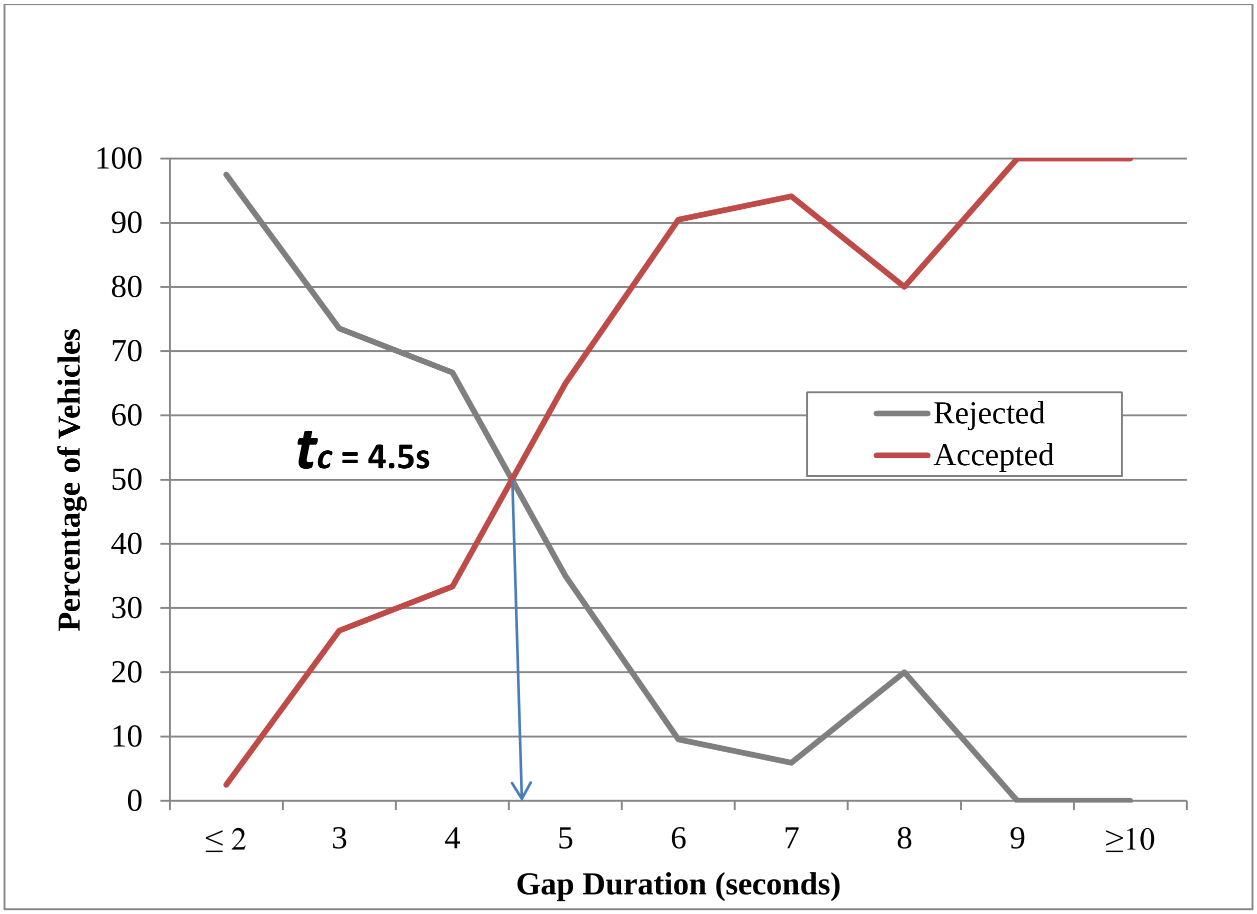

Figure 6: After Study: Critical Gap for the Bay Road Evening Peak Using the Raff Method

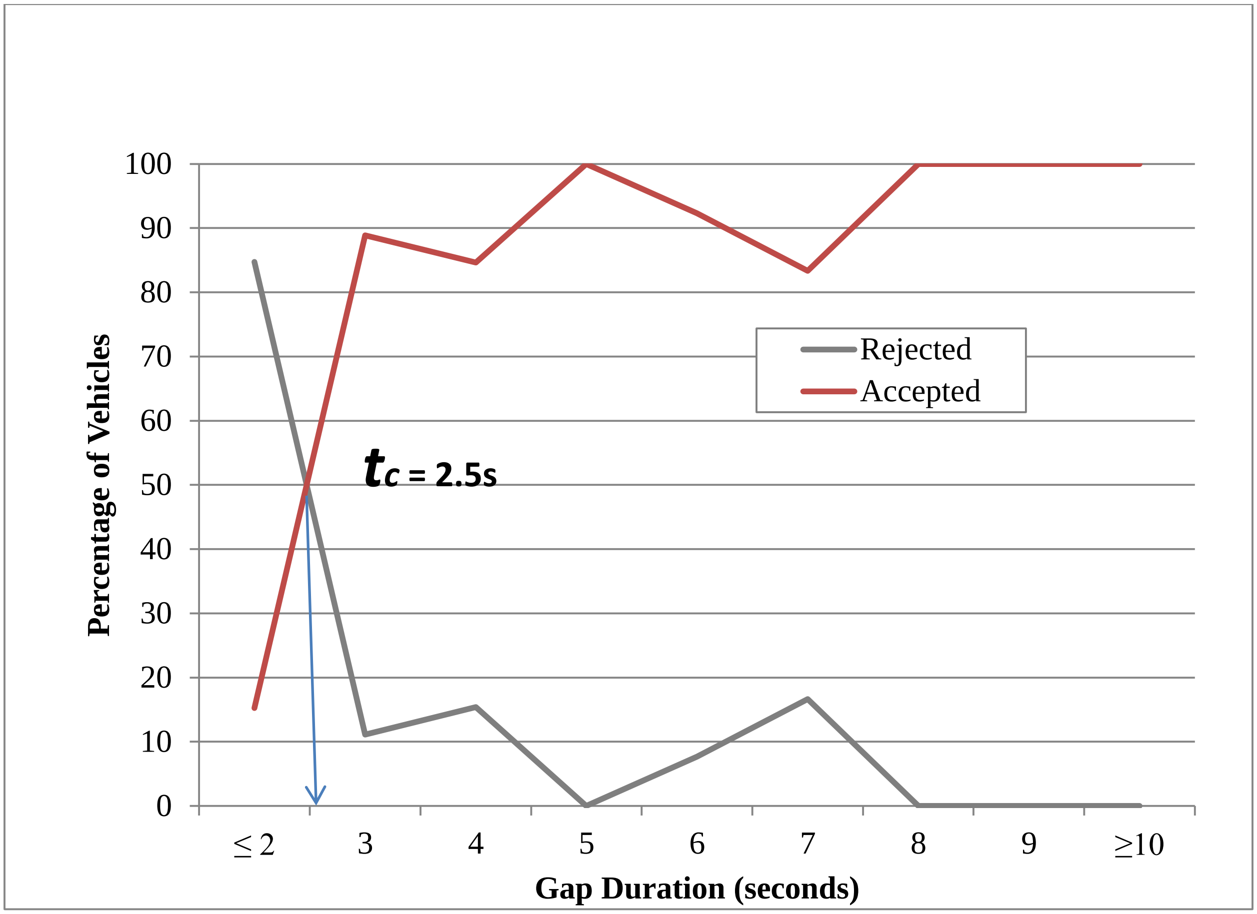

Figure 7: After Study: Critical Gap for the West Bay Road Morning Peak Using the Raff Method

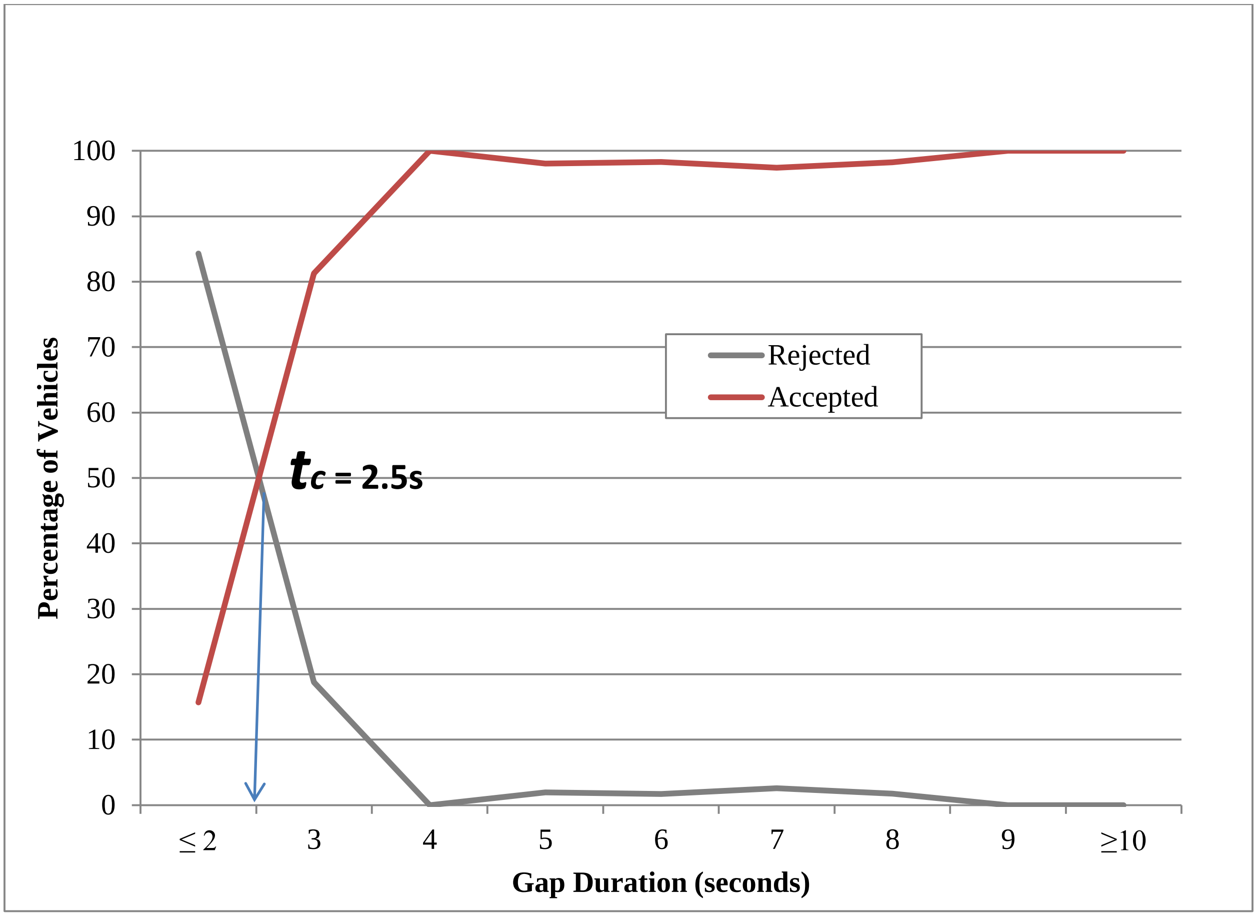

Figure 8: After Study: Critical Gap for the West Bay Road Evening Peak Using the Raff Method

Cumulative Acceptance Method

The second evaluation method does not define the critical gap the same way as the Raff method. In this case the length of the critical gap is one that is acceptable to 85% of the drivers. By binning the count of accepted gaps in 0.25 second intervals and calculating the cumulative percentage of accepted gaps, the critical gap is determined as the gap length where the cumulative percentage is greater than or equal to 15 percent. All gap lengths larger than that point are accepted by 85 percent of the sample. The values of critical gap using the Cumulative Acceptance Method are summarized next.

Tables 8 and 9 summarize the values, obtained using the Cumulative Acceptance Method, for the before and after studies. The comparison of Tables 8 and 9 is less conclusive than the comparison of Tables 6 and 7. The critical gap decreased in the evening peak at the West Bay Road approach and in the morning peak at the Bay Road approach. However, it increased at the West Bay Road approach in the morning peak and the Bay Road approach in the evening peak. The increases in the critical gap have a lager magnitude than those of the decreases in the critical gap. Figures 5-8 show how the critical gap was obtained graphically for the after study data for both approaches and both the morning and evening peak hours using the Cumulative Acceptance Method. The critical gap, t_c, was estimated to the nearest 0.25 seconds.

Table 8: Before Study: Summary of Critical Gap Using the Cumulative Acceptance Method

Approach	**West Bay Road**		**Bay Road**	
	Morning	Evening	Morning	Evening
Critical Gap	4.00 s	4.25 s	4.00 s	4.25 s

Table 9: After Study: Summary of Critical Gap found using Cumulative Acceptance Method

Approach	**West Bay Road**		**Bay Road**	
	Morning	Evening	Morning	Evening
Critical Gap	5.50 s	3.50 s	3.75 s	6.50 s

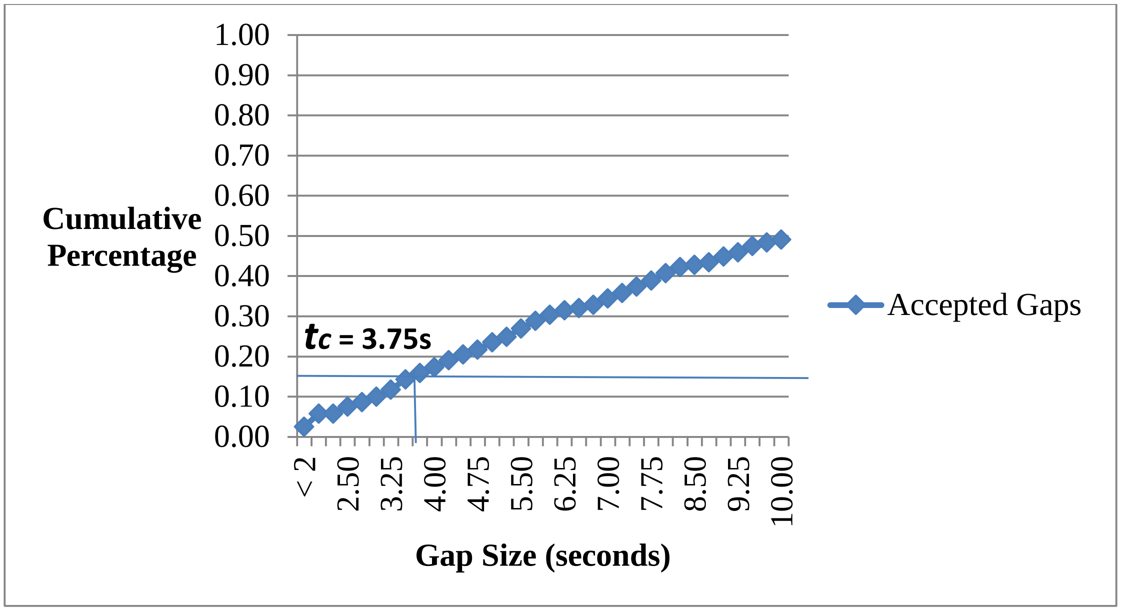

Figure 9: After Study: Critical Gap for the Bay Road Morning Peak Using the Cumulative Acceptance Method

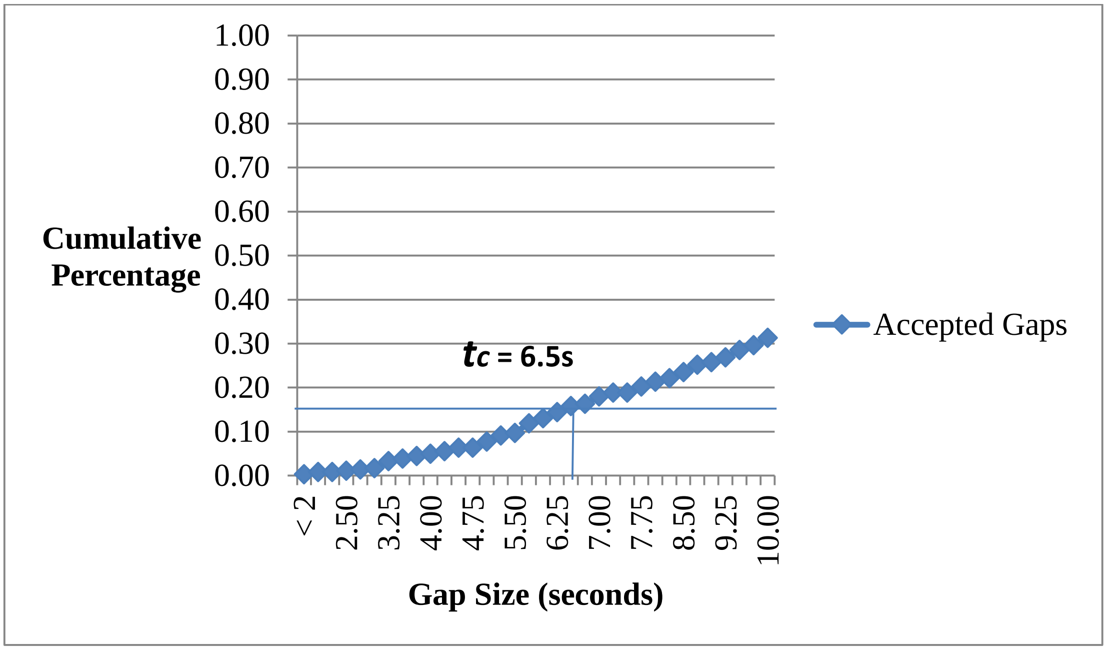

Figure 10: After Study: Critical Gap for the Bay Road Evening Peak Using the Cumulative Acceptance Method

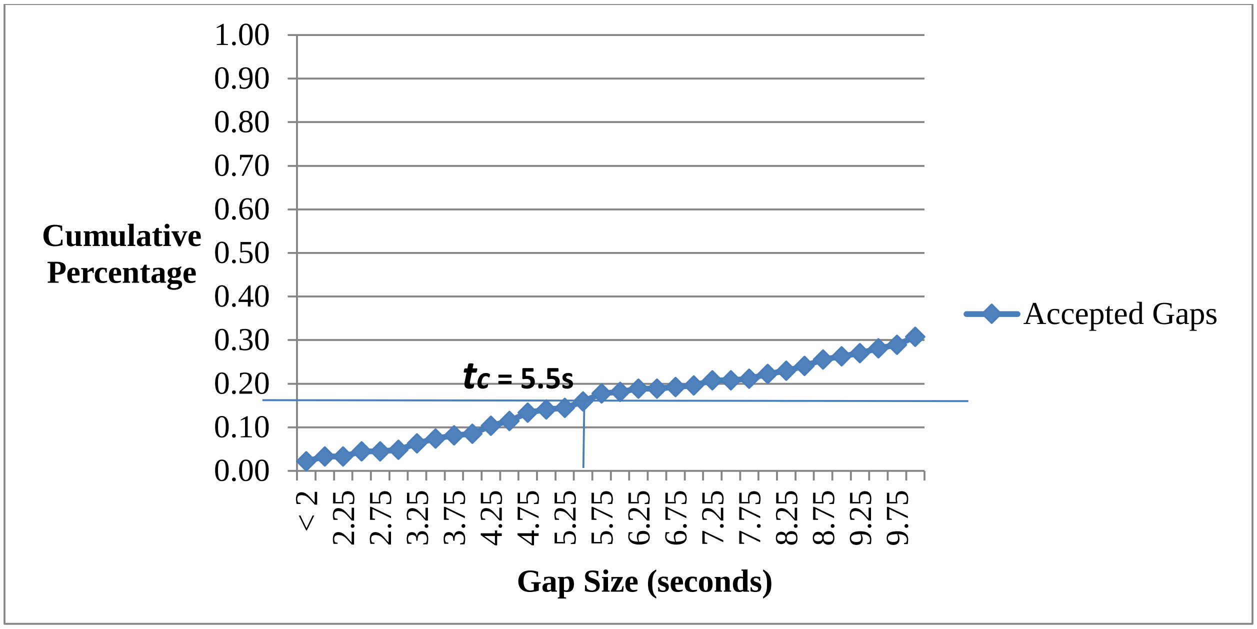

Figure 11: After Study: Critical Gap for the West Bay Road Morning Peak Using the Cumulative Acceptance Method

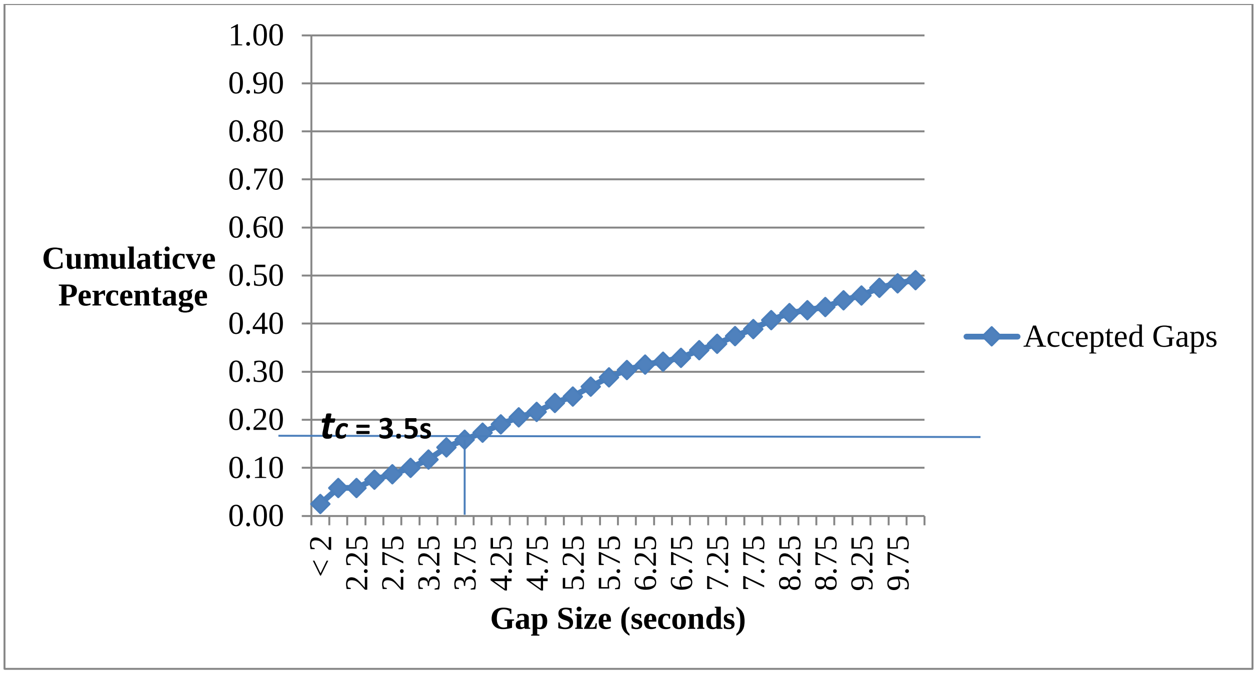

Figure 12: After Study: Critical Gap for the West Bay Road Evening Peak Using the Cumulative Acceptance Method

CHAPTER 5

CALIBRATION AND VALIDATION OF VISSIM MODELS

The following chapter details the development of four micro-simulation models with the help of VISSIM. These models were developed to assess emissions and safety at roundabouts. The models consist of the before and after conditions at both the Atkins Corner and UMass roundabouts. The Atkins Corner before condition consisted of two stop-controlled intersections located at the Bay Road and West Bay Road approaches. Route 116 was uncontrolled in the before condition. The UMass campus single-lane roundabout was previously a pre-timed signalized intersection. The signal consisted of two phases: North/South all movements then East/West all movements. The total cycle time was 75 seconds. The East/West phase was allotted 36 seconds of green, 3 seconds of yellow, and one second of all red and the North/South Phase was allotted 32 seconds of green, 3 seconds of yellow, and one second of all red. Figure 13 shows which approaches to the UMass campus single-lane roundabout comprise the various signal phases.

These models require calibration and validation before they can be used to assess emissions and safety. The calibration process requires collecting video data to obtain approach entry volumes. For these models an hour of video data were collected. The first half hour of the data were used to calibrate the models while the second half was used to validate the models. The volume data used for the before models is the same data that was collected for the after models.

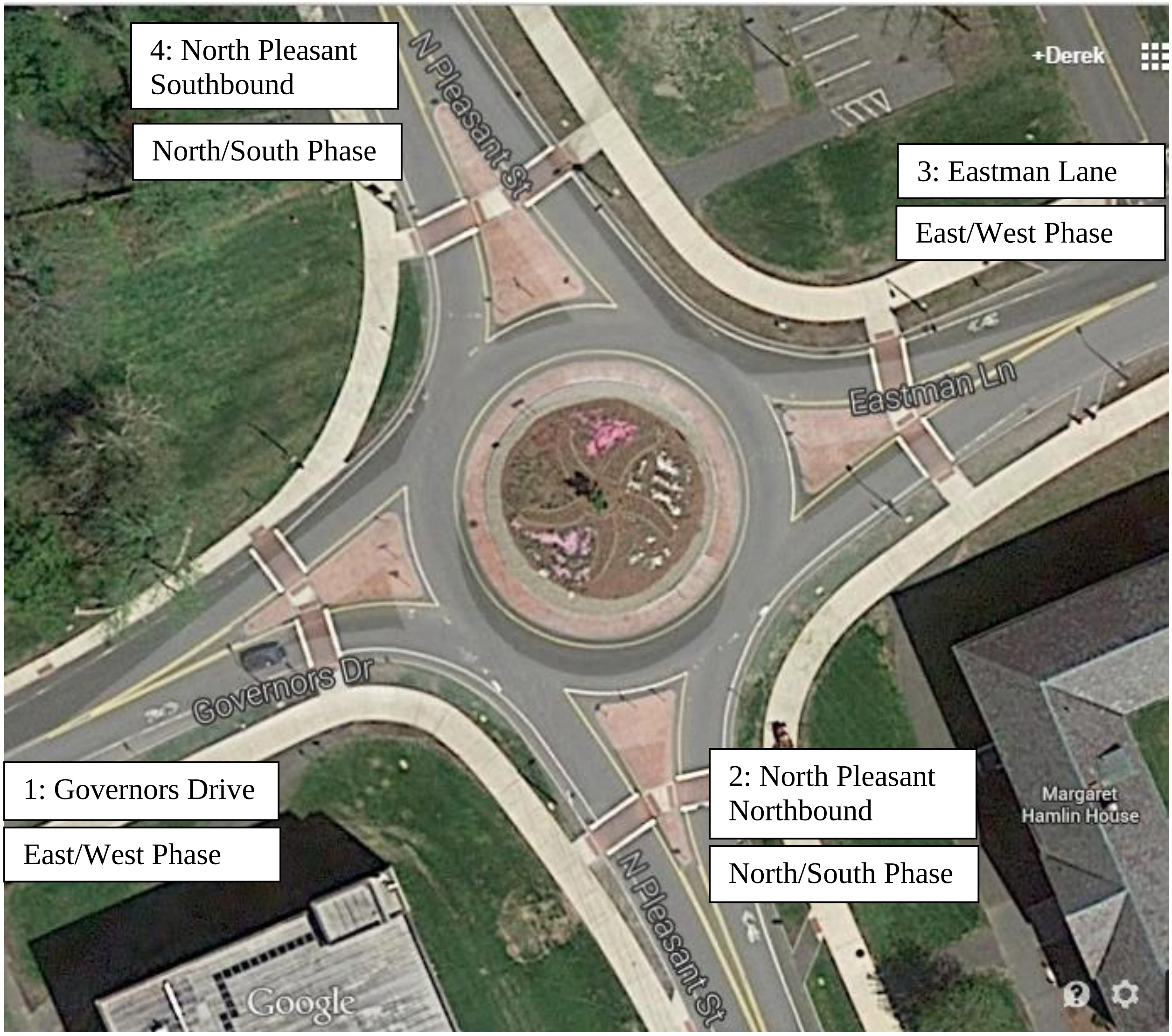

Figure 13: UMass Campus Single-Lane Roundabout: Before Conditions Signal Phasing
https://www.google.com/maps

Calibration Process

Data at the UMass campus single-lane roundabout were collected from 9:00 to 10:00 AM on Wednesday September 10th 2014 and from 4:00 to 5:00 PM on Tuesday September 9th 2014. Data at the Atkins Corner double single-lane roundabout were collected from 10:00 to 11:00 AM and from 4:00 to 5:00 PM on Wednesday October 15th 2014 and Wednesday October 22nd 2014.

Atkins Corner has a northern and a southern roundabout as can be seen in Figure 14. Data for the southern roundabout was collected on Wednesday October 15th 2014 and data for the northern roundabout was collected on Wednesday October 22nd 2014. The two dates are precisely a week apart to ensure traffic conditions were similar. The time periods selected for all recordings at both roundabouts were chosen to capture peak hour traffic.

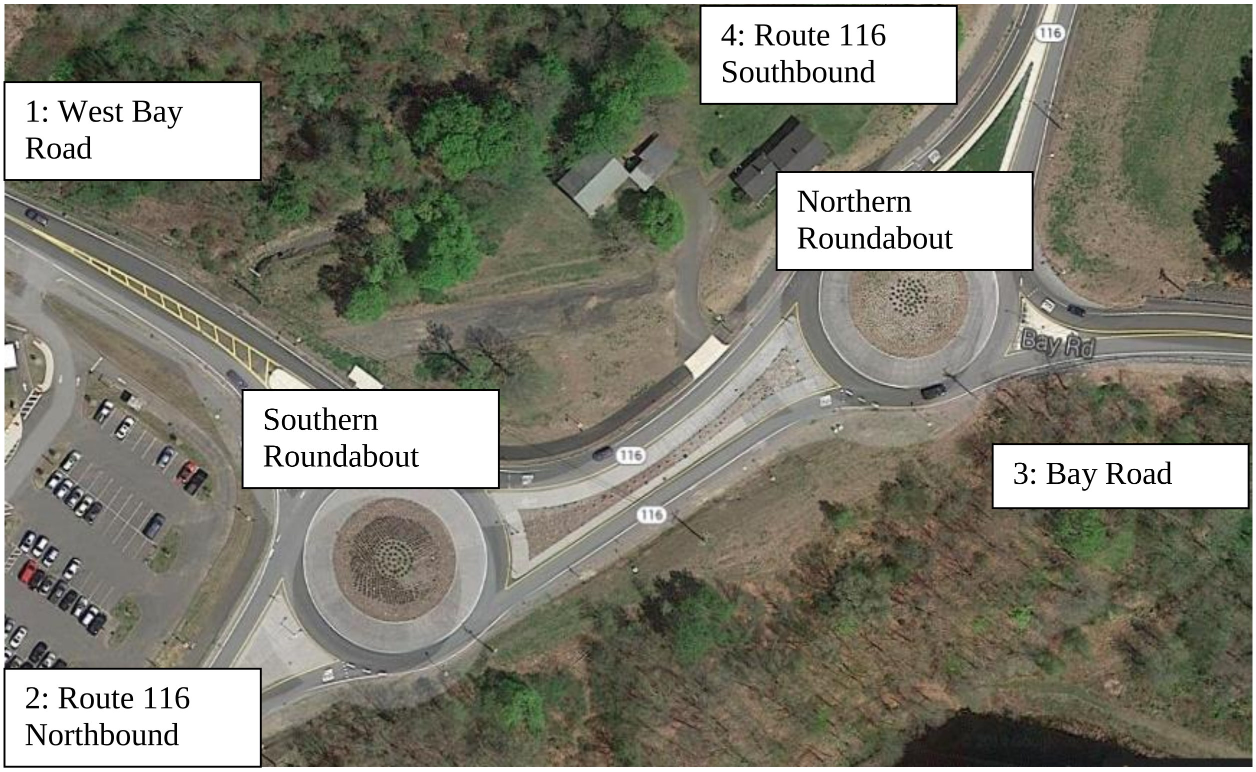

Figure 14: Atkins Corner Double Single-Lane Roundabout
https://www.google.com/maps

Using the video data, demand volumes and turning ratios were determined for both roundabouts and peak periods for the after conditions. This data were then input into the micro-simulation model that was developed with the VISSIM software. The physical geometry of the intersections was modeled by tracing the networks from a scaled image imported into VISSIM. Speed limits, lane widths, turning movements, priority rules, signal timings, signal phasing, and stop signs were all input to match existing conditions. Vehicle types include: cars, buses, and trucks. The arrival distribution was Poisson. All other parameters were kept as the default values.

Tables 10-13 show the link entry volumes for 10 half hour-long simulation runs for the Atkins Corner double single-lane roundabout. Tables 14-17 show the link entry volumes for 10 simulation runs for the UMass campus single-lane roundabout. The first 30 minutes shows the link entry volumes obtained through simulation based on the observed link entry volumes from the first 30 minutes of video data. The Traffic Analysis Toolbox Volume III: Guidelines for Applying Traffic Micro-simulation Modeling Software (*54*) states that models with entering volumes under 700 veh/hr can be considered calibrated if the simulated link entry volume is within 100 veh/hr of the observed link entry volume in the field. If this statement is true for 85% or more of the simulation runs then calibration has been achieved. The "calibration change in volume" column in Tables 10-17 shows that all the simulation entry link volumes are within plus or minus 100 veh/hr of their observed values; note that the volumes presented in the table are expressed as per half hour. Therefore, both models can be considered calibrated and there is no need for changing any of the default VISSIM driver behavior parameters such as acceleration and deceleration behavior, car following behavior, or lane changing behavior.

Validation Process

When calibrating models it is important to also validate them. This requires replacing the volume data in the models from the values obtained from the first 30 minutes of video data to that obtained from the second 30 minutes of data. If this data also produces link entry volumes within 100 veh/hr of the observed link entry volumes for more than 85% of runs then the model can be considered validated. Column labeled “validation change in volume” shows that the entry link volumes for all simulation runs where within the acceptable range thus, validating the models for both site locations and both the morning and the evening peak hours.

Due to the low link entry volumes driver behavior parameters in VISSIM did not need to be manipulated in order to achieve calibration of the models.

Table 10: Akins Corner Roundabout Before Model, Morning Peak: Link Entry Volume Data (Number of Vehicles)

Approach	Simulation Run	10:00-10:30 AM	Observed	Calibration Change in Volume	10:30-11:00 AM	Observed	Validation Change in Volume
1	1	73	84	11	73	83	10
	2	80	84	4	82	83	1
	3	88	84	-4	79	83	4
	4	70	84	14	80	83	3
	5	88	84	-4	68	83	15
	6	66	84	18	87	83	-4
	7	82	84	2	66	83	17
	8	73	84	11	87	83	-4
	9	83	84	1	79	83	4
	10	79	84	5	73	83	10
2	1	122	120	-2	140	157	17
	2	133	120	-13	126	157	31
	3	96	120	24	152	157	5
	4	128	120	-8	147	157	10
	5	99	120	21	148	157	9
	6	116	120	4	132	157	25
	7	114	120	6	169	157	-12
	8	104	120	16	129	157	28
	9	101	120	19	171	157	-14
	10	112	120	8	168	157	-11
3	1	124	114	-10	52	67	15
	2	90	114	24	55	67	12
	3	120	114	-6	63	67	4
	4	94	114	20	68	67	-1
	5	112	114	2	70	67	-3
	6	109	114	5	68	67	-1
	7	109	114	5	53	67	14
	8	102	114	12	68	67	-1
	9	96	114	18	49	67	18
	10	94	114	20	73	67	-6
4	1	59	76	17	121	96	-25
	2	80	76	-4	104	96	-8
	3	60	76	16	98	96	-2
	4	75	76	1	97	96	-1
	5	77	76	-1	110	96	-14
	6	75	76	1	109	96	-13
	7	69	76	7	113	96	-17
	8	83	76	-7	94	96	2
	9	65	76	11	122	96	-26
	10	66	76	10	92	96	4

Table 11: Akins Corner Roundabout Before Model, Evening Peak: Link Entry Volume Data (Number of Vehicles)

Approach	Simulation Run	4:00-4:30 PM	Observed	Calibration Change in Volume	4:30-5:00 PM	Observed	Validation Change in Volume
1	1	201	252	51	191	241	50
	2	209	252	43	215	241	26
	3	204	252	48	193	241	48
	4	209	252	43	196	241	45
	5	197	252	55	188	241	53
	6	205	252	47	195	241	46
	7	189	252	63	185	241	56
	8	207	252	45	195	241	46
	9	198	252	54	194	241	47
	10	192	252	60	186	241	55
2	1	154	173	19	210	219	9
	2	138	173	35	178	219	41
	3	164	173	9	227	219	-8
	4	158	173	15	203	219	16
	5	167	173	6	210	219	9
	6	148	173	25	194	219	25
	7	188	173	-15	228	219	-9
	8	147	173	26	184	219	35
	9	187	173	-14	226	219	-7
	10	187	173	-14	230	219	-11
3	1	99	109	10	90	102	12
	2	89	109	20	84	102	18
	3	92	109	17	82	102	20
	4	104	109	5	99	102	3
	5	100	109	9	94	102	8
	6	107	109	2	103	102	-1
	7	89	109	20	83	102	19
	8	114	109	-5	103	102	-1
	9	88	109	21	83	102	19
	10	119	109	-10	108	102	-6
4	1	192	198	6	203	207	4
	2	199	198	-1	212	207	-5
	3	185	198	13	200	207	7
	4	159	198	39	168	207	39
	5	196	198	2	210	207	-3
	6	182	198	16	192	207	15
	7	186	198	12	198	207	9
	8	170	198	28	108	207	99
	9	207	198	-9	219	207	-12
	10	168	198	30	175	207	32

Table 12: Akins Corner Roundabout After Model, Morning Peak: Link Entry Volume Data (Number of Vehicles)

Approach	Simulation Run	10:00-10:30 AM	Observed	Calibration Change in Volume	10:00-10:30 AM	Observed	Validation Change in Volume
1	1	73	84	11	73	83	10
	2	83	84	1	82	83	1
	3	79	84	5	79	83	4
	4	82	84	2	80	83	3
	5	69	84	15	68	83	15
	6	88	84	-4	87	83	-4
	7	70	84	14	66	83	17
	8	88	84	-4	87	83	-4
	9	80	84	4	79	83	4
	10	73	84	11	73	83	10
2	1	104	120	16	140	157	17
	2	101	120	19	126	157	31
	3	112	120	8	152	157	5
	4	114	120	6	147	157	10
	5	116	120	4	147	157	10
	6	99	120	21	131	157	26
	7	128	120	-8	168	157	-11
	8	96	120	24	128	157	29
	9	133	120	-13	171	157	-14
	10	122	120	-2	167	157	-10
3	1	102	114	12	52	67	15
	2	96	114	18	55	67	12
	3	94	114	20	63	67	4
	4	109	114	5	68	67	-1
	5	108	114	6	70	67	-3
	6	112	114	2	68	67	-1
	7	94	114	20	53	67	14
	8	120	114	-6	68	67	-1
	9	90	114	24	49	67	18
	10	124	114	-10	73	67	-6
4	1	83	76	-7	97	96	-1
	2	65	76	11	85	96	11
	3	60	76	16	81	96	15
	4	69	76	7	78	96	18
	5	76	76	0	92	96	4
	6	77	76	-1	87	96	9
	7	75	76	1	95	96	1
	8	60	76	16	81	96	15
	9	80	76	-4	97	96	-1
	10	59	76	17	81	96	15

Table 13: Akins Corner Roundabout After Model, Evening Peak: Link Entry Volume Data (Number of Vehicles)

Approach	Simulation Run	4:00-4:30 PM	Observed	Calibration Change in Volume	4:30-5:00 PM	Observed	Validation Change in Volume
1	1	219	252	33	204	241	37
	2	256	252	-4	242	241	-1
	3	234	252	18	220	241	21
	4	238	252	14	229	241	12
	5	234	252	18	220	241	21
	6	261	252	-9	257	241	-16
	7	208	252	44	200	241	41
	8	258	252	-6	243	241	-2
	9	256	252	-4	248	241	-7
	10	213	252	39	202	241	39
2	1	154	173	19	209	219	10
	2	138	173	35	178	219	41
	3	164	173	9	227	219	-8
	4	158	173	15	203	219	16
	5	167	173	6	210	219	9
	6	148	173	25	193	219	26
	7	188	173	-15	226	219	-7
	8	147	173	26	184	219	35
	9	187	173	-14	226	219	-7
	10	186	173	-13	230	219	-11
3	1	99	109	10	91	102	11
	2	89	109	20	84	102	18
	3	91	109	18	85	102	17
	4	104	109	5	100	102	2
	5	100	109	9	96	102	6
	6	107	109	2	104	102	-2
	7	89	109	20	84	102	18
	8	114	109	-5	103	102	-1
	9	88	109	21	85	102	17
	10	119	109	-10	108	102	-6
4	1	192	116	-76	220	207	-13
	2	199	116	-83	192	207	15
	3	186	116	-70	178	207	29
	4	160	116	-44	176	207	31
	5	196	116	-80	208	207	-1
	6	182	116	-66	200	207	7
	7	186	116	-70	212	207	-5
	8	170	116	-54	176	207	31
	9	207	116	-91	228	207	-21
	10	168	116	-52	176	207	31

Table 14: UMass Campus Single-Lane Roundabout Before Model, Morning Peak: Link Entry Volume Data (Number of Vehicles)

Approach	Simulation Run	9:00-9:30 AM	Observed	Calibration Change in Volume	9:30-10:00 AM	Observed	Validation Change in Volume
1	1	92	112	20	75	87	12
	2	106	112	6	86	87	1
	3	105	112	7	80	87	7
	4	110	112	2	85	87	2
	5	92	112	20	71	87	16
	6	117	112	-5	91	87	-4
	7	88	112	24	72	87	15
	8	123	112	-11	92	87	-5
	9	111	112	1	83	87	4
	10	94	112	18	75	87	12
2	1	81	95	14	72	82	10
	2	77	95	18	73	82	9
	3	91	95	4	82	82	0
	4	86	95	9	79	82	3
	5	93	95	2	79	82	3
	6	80	95	15	66	82	16
	7	95	95	0	87	82	-5
	8	80	95	15	65	82	17
	9	101	95	-6	87	82	-5
	10	87	95	8	78	82	4
3	1	158	159	1	133	136	3
	2	140	159	19	121	136	15
	3	126	159	33	115	136	21
	4	153	159	6	131	136	5
	5	148	159	11	129	136	7
	6	149	159	10	128	136	8
	7	133	159	26	111	136	25
	8	166	159	-7	139	136	-3
	9	129	159	30	102	136	34
	10	171	159	-12	145	136	-9
4	1	227	229	2	208	205	-3
	2	235	229	-6	182	205	23
	3	218	229	11	168	205	37
	4	186	229	43	172	205	33
	5	232	229	-3	202	205	3
	6	209	229	20	192	205	13
	7	216	229	13	208	205	-3
	8	202	229	27	168	205	37
	9	244	229	-15	212	205	-7
	10	190	229	39	170	205	35

Table 15: UMass Campus Single-Lane Roundabout Before Model, Evening Peak: Link Entry Volume Data (Number of Vehicles)

Approach	Simulation Run	4:00-4:30 PM	Observed	Calibration Change in Volume	4:30-5:00 PM	Observed	Validation Change in Volume
1	1	158	199	41	203	224	21
	2	195	199	4	243	224	-19
	3	181	199	18	221	224	3
	4	185	199	14	229	224	-5
	5	170	199	29	220	224	4
	6	207	199	-8	256	224	-32
	7	167	199	32	200	224	24
	8	205	199	-6	245	224	-21
	9	208	199	-9	249	224	-25
	10	155	199	44	203	224	21
2	1	84	102	18	96	115	19
	2	84	102	18	95	115	20
	3	99	102	3	110	115	5
	4	95	102	7	109	115	6
	5	104	102	-2	112	115	3
	6	83	102	19	94	115	21
	7	103	102	-1	120	115	-5
	8	83	102	19	91	115	24
	9	108	102	-6	124	115	-9
	10	98	102	4	117	115	-2
3	1	113	123	10	155	156	1
	2	107	123	16	137	156	19
	3	102	123	21	124	156	32
	4	117	123	6	150	156	6
	5	116	123	7	145	156	11
	6	117	123	6	144	156	12
	7	100	123	23	130	156	26
	8	130	123	-7	161	156	-5
	9	96	123	27	125	156	31
	10	134	123	-11	168	156	-12
4	1	181	184	3	264	256	-8
	2	183	184	1	260	256	-4
	3	165	184	19	250	256	6
	4	149	184	35	220	256	36
	5	179	184	5	263	256	-7
	6	168	184	16	240	256	16
	7	175	184	9	239	256	17
	8	155	184	29	235	256	21
	9	195	184	-11	264	256	-8
	10	157	184	27	212	256	44

Table 16: UMass Campus Single-Lane Roundabout After Model, Morning Peak: Link Entry Volume Data (Number of Vehicles)

Approach	Simulation Run	9:00-9:30 AM	Observed	Calibration Change in Volume	9:30-10:00 AM	Observed	Validation Change in Volume
1	1	115	112	-3	94	87	-7
	2	100	112	12	79	87	8
	3	92	112	20	78	87	9
	4	92	112	20	75	87	12
	5	106	112	6	87	87	0
	6	105	112	7	84	87	3
	7	110	112	2	87	87	0
	8	93	112	19	73	87	14
	9	117	112	-5	92	87	-5
	10	88	112	24	73	87	14
2	1	77	95	18	73	82	9
	2	91	95	4	82	82	0
	3	86	95	9	79	82	3
	4	93	95	2	79	82	3
	5	80	95	15	66	82	16
	6	95	95	0	87	82	-5
	7	80	95	15	65	82	17
	8	101	95	-6	87	82	-5
	9	87	95	8	78	82	4
	10	81	95	14	71	82	11
3	1	140	159	19	122	136	14
	2	127	159	32	115	136	21
	3	153	159	6	131	136	5
	4	149	159	10	129	136	7
	5	152	159	7	128	136	8
	6	134	159	25	111	136	25
	7	170	159	-11	139	136	-3
	8	129	159	30	102	136	34
	9	173	159	-14	145	136	-9
	10	170	159	-11	142	136	-6
4	1	235	229	-6	207	205	-2
	2	218	229	11	196	205	9
	3	187	229	42	166	205	39
	4	232	229	-3	209	205	-4
	5	209	229	20	189	205	16
	6	216	229	13	196	205	9
	7	202	229	27	178	205	27
	8	244	229	-15	214	205	-9
	9	191	229	38	175	205	30
	10	234	229	-5	211	205	-6

Table 17: UMass Campus Single-Lane Roundabout After Model, Evening Peak: Link Entry Volume Data (Number of Vehicles)

Approach	Simulation Run	4:00-4:30 PM	Observed	Calibration Change in Volume	4:30-5:00 PM	Observed	Validation Change in Volume
1	1	192	199	7	248	224	-24
	2	197	199	2	251	224	-27
	3	185	199	14	228	224	-4
	4	159	199	40	206	224	18
	5	196	199	3	244	224	-20
	6	182	199	17	222	224	2
	7	186	199	13	229	224	-5
	8	170	199	29	221	224	3
	9	207	199	-8	258	224	-34
	10	168	199	31	200	224	24
2	1	84	102	18	95	115	20
	2	99	102	3	110	115	5
	3	96	102	6	109	115	6
	4	104	102	-2	112	115	3
	5	83	102	19	94	115	21
	6	103	102	-1	121	115	-6
	7	83	102	19	91	115	24
	8	108	102	-6	124	115	-9
	9	98	102	4	117	115	-2
	10	87	102	15	97	115	18
3	1	107	123	16	137	156	19
	2	103	123	20	124	156	32
	3	117	123	6	151	156	5
	4	117	123	6	145	156	11
	5	117	123	6	145	156	11
	6	100	123	23	130	156	26
	7	130	123	-7	166	156	-10
	8	98	123	25	125	156	31
	9	135	123	-12	171	156	-15
	10	124	123	-1	165	156	-9
4	1	183	184	1	260	256	-4
	2	165	184	19	250	256	6
	3	149	184	35	223	256	33
	4	181	184	3	263	256	-7
	5	168	184	16	241	256	15
	6	175	184	9	240	256	16
	7	155	184	29	263	256	-7
	8	196	184	-12	264	256	-8
	9	157	184	27	212	256	44
	10	195	184	-11	263	256	-7

CHAPTER 6

EMISSION EVALUATION OF VISSIM MODELS

UMass Campus Single-Lane Roundabout

The developed models were used to estimate emission levels at the UMass campus single-lane roundabout during both the morning and evening peak periods. This data were compared to the emission levels seen from the before model condition. The same volumes and turning ratios were used for the before and after condition models. The emissions estimated by VISSIM through node evaluation included carbon monoxide (CO) and Nitrogen Oxides (NO_x). Node evaluations in VISSIM produce values that are average values over an area, which is defined by the selected nodes. Polygon areas were defined by nodes drawn around the intersections of the two sites. Ten one hour simulation runs were conducted for each site location for both conditions during both peak periods.

The average emission levels at the UMass campus intersection are shown in Tables 18 and 19. The Atkins Corner double single-lane roundabout average emission levels are presented in Tables 20 and 21. Figures 15-18 show the emission levels and error bars showing one standard deviation for CO and NO_x for the UMass campus single-lane roundabout during both morning and evening peak periods and under both the before and after conditions. Similarly, Figures 19-22 show the emission levels and error bars showing one standard deviation for CO and NO_x for the Atkins Corner double single-lane roundabout during both morning and evening peak periods and under both the before and after conditions.

The before condition of the UMass campus single-lane roundabout as previously described consisted of a pre-timed signalized intersection with two phases and no protected turning phases. The data shows that the signalized intersection produced fewer CO and NO_x emissions than the current single-lane roundabout. The morning peak period showed an increase of 72% for CO emissions and NO_x emissions when the signalized intersection was compared to the roundabout. Similar increases in emissions were seen during the evening peak period, 75% for both CO and NO_x emission levels.

The UMass data shows an increase in emission levels at the roundabout compared to the signalized intersection. This finding differs from the results found in studies in the literature. One study (*46*), which used the SIDRA software, showed that CO and NO_x decreased between 21-42% and 20-48% respectively, when intersections where converted from signalized intersections to roundabouts. A second study (48), which also used SIDRA, found that CO decreased by 45% when converted from signalized or stop-controlled intersections. Lastly, a study (49) using INTEGRATION software found that NO_x was lowest at a signalized intersection under a specific approach demand condition but lowest at roundabouts under the rest of the conditions assessed. The past literature indicates that emission levels should decrease when signalized intersections are converted to roundabouts, which is contrary to our findings.

Atkins Corner Double Roundabout

The before condition of the double single-lane roundabout in Atkins Corner was two stop-controlled intersections. Bay Road and West Bay Road were the approaches constrained by stop signs and vehicles on Route 116 had priority. VISSIM estimated that the stop-controlled intersections produced emission levels higher than those experienced by the double single-lane roundabout. During the morning peak hour the stop sign controlled intersections experienced 1270 % the CO and NO_x level of that experienced at the double single-lane roundabout. The evening peak period showed the stop-controlled intersections produced CO and NO_x levels that were 630% larger than the ones seen at the double single-lane roundabout.

The Atkins Corner double single-lane roundabout data show that both CO and NO_x decrease when stop-controlled intersections are converted to roundabouts. This agrees with the findings of a couple studies from the literature. One study (48), which used the SIDRA software, found that CO decreased by 15% when a stop-controlled intersection was converted to a single-lane roundabout. Again this is similar to VISSIM's results, which indicate an increase in emission levels at roundabouts compared to stop-controlled intersections. A second study (51), which used VT-MICRO and CHEM emission models, found that CO and NO_x were increased by 203% and 38% according to VT-MICRO and by 456% and 95% according to CMEM when roundabouts were converted to stop-controlled intersections. This study has contradictory results compared to our study, which indicates that emission levels decrease when stop-controlled intersections are converted to roundabouts.

Table 18: Average Emission Levels at the UMass Campus Single-Lane Roundabout, Morning Peak

UMass Morning Peak Hour	Before Condition		After Condition	
Simulation Run	Average Emission Level (g)		Average Emission Level (g)	
	CO	NO_x	CO	NO_x
1	14.59	2.84	25.13	4.89
2	14.55	2.83	27.83	5.41
3	14.84	2.89	26.21	5.10
4	14.73	2.87	26.33	5.12
5	15.33	2.98	25.82	5.02
6	15.04	2.93	26.47	5.15
7	14.93	2.91	25.13	4.89
8	14.98	2.91	23.70	4.61
9	15.39	3.00	24.94	4.85
10	15.01	2.92	25.45	4.95
Average	14.94	2.91	25.70	5.00
Standard Deviation	0.28	0.05	1.11	0.22

Table 19: Average Emission Levels at the UMass Campus Single-Lane Roundabout, Evening Peak

UMass Evening Peak Hour	Before Condition		After Condition	
Simulation Run	Average Emission Level (g)		Average Emission Level (g)	
	CO	NO_x	CO	NO_x
1	20.30	3.95	35.91	6.99
2	20.12	3.91	35.85	6.97
3	19.97	3.89	34.01	6.62
4	20.45	3.98	35.54	6.91
5	20.59	4.01	36.42	7.09
6	20.93	4.07	36.53	7.11
7	20.32	3.95	33.95	6.61
8	20.63	4.01	37.31	7.26
9	21.43	4.17	36.41	7.08
10	19.97	3.88	35.43	6.89
Average	20.47	3.98	35.74	6.95
Standard Deviation	0.45	0.09	1.08	0.21

Table 20: Average Emission Levels at the Atkins Corner Double Single-Lane Roundabout, Morning Peak

Atkins Corner Morning Peak Hour	Before Condition		After Condition	
Simulation Run	Average Emission Level (g)		Average Emission Level (g)	
	CO	NO_x	CO	NO_x
1	98.39	19.14	10.25	2.00
2	123.92	24.11	8.03	1.56
3	121.28	23.60	9.90	1.93
4	128.86	25.07	9.75	1.90
5	117.32	22.83	9.67	1.88
6	125.68	24.45	9.74	1.90
7	122.51	23.84	9.65	1.88
8	131.77	25.64	9.31	1.81
9	123.44	24.02	9.21	1.79
10	111.99	21.79	9.37	1.82
Average	120.52	23.45	9.49	1.85
Standard Deviation	9.55	1.86	0.60	0.12

Table 21: Average Emission Levels at the Atkins Corner Double Single-Lane Roundabout, Evening Peak

Atkins Corner PM Peak Hour	Before Condition		After Condition	
Simulation Run	Average Emission Level (g)		Average Emission Level (g)	
	CO	NO_x	CO	NO_x
1	111.95	21.78	18.60	3.62
2	123.69	24.07	19.51	3.80
3	131.62	25.61	20.18	3.93
4	123.29	23.99	19.45	3.79
5	125.37	24.39	19.26	3.75
6	123.92	24.11	19.99	3.89
7	128.72	25.05	19.50	3.79
8	120.94	23.53	19.16	3.73
9	98.72	19.21	18.79	3.66
10	123.92	24.11	18.74	3.65
Average	121.22	23.58	19.32	3.76
Standard Deviation	9.42	1.83	0.52	0.10

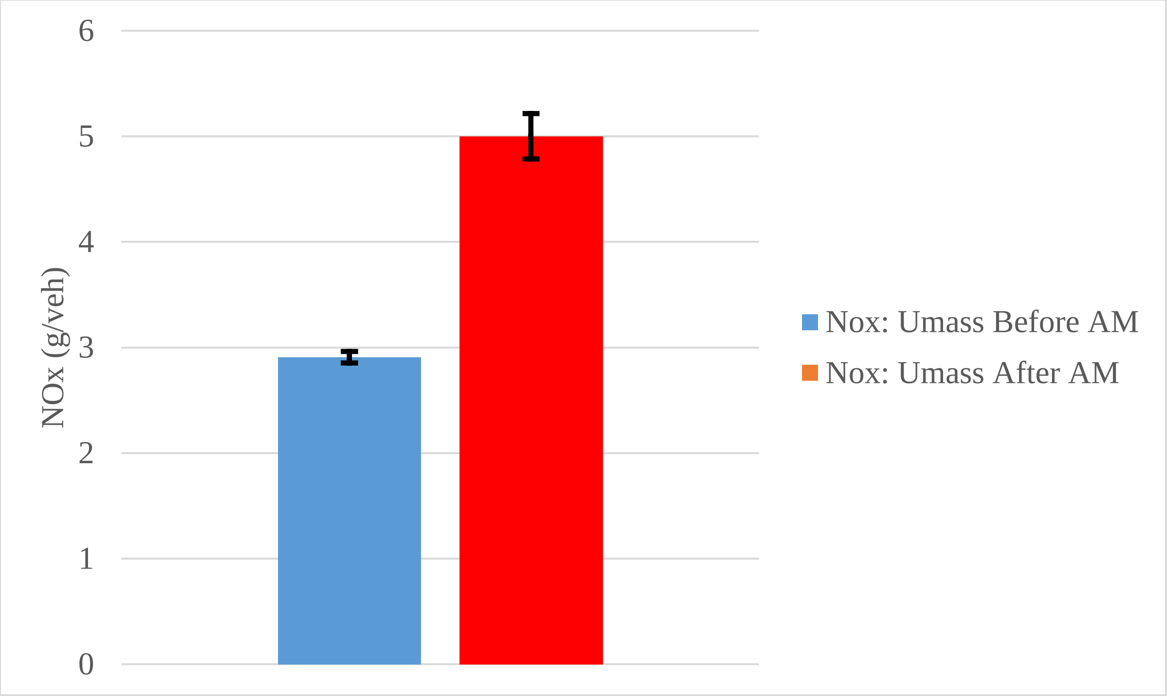

Figure 15: NO_x Levels: UMass Campus Single-Lane Roundabout, Morning Peak

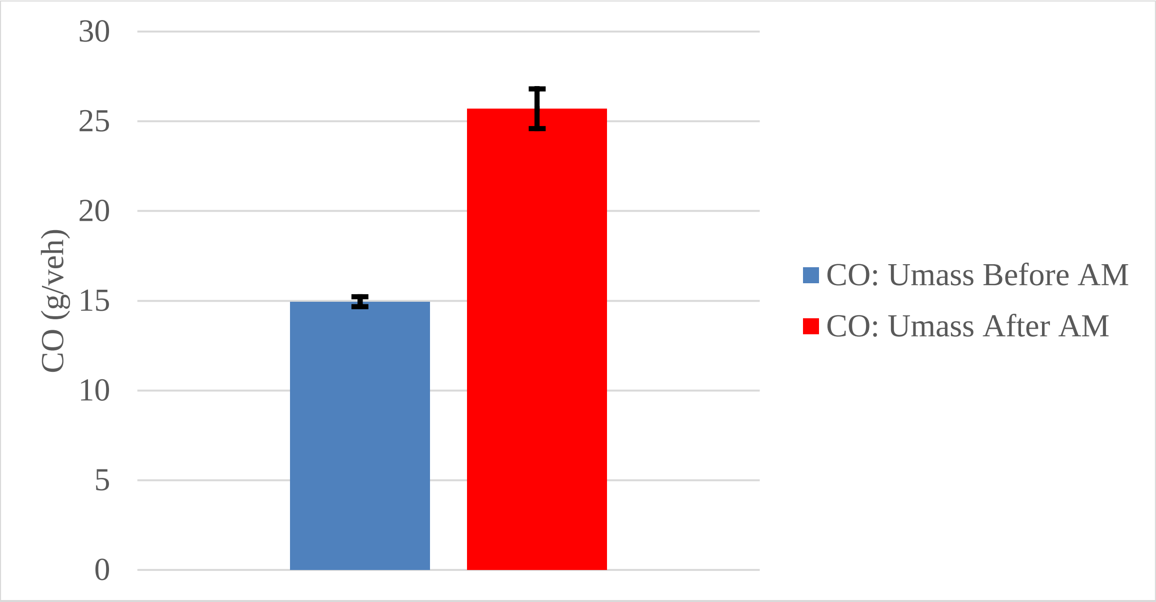

Figure 16: CO Levels: UMass Campus Single-lane Roundabout, Morning Peak

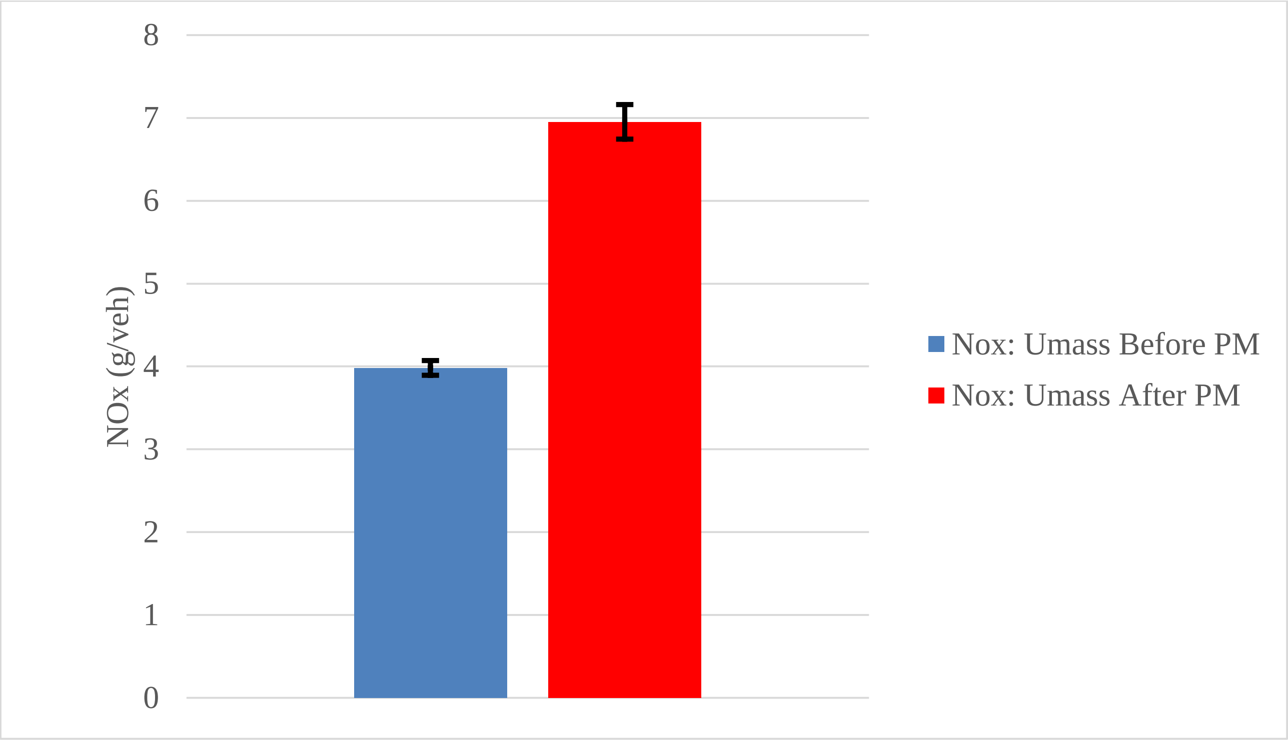

Figure 17: NOx Levels: UMass Campus Single-Lane Roundabout, Evening Peak

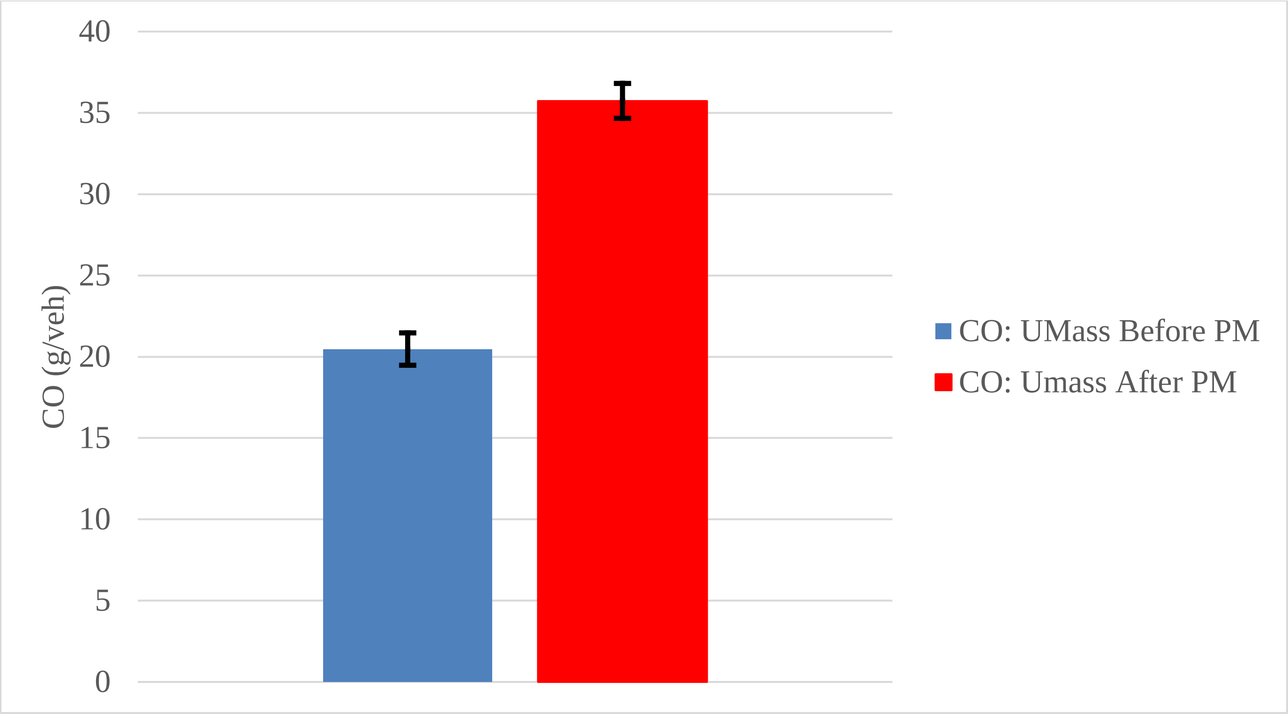

Figure 18: CO Levels: UMass Campus Single-Lane Roundabout, Evening Peak

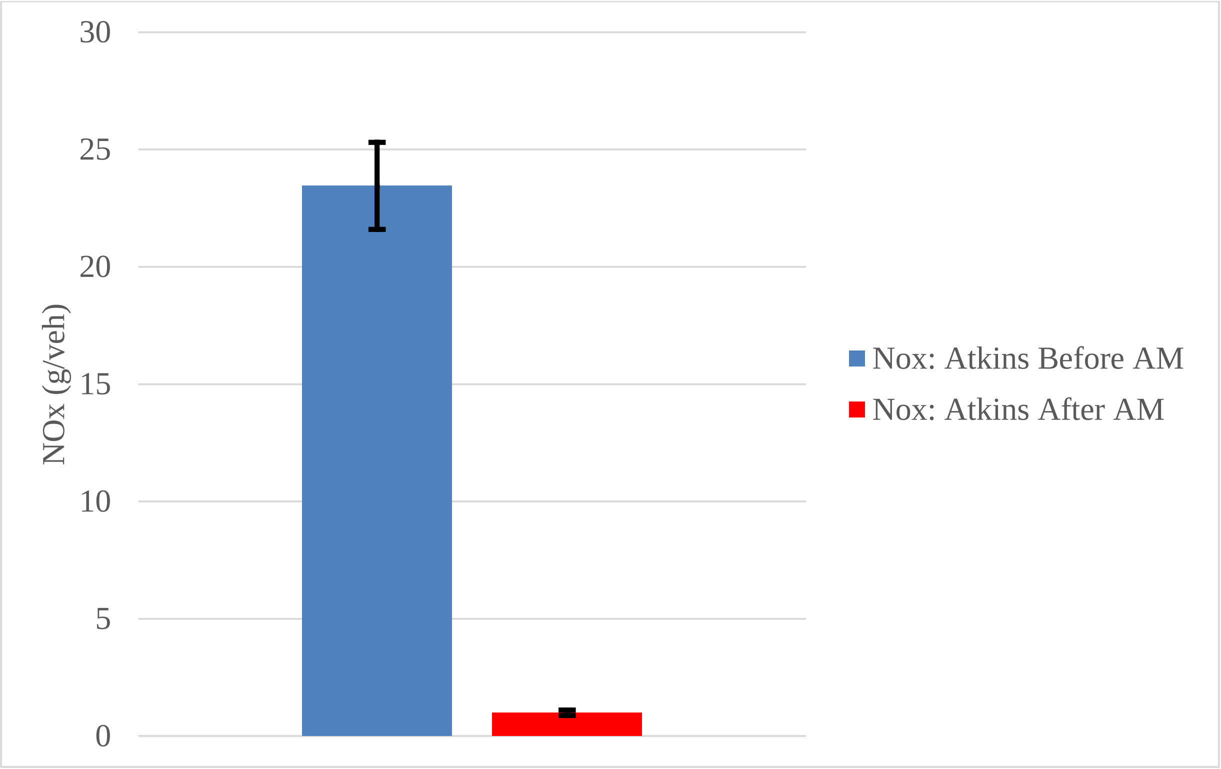

Figure 19: NO_x Levels: Atkins Corner Double Single-Lane Roundabout, Morning Peak

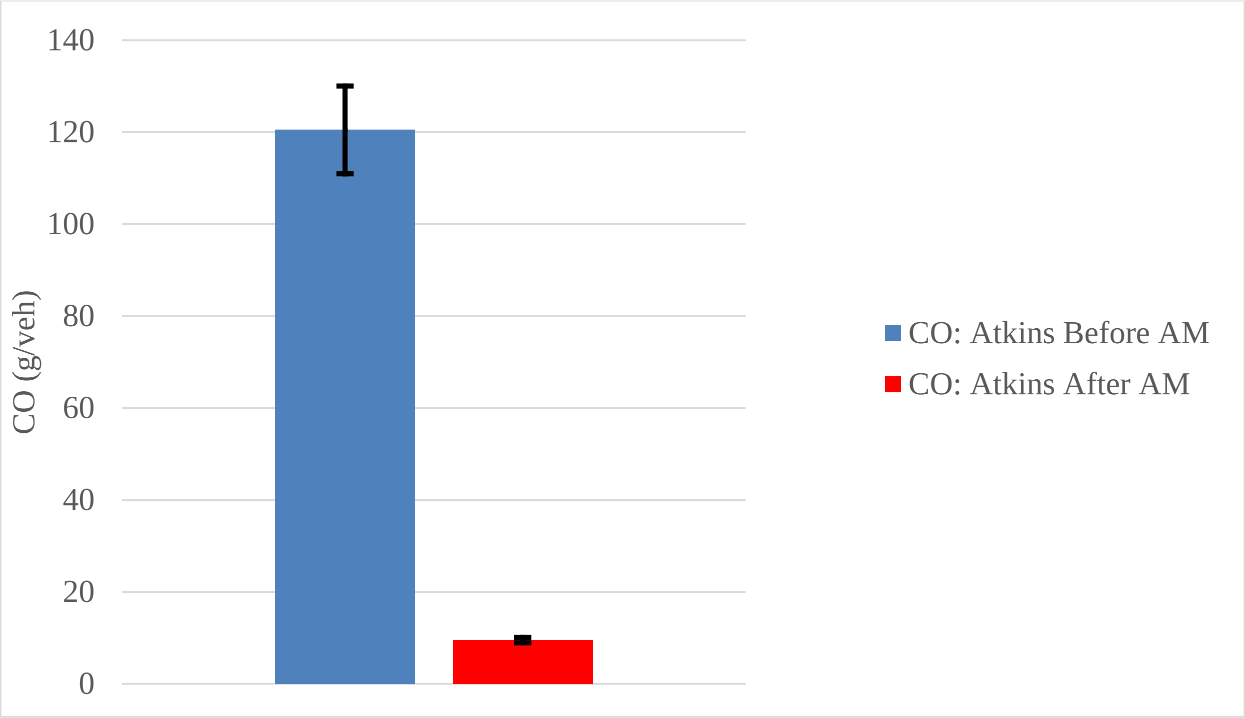

Figure 20: CO Levels: Atkins Corner Double Single-Lane Roundabout, Morning Peak

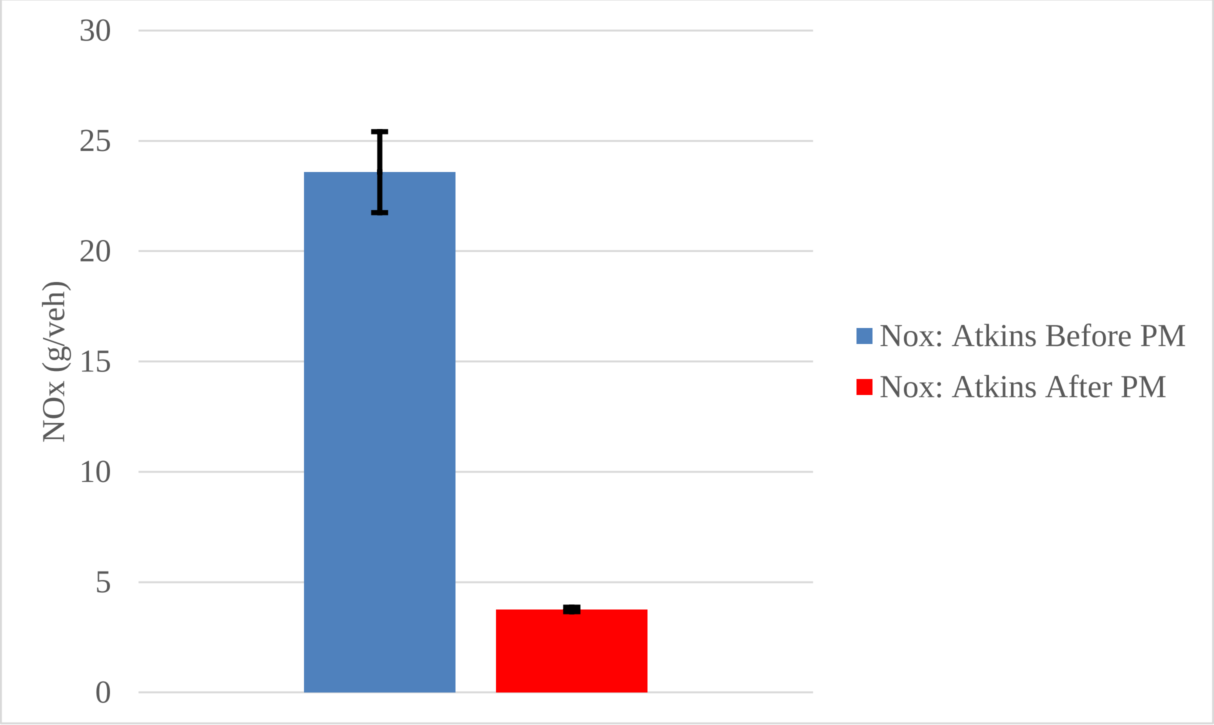

Figure 21: NOx Levels: Atkins Corner Double Single-Lane Roundabout, Evening Peak

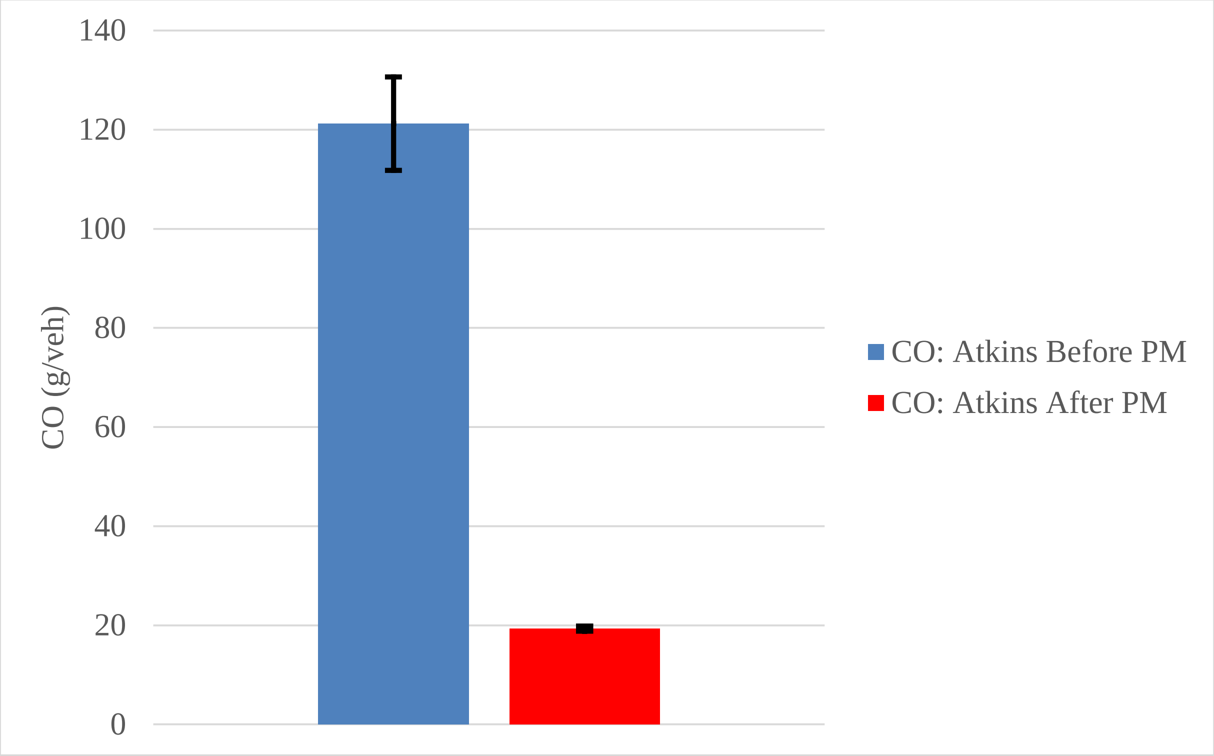

Figure 22: CO Levels: Atkins Corner Double Single-Lane Roundabout, Evening Peak

CHAPTER 7

COMPARISON OF SSAM CONFLICT ESTIMATION AND FIELD DATA

SSAM processes vehicle trajectory files obtained through micro-simulation in order to estimate number and type of conflicts experienced under a certain geometric design and certain traffic conditions. These trajectory files can be produced from VISSIM and imported into SSAM. Vehicle trajectory files for the after conditions for both the UMass Campus and the Atkins Corner double single-lane roundabout models during the morning and evening peak period were obtained. Ten vehicle trajectory files were obtained through ten simulation runs preformed in VISSIM. SSAM was then used to read the trajectory files and estimate the number and type of conflicts that were present during the simulation runs.

SSAM estimates conflicts based on surrogate measures of safety: minimum time-to-collision, minimum post-encroachment, maximum speed, maximum speed differential, initial deceleration rate, maximum deceleration rate, maximum deceleration deferential, and conflict angle. Post-encroachment is defined as the time interval between the end of encroachment of a turning vehicle and the time at which the through vehicle actually arrives at the potential point of collision. The conflict angle determines the type of conflict: rear-end, lane change, or crossing. Figure 13 presents a conflict angle diagram, which shows the difference between rear-end, lane change, and crossing conflicts. The minimum time-to-collision was set to the default value of 1.5 seconds or less while the minimum post-encroachment time was set to the default value of 5 seconds or less. The rest of the surrogate measures of safety cannot be adjusted. The following sections present the SSAM results in detail.

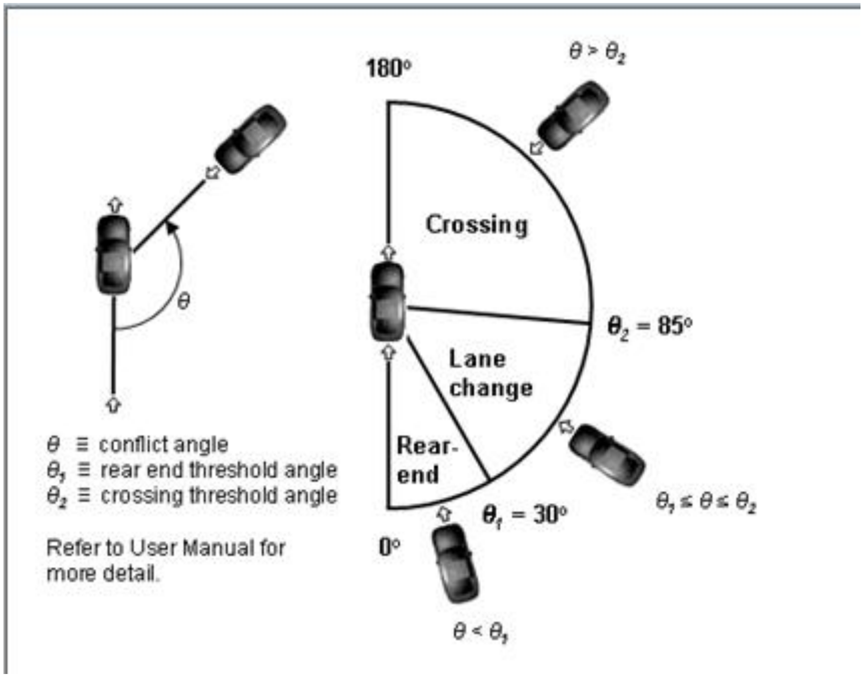

Figure 23: SSAM Conflict Angle Diagram

UMass Campus Roundabout: Morning Peak, After Conditions

Table 22 summarizes the number and type of conflicts experienced at the UMass campus single-lane roundabout during the morning peak hour. Figure 14 shows the location of the conflicts presented in Table 22. The green circles indicate rear-end, the blue lane changing, and the red crossing conflicts. This color scheme holds true for all the figures presenting conflicts in this section. Based on the data from Table 22 the average number of conflicts was 11 conflicts/hr, which consisted of 9 rear-end conflicts/hr and 2 lane change conflicts/hr. No crossing conflicts were experienced, which is expected based on the geometric design of a roundabout that does not allow for crossing conflicts if navigated properly. Most of the conflicts occurred on the entering and exiting legs, and on the circulating segments that are just before and after the roundabout entries and exits. More specifically, in this case the majority of the conflicts occurred on the North Pleasant southbound entering and exiting legs and the Governors Drive exit leg.

Table 22: SSAM-Estimated Conflicts: UMass Campus Single-Lane Roundabout (Morning Peak, After Conditions)

Simulation Run	Estimated Conflicts			
	Total	Crossing	Rear-end	Lane Change
1	10	0	8	3
2	12	0	9	2
3	13	0	7	3
4	9	0	12	1
5	14	0	8	1
6	14	0	13	1
7	9	0	12	2
8	8	0	7	2
9	11	0	7	1
10	10	0	7	4
Average	11	0	9	2

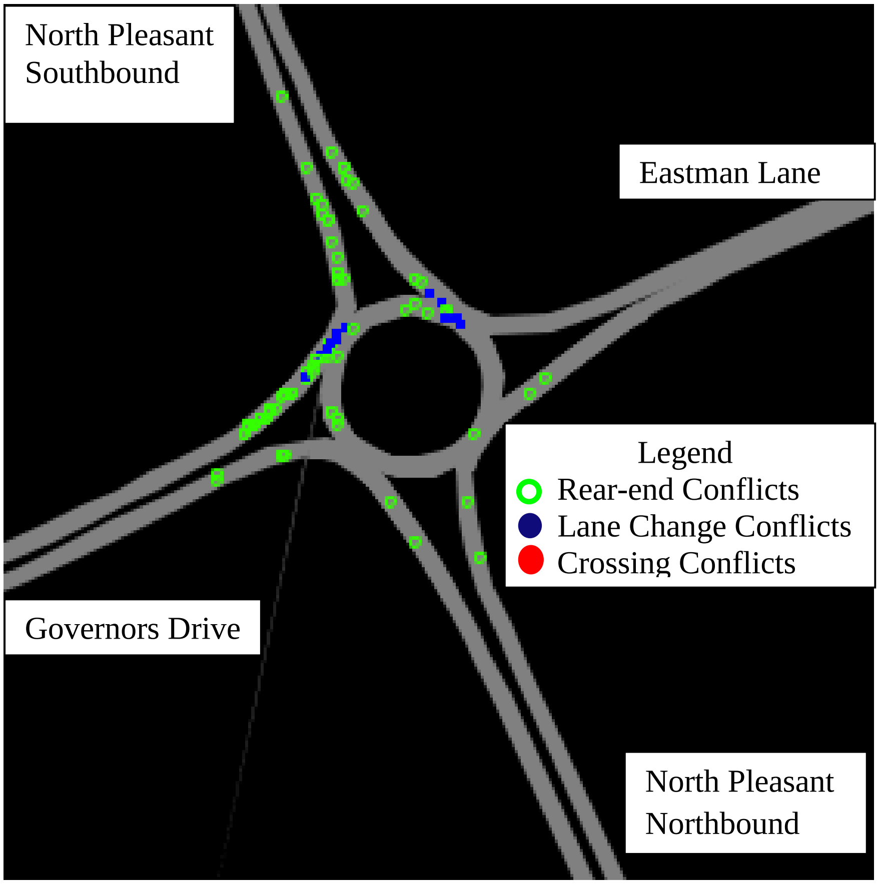

Figure 24: Location of SSAM-Estimated Conflicts: UMass Campus Single-Lane Roundabout (Morning Peak, After Conditions)

UMass Campus Single-Lane Roundabout: Evening Peak, After Conditions

Table 23 summarizes the number and type of conflicts experienced at the UMass campus single-lane roundabout during the evening peak hour. Figure 15 shows the location of the conflicts presented in Table 23. Based on the data from Table 23 the average number of conflicts was 14.5 conflicts/hr, which consisted of 11.6 rear-end conflicts/hr and 2.9 lane change conflicts/hr. Again no crossing conflicts were experienced. As before most of the conflicts occurred on the entering legs, exiting legs, and on the circulating segments that are just before and after the roundabout entries and exits. The conflicts were almost equally distributed among all the approaches.

Table 23: SSAM-Estimated Conflicts: UMass Campus Single-Lane Roundabout (Evening Peak, After Conditions)

Simulation Run	Estimated Conflicts			
	Total	Crossing	Rear-end	Lane Change
1	14	0	10	4
2	20	0	17	3
3	21	0	18	3
4	13	0	11	2
5	14	0	12	2
6	11	0	9	2
7	19	0	15	4
8	11	0	10	1
9	11	0	8	3
10	11	0	6	5
Average	14.5	0	11.6	2.9

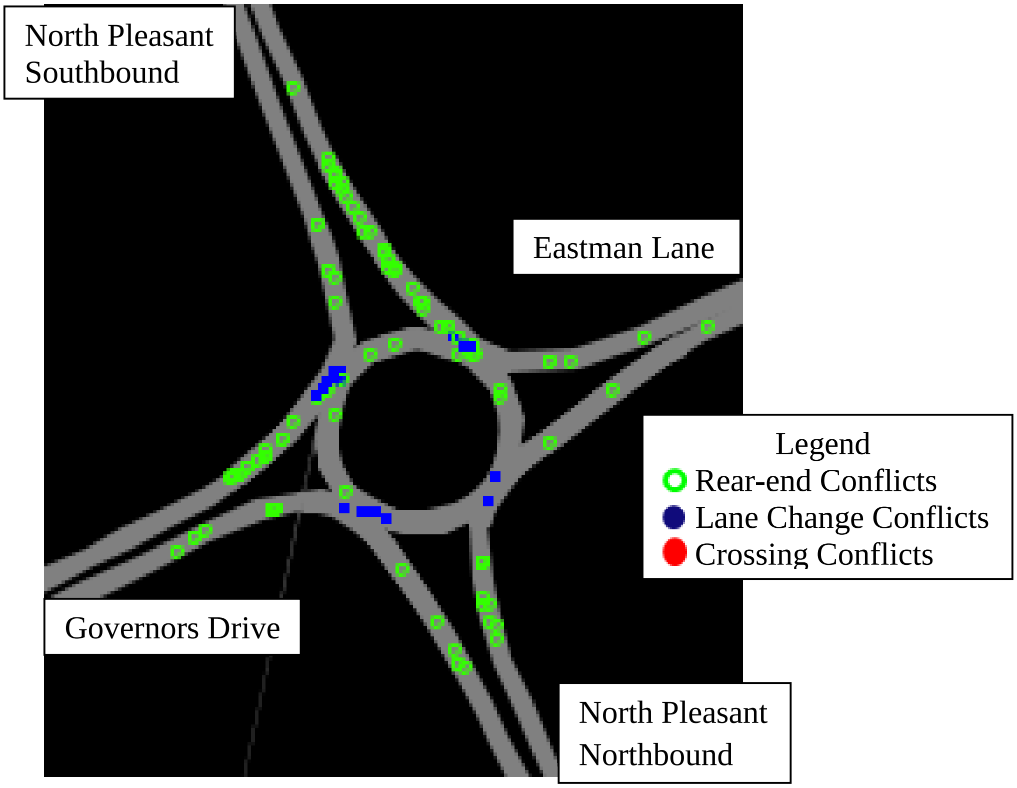

Figure 25: Location of SSAM-Estimated Conflicts: UMass Campus Single-Lane Roundabout (Evening Peak, After Conditions)

Atkins Corner Double Single-Lane Roundabout: Morning Peak, After Conditions

Table 24 summarizes the number and type of conflicts experienced at the Atkins Corner double single-lane roundabout during the morning peak hour. Figure 16 shows the location of the conflicts presented in Table 24. Based on the data from Table 24 the average number of conflicts was 2.6 conflicts/hr, which consisted of 0.9 rear-end conflicts/hr, 1.5 lane change conflicts/hr, and 0.2 crossing conflicts/hr. The two crossing conflicts are most likely due to the geometry of the network. The conflict angles for the two crossing conflicts are 83 degrees and 81 degrees, which are very close to the threshold of 80 degrees. Essentially they are lane changing conflicts with angles larger than expected. This is most likely due to the entrance leg having a small deflection angle allowing cars to enter almost perpendicular to the roundabout.

As for the UMass campus single-lane roundabout, most of the conflicts occurred on the entering and exiting legs, and on the circulating segments that are just before and after the roundabout entries and exits. The conflicts were mostly seen at the Bay Road and West Bay Road entering legs, which seems appropriate when considering that Bay Road and West Bay Road had larger volumes than Route 116 southbound. 116 northbound has more equivalent volumes to Bay Road and West Bay Road but the sight distance is better on this approach compared to the southbound approach of Route 116. The northbound leg has a higher elevation and drivers get a good view of the roundabout before attempting to navigate it.

Table 24: SSAM-Estimated Conflicts: Atkins Corner Double Single-Lane Roundabout (Morning Peak, After Conditions)

Simulation Run	Estimated Conflicts			
	Total	Crossing	Rear-end	Lane Change
1	2	0	1	1
2	4	0	0	4
3	6	1	2	3
4	2	1	6	1
5	7	0	0	1
6	1	0	0	1
7	0	0	0	0
8	1	0	0	1
9	1	0	0	1
10	2	0	0	2
Average	2.6	0.2	0.9	1.5

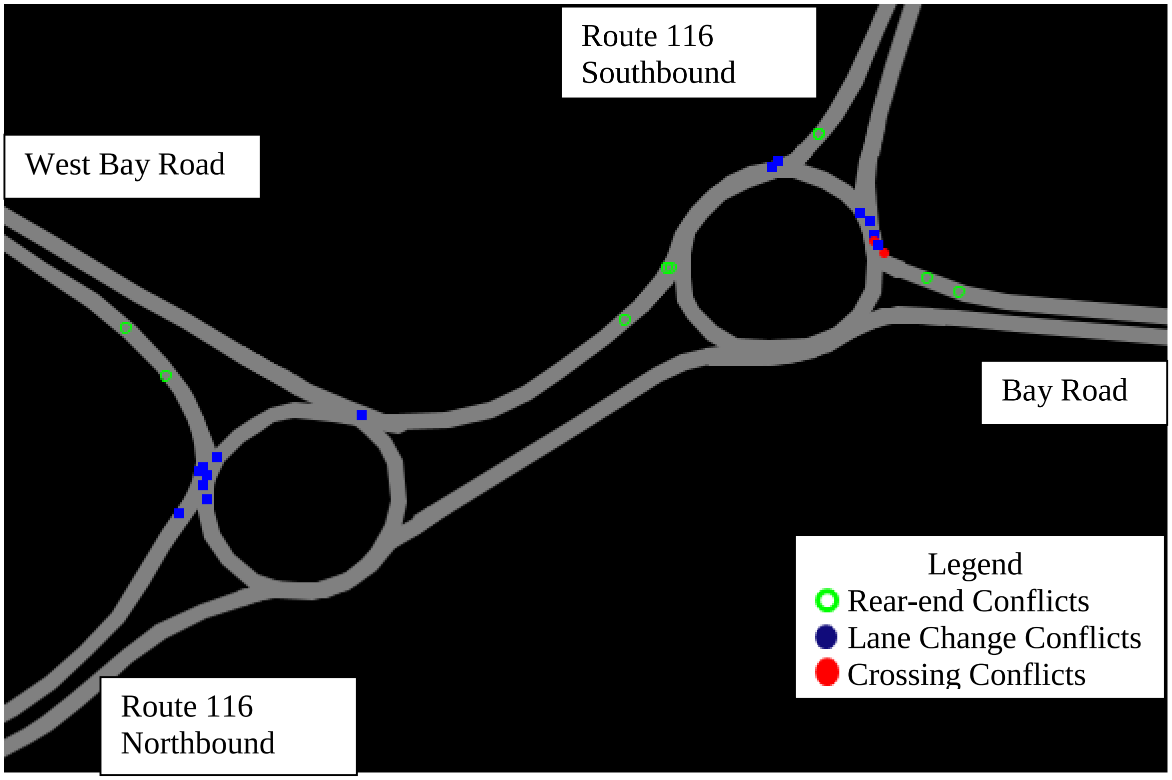

Figure 26: Location of SSAM-Estimated Conflicts: Atkins Corner Double Single-Lane Roundabout (Morning Peak, After Conditions)

<u>Atkins Corner Double Single-Lane Roundabout: Evening Peak, After Conditions</u>

Table 25 summarizes the number and type of conflicts experienced at the Atkins Corner double single-lane roundabout during the evening peak hour. Figure 17 shows the location of the conflicts presented in Table 25. Based on the data from Table 25 the average number of conflicts was 7.3 conflicts/hr, which consisted of 4 rear-end conflicts/hr, 3.2 lane change conflicts/hr, and 0.1 crossing conflicts/hr. The one crossing conflict is most likely due to the geometry of the network. The conflict angle for the crossing conflict is 83 degrees, which is very close to the threshold of 80 degrees. Essentially, this is a lane changing conflict with an angle larger than expected. Most of the conflicts occurred on the entering and exiting legs, and on the circulating segments that are just before the roundabout entries and exits. The conflicts were mostly seen at the West Bay Road and Route 116 northbound entering legs. Again the location of the conflicts is most likely due to these two legs having relatively higher entry volumes and the sight distance at these locations being worse than at the other legs.

Table 25: SSAM-Estimated Conflicts: Atkins Corner Double Single-Lane Roundabout (Evening Peak, After Conditions)

Simulation Run	Estimated Conflicts			
	Total	Crossing	Rear End	Lane Change
1	8	1	3	4
2	11	0	8	3
3	7	0	4	3
4	8	0	5	3
5	10	0	5	5
6	3	0	1	2
7	4	0	2	2
8	9	0	6	3
9	3	0	1	2
10	10	0	5	5
Average	7.3	0.1	4	3.2

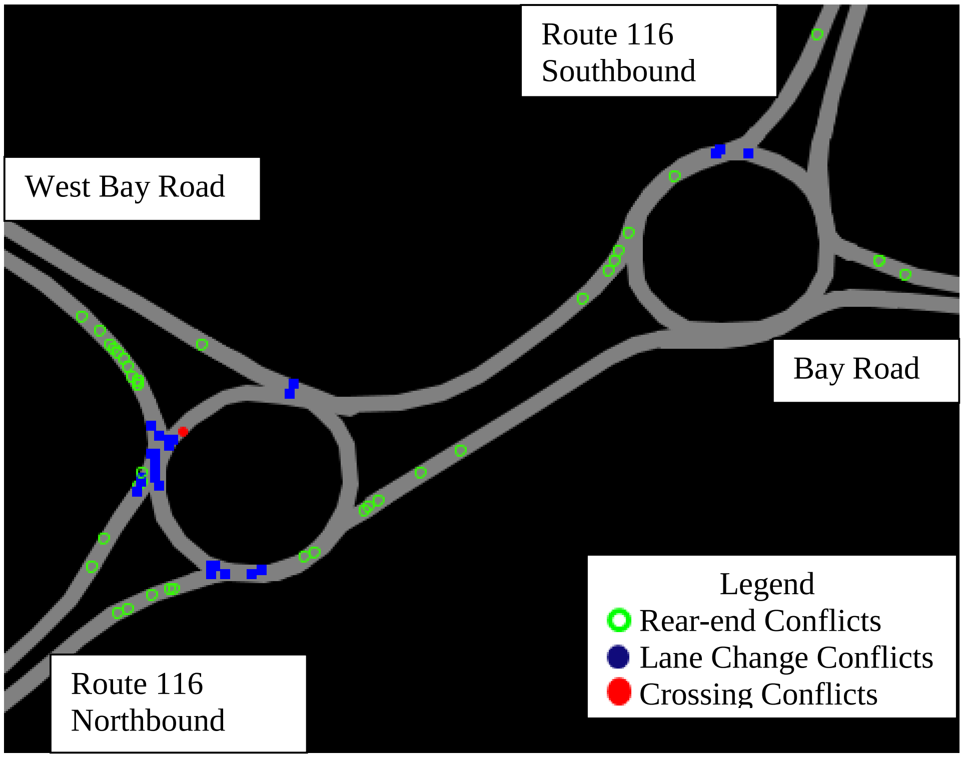

Figure 27: Location of SSAM-Estimated Conflicts: Atkins Corner Double Single-Lane Roundabout (Evening Peak, After Conditions)

Field Safety Assessment

Video data were evaluated for conflicts for both roundabouts during both the morning and evening peak hours for the after conditions. A conflict was defined as the case when two vehicles would occupy the same space at the same time if no evasive maneuver were to be taken. The after conditions of the two locations are the focus of this study because we want to investigate the accuracy of SSAM at roundabouts. Specific time and distance measures were not calculated from the video data but instead any action that deviated from normal behavior was recorded and further assessed to determine if this action was worthy of being reported as a conflict. The location that these conflicts occurred was also recorded. The locations were categorized as entering leg, exit leg, circulating, before and after exit, and before and after entry.

The conflicts were categorized into either lane change or rear-end conflicts. Crossing conflicts were ignored because roundabout geometry is designed to eliminate these types of conflicts. Any potential conflict that SSAM may define as a crossing conflict (i.e., crossing angle greater than 80 degrees) were called lane change conflicts due to the limitations of measuring conflict angles from video data.

UMass Campus Single-Lane Roundabout: Morning Peak, After Conditions

Table 26 presents the number and type of conflicts obtained from the one hour of video data for the UMass campus single-lane roundabout during the morning peak hour. The number of rear-end conflicts, 6 conflicts/hr, is less than the average number from SSAM which was 9 conflicts/hr. 3 lane change conflicts were observed and this number was similar to the 2 conflicts/hr obtained from SSAM. The location of the conflicts from the video data is in accordance to the ones estimated by SSAM in that most of them are in or around the entering and exiting legs and not in the circulating segments.

Table 26: Conflicts Obtained from Video Data: UMass Campus Single-Lane Roundabout (Morning Peak, After Conditions)

Conflict Number	Type of Conflict		Location of Conflict				
	Rear end	Lane Change	Entering Leg	Exit Leg	Before and After Exit	Circulating-Exit	Before and After Entry
1	x		x				
2		x				x	
3	x		x				
4	x			x			
5		x					x
6	x						
7		x					x
8	x			x			
9	x		x				
Total	6	3	3	2	0	1	2

UMass Campus Single-Lane Roundabout: Evening Peak, After Conditions

Table 27 presents the number and type of conflicts obtained from the one hour of video data for the UMass campus single-lane roundabout during the evening peak hour. The number of rear-end conflicts, 11 conflicts/hr, is equivalent to the average number from SSAM which was 11.6 conflicts/hr. Five lane change conflicts/hr were observed which was larger than the 2.9 conflicts/hr estimated by SSAM. The location of the conflicts from the video data is in accordance to the ones estimated by SSAM in that most of them are in or around the entering and exiting legs and not in the circulating segments.

Table 27: Conflicts Obtained from Video Data: UMass Campus Single-Lane Roundabout (Evening Peak, After Conditions)

Conflict Number	Type of Conflict		Location of Conflict				
	Rear end	Lane Change	Entering Leg	Exit Leg	Before and After Exit	Circulating-Exit	Before and After Entry
1	x		x				
2	x			x			
3	x			x			
4		x				x	
5		x					x
6	x				x		
7	x		x				
8	x		x				
9	x			x			
10		x					
11	x		x				
12		x					x
13		x					x
14	x		x				
15	x			x			
16	x			x			
Total	11	5	5	5	1	1	3

Atkins Corner Double Single-Lane Roundabout: Morning Peak, After Conditions

Table 28 presents the number and type of conflicts obtained from the one hour of video data for the Atkins Corner double single-lane roundabout during the morning peak hour. The number of rear-end conflicts, 2 conflict/hr, is larger than the average number from SSAM which was 0.9 conflicts/hr. Zero lane change conflicts/hr were observed in the video data, which was less than the 1.5 conflicts/hr estimated by SSAM. The low entering volumes and relatively large size of the double single-lane roundabout may account for any slight differences in the SSAM and video conflict assessment. We suggest that more data is collected at this site to better understand the difference between SSAM and the field data.

Table 28: Conflicts Obtained from Video Data: Atkins Corner Double Single-Lane Roundabout (Morning Peak, After Conditions)

Conflict Number	Type of Conflict		Location of Conflict				
	Rear end	Lane Change	Entering Leg	Exit Leg	Before and After Exit	Circulating-Exit	Before and After Entry
1	x						x
2	x						x
Total	2	0	0	0	0	0	2

Atkins Corner Double Single-Lane Roundabout: Evening Peak, After Conditions

Table 29 presents the number and type of conflicts obtained from the one hour of video data for the Atkins Corner double single-lane roundabout during the evening peak hour. The number of rear-end conflicts, 4 conflicts/hr, is equivalent to the average number from SSAM which was 4 conflicts/hr. Three lane change conflicts were observed which was similar to the 3.2 conflicts/hr estimated by SSAM. The location of the conflicts from the video data is in accordance to the ones estimated by SSAM in that most of them are in or around the entering and exiting legs and not in the circulating segments. The high entering volumes during this evening peak period may explain why SSAM and the field data match in this case but not during the morning peak period which had considerably lower entering volumes.

Table 29: Conflicts Obtained from Video Data: Atkins Corner Double Single-Lane Roundabout (Evening Peak, After Conditions)

Conflict Number	Type of Conflict		Location of Conflict				
	Rear end	Lane Change	Entering Leg	Exit Leg	Before and After Exit	Circulating-Exit	Before and After Entry
1	x		x				
2		x				x	
3		x					x
4		x					x
5	x		x				
6	x		x				
7	x		x				
Total	4	3	4			1	2

Conflict Number	Type of Conflict		Location of Conflict				
	Rear end	Lane Change	Entering Leg	Exit Leg	Before and After Exit	Circulating-Exit	Before a Entry
1	x		x				
2		x				x	
3		x					
4		x					
5	x		x				
6	x		x				
7	x		x				
Total	4	3	4			1	

Summary of Findings

Overall, it appears that SSAM is an adequate tool for estimating conflicts at single-lane roundabout and double single-lane roundabouts as long as the entry volumes are high enough to cause a considerable number of conflicts per hour. Only during the morning peak period at the Atkins Corner double single-lane roundabout the SSAM estimated a number of conflicts that did not match the conflicts observed from the video data. The location of the conflicts estimated by SSAM at both roundabouts during both peak periods had a strong correlation with the location of the conflicts obtained from the video data. The most common location of conflicts was on the entering and exiting legs. SSAM and the field data had a similar percent split between rear-end conflicts and lane change conflicts at each roundabout during both peak period. The percent split was different for each model but there was a trend that more rear-end conflicts occurred than lane change conflicts.

CHAPTER 8

FIELD STUDY ON THE IMPACT OF PEDESTRIANS ON EMISSIONS

The following chapter details the field study performed to evaluate the impact of pedestrian volumes on vehicular emissions, in particular, carbon dioxide (CO_2) emissions. The data collection part of the field study was performed with the use of the Intelligence to Drive (i2D) technology, which is a device that plugs into a vehicle's on board diagnostic port. The device is comprised of several components: 1) a General Packet Radio Service (GPRS) machine to machine 24/7 communication (Sim or Embeded Car), 2) a memory card, 3) assisted Global Positioning System GPS, and 4) a power supply for external devices. This technology was the result of a research and development and technology demonstration project sponsored by the Instituto de I&D do Departamento de Engenharia Mecanica do IST (IDMEC) and Internet, Technologies & Desenvolvimento De Software (ITDS) and it was funded by Fundo de Apoio a Inovacao (FAI).

The device stores the trajectory of the vehicle it is plugged into and sends this information to a server. The data stored in the server are then used as inputs to a model to estimate levels of emissions. The model was developed from eight years of second by second raw data collected by IDMEC and IST. The models can estimate CO_2, CO, fuel consumption, acceleration and deceleration rates, speed, and elevation. This study was focused on the level of CO_2 emissions. The outputs of these models are accessible through a website. The device outputs second by second data for speed, revolutions per minute (RPM), lateral, longitudinal and vertical acceleration and deceleration, and elevation. Though there is not second by second emission data available to the user, the website is capable of showing locations of high CO_2 emission along a vehicle trajectory as well as average CO_2 emission data for each run. A high

CO_2 emissions event is defined as any instant when CO_2 emission levels are higher than 6 g/s. Using video recordings, a comparison was made to determine if those high level of CO_2 emissions were experienced when pedestrians were present at crosswalks, which made vehicles slow down or stop. The higher the number of stops and acceleration/deceleration cycles a vehicle goes through, the higher the level of emission output from that vehicle (*40, 41*). Comparisons of speed profiles during different events, such as yielding to a pedestrian at the roundabout, yielding to a vehicle at the roundabout, being in a queue at the roundabout, or yielding to multiple pedestrians were also made.

Ten subjects were asked to drive a 2005 Hyundai Elantra GT from the University of Massachusetts Amherst police station down Eastman Lane, straight through the roundabout and down Governors Drive to the parking services parking lot (Figure 28). The subjects then had to drive back from parking services to the police station. The loop is 4.26 km in total or 2.13 km in each direction. This full loop was driven five times by each subject. Video data were collected through the UbiPix smart phone application, which captured any pedestrians that crossed the path of the subjects. This video data were used to assess the total number of stops in a run, the cause of the stops, and the location of the stops.

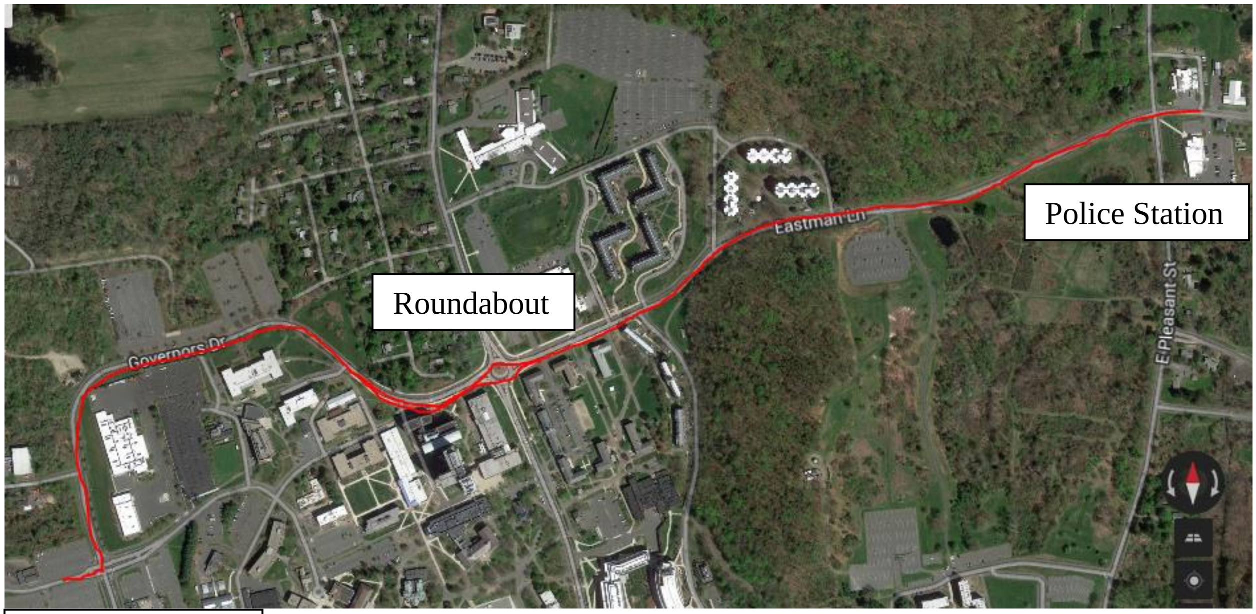

Figure 28: Field Study Route
https://www.google.com/maps

Subjects were scheduled based on convenience so not all subjects were run during the same time of day or day of the week. Runs were constrained to weekdays from about 8:00 AM to 5:00 PM in order to ensure that runs were conducted during times pedestrians are most likely to be walking around campus. An even number of male and female participants were engaged in the study. Tables 30-39 display the results of the field study for all 5 loops, for each subject broken up into 10 runs one for the eastbound direction of every the loop and one for the westbound direction of every loop.

Table 30: Subject 1: Male: Monday 10/20/2014, 12:00-1:00pm

Subject	Run	Average CO2 (g/km)	Distance Traveled (km)	Total CO2 (g)	Total Number of Stops	Number of Stops at Roundabout	High CO_2 Emissions	Caused by Pedestrian	Location of High Emissions
1	1	225	2.13	479.25	5	2	1	Yes	At Roundabout
	2	223	2.13	474.99	3	0	1	No	Not at Roundabout
	3	221	2.13	470.73	2	1	1	Yes	Not at Roundabout
	4	219	2.13	466.47	3	1	1	No	At Roundabout
							2	No	Not at Roundabout
	5	222	2.13	472.86	2	1	1	No	Not at Roundabout
	6	217	2.13	462.21	3	0	1	No	Not at Roundabout
	7	221	2.13	470.73	4	1	0	-	-
	8	215	2.13	457.95	4	0	0	-	-
	9	217	2.13	462.21	4	1	0	-	-
	10	220	2.13	468.6	4	2	1	No	Not at Roundabout
	Average	220	2.13	468.6	3.4	0.9	0.82		

Table 31: Subject 2: Female: Tuesday 10/21/2014, 11:30am-12:30pm

Subject	Run	Average CO2 (g/km)	Distance Traveled (km)	Total CO2 (g)	Total Number of Stops	Number of Stops at Roundabout	High CO_2 Emissions	Caused by Pedestrian	Location of High Emissions
2	1	287	2.13	611.31	5	1	1	Yes	Not at Roundabout
	2	292	2.13	621.96	2	0	0	-	-
	3	289	2.13	615.57	2	0	0	-	-
	4	293	2.13	615.57	5	1	1	Yes	At Roundabout
							2	Yes	Not at Roundabout
	5	291	2.13	619.83	2	0	0	-	-
	6	289	2.13	615.57	4	1	1	No	Not at Roundabout
	7	286	2.13	609.18	2	1	0	-	-
	8	285	2.13	607.05	4	1	1	No	Not at Roundabout
	9	288	2.13	613.44	2	0	0	-	-
	10	290	2.13	617.7	5	1	0	-	-
	Average	289	2.13	614.72	3.3	0.6	0.55		

Table 32: Subject 3: Female: Wednesday 10/22/2014, 1:00-2:00pm

Subject	Run	Average CO2 (g/km)	Distance Traveled (km)	Total CO2 (g)	Total Number of Stops	Number of Stops at Roundabout	High CO_2 Emissions	Caused by Pedestrian	Location of High Emissions
3	1	255	2.13	543.15	2	1	0	-	-
	2	254	2.13	541.02	2	0	1	No	Not at Roundabout
	3	253	2.13	538.89	1	0	1	No	Not at Roundabout
	4	260	2.13	553.8	3	0	0	-	-
	5	258	2.13	549.54	5	1	1	Yes	Not at Roundabout
	6	261	2.13	555.93	6	3	1	No	Not at Roundabout
	7	254	2.13	541.02	9	3	1	Yes	Not at Roundabout
							2	Yes	At Roundabout
	8	258	2.13	549.54	7	1	1	No	Not at Roundabout
	9	255	2.13	543.15	3	0	1	No	Not at Roundabout
							2	No	Not at Roundabout
	10	252	2.13	536.76	5	3	1	No	Not at Roundabout
	Average	256	2.13	545.28	4.3	1.2	1		

Table 33: Subject 4: Male: Wednesday 10/22/2014, 2:15-3:15pm

Subject	Run	Average CO2 (g/km)	Distance Traveled (km)	Total CO2 (g)	Total Number of Stops	Number of Stops at Roundabout	High CO_2 Emissions	Caused by Pedestrian	Location of High Emissions
4	1	260	2.13	553.8	4	1	0	-	-
	2	263	2.13	560.19	2	0	0	-	-
	3	257	2.13	547.41	3	0	1	Yes	Not at Roundabout
	4	266	2.13	566.58	3	1	0	-	-
	5	262	2.13	558.06	5	1	1	Yes	Not at Roundabout
	6	261	2.13	555.93	3	1	0	-	-
	7	266	2.13	566.58	4	0	0	-	-
	8	264	2.13	562.32	6	2	0	-	-
	9	267	2.13	568.71	6	2	1	No	Not at Roundabout
	10	264	2.13	562.32	7	1	1	No	Not at Roundabout
	Average	263	2.13	560.19	4.3	0.9	0.4		

Table 34: Subject 5: Female: Tuesday 11/4/2014, 10:45-11:45am

Subject	Run	Average CO2 (g/km)	Distance Traveled (km)	Total CO2 (g)	Total Number of Stops	Number of Stops at Roundabout	High CO_2 Emissions	Caused by Pedestrian	Location of High Emissions
5	1	253	2.13	538.89	4	1	1	Yes	Not at Roundabout
							2	No	Not at Roundabout
	2	246	2.13	523.98	4	1	1	No	Not at Roundabout
	3	248	2.13	528.24	6	1	1	No	Not at Roundabout
							2	Yes	Not at Roundabout
							3	Yes	Not at Roundabout
	4	251	2.13	534.63	7	1	1	Yes	Not at Roundabout
							2	No	Not at Roundabout
	5	252	2.13	536.76	4	2	0	-	-
	6	248	2.13	528.24	4	1	0	-	-
	7	244	2.13	519.72	5	1	0	-	-
	8	245	2.13	521.85	4	1	0	-	-
	9	243	2.13	517.59	2	0	0	-	-
	10	250	2.13	532.5	2	0	0	-	-
	Average	248	2.13	528.24	4.2	0.9	0.93		

Table 35: Subject 6: Male: Wednesday 11/5/2014, 9:30-10:30am

Subject	Run	Average CO2 (g/km)	Distance Traveled (km)	Total CO2 (g)	Total Number of Stops	Number of Stops at Roundabout	High CO_2 Emissions	Caused by Pedestrian	Location of High Emissions
6	1	260	2.13	553.8	4	1	1	Yes	Not at Roundabout
	2	274	2.13	583.62	3	0	1	No	Not at Roundabout
	3	266	2.13	566.58	4	0	1	No	Not at Roundabout
							2	Yes	Not at Roundabout
							3	No	Not at Roundabout
	4	264	2.13	562.32	3	0	1	Yes	Not at Roundabout
	5	269	2.13	572.97	4	1	0	-	-
	6	271	2.13	577.23	2	0	0	-	-
	7	263	2.13	560.19	4	3	0	-	-
	8	262	2.13	558.06	2	1	0	-	-
	9	264	2.13	562.32	2	0	1	No	Not at Roundabout
	10	267	2.13	568.71	5	1	0	-	-
	Average	266	2.13	566.58	3.3	0.7	0.83		

Table 36: Subject 7: Male: Wednesday 11/5/2014, 3:30-4:30pm

Subject	Run	Average CO2 (g/km)	Distance Traveled (km)	Total CO2 (g)	Total Number of Stops	Number of Stops at Roundabout	High CO_2 Emissions	Caused by Pedestrian	Location of High Emissions
7	1	233	2.13	496.29	4	1	1	No	Not at Roundabout
	2	234	2.13	498.42	2	1	1	Yes	At Roundabout
	3	242	2.13	515.46	4	2	1	No	Not at Roundabout
							2	No	At Roundabout
	4	237	2.13	504.81	2	0	0	-	-
	5	239	2.13	509.07	5	1	1	No	Not at Roundabout
	6	238	2.13	506.94	7	1	1	Yes	Not at Roundabout
	7	231	2.13	492.03	3	1	0	-	-
	8	243	2.13	517.59	4	1	0	-	-
	9	241	2.13	513.33	2	0	0	-	-
	10	232	2.13	494.16	3	0	1	No	Not at Roundabout
	Average	237	2.13	504.81	3.6	0.8	0.8		

Table 37: Subject 8: Male: Thursday 11/6/2014, 8:00-9:00am

Subject	Run	Average CO2 (g/km)	Distance Traveled (km)	Total CO2 (g)	Total Number of Stops	Number of Stops at Roundabout	High CO_2 Emissions	Caused by Pedestrian	Location of High Emissions
8	1	226	2.13	481.38	2	0	1	Yes	Not at Roundabout
	2	233	2.13	496.29	4	1	1	No	Not at Roundabout
	3	227	2.13	483.51	6	1	1	No	Not at Roundabout
							2	Yes	Not at Roundabout
	4	235	2.13	500.55	5	2	1	No	Not at Roundabout
							2	Yes	At Roundabout
	5	231	2.13	492.03	3	0	0	-	-
	6	236	2.13	502.68	2	0	0	-	-
	7	227	2.13	483.51	3	0	1	No	Not at Roundabout
	8	223	2.13	474.99	4	1	0	-	-
	9	227	2.13	483.51	6	3	1	No	Not at Roundabout
							2	Yes	At Roundabout
	10	225	2.13	479.25	5	1	0	-	-
	Average	229	2.13	487.77	4	0.9	1.2		

Table 38: Subject 9: Female: Thursday 11/6/2014, 11:30am-12:30pm

Subject	Run	Average CO2 (g/km)	Distance Traveled (km)	Total CO2 (g)	Total Number of Stops	Number of Stops at Roundabout	High CO_2 Emissions	Caused by Pedestrian	Location of High Emissions
9	1	251	2.13	534.63	4	1	1	No	Not at Roundabout
	2	261	2.13	555.93	3	0	1	No	Not at Roundabout
	3	253	2.13	538.89	2	1	1	No	At Roundabout
	4	248	2.13	528.24	2	0	0	-	-
	5	257	2.13	547.41	5	2	1	No	Not at Roundabout
	6	259	2.13	551.67	4	1	1	No	Not at Roundabout
							2	Yes	Not at Roundabout
	7	255	2.13	543.15	4	1	0	-	-
	8	251	2.13	534.63	2	1	1	Yes	At Roundabout
	9	249	2.13	530.37	2	1	0	-	-
	10	256	2.13	545.28	3	0	1	No	Not at Roundabout
	Average	254	2.13	541.02	3.1	0.8	0.82		

Table 39: Subject 10: Female: Friday 11/7/2014, 11:00am-12:00pm

Subject	Run	Average CO2 (g/km)	Distance Traveled (km)	Total CO2 (g)	Total Number of Stops	Number of Stops at Roundabout	High CO_2 Emissions	Caused by Pedestrian	Location of High Emissions
10	1	267	2.13	568.71	2	0	0	-	-
	2	263	2.13	560.19	5	1	1	No	Not at Roundabout
							2	No	Not at Roundabout
	3	281	2.13	598.53	2	0	0	-	-
	4	277	2.13	590.01	3	0	1	No	Not at Roundabout
	5	274	2.13	583.62	4	0	0	-	-
	6	262	2.13	558.06	6	1	1	Yes	Not at Roundabout
							2	No	Not at Roundabout
	7	267	2.13	568.71	3	0	0	-	-
	8	274	2.13	583.62	2	0	0	-	-
	9	275	2.13	585.75	3	1	1	No	Not at Roundabout
	10	270	2.13	575.1	2	0	0	-	-
	Average	271	2.13	577.23	3.2	0.3	0.67		

Speed Profiles

Speed profiles for specific types of events that occurred at the roundabout are displayed in Figures 29-34. The speed profile are outputs from the Ubipix smart phone application. The blue lines represent the vehicle speed in kph and the turquoise lines the elevation. The arrows designate the section of the trajectory that is of interest. As stated previously the higher the number of stops and acceleration/deceleration cycles a vehicle goes through, the higher the level of emissions output from that vehicle (*40, 41*). So events that cause vehicle trajectories to have one or more dramatic increases/decreases in speed near the roundabout would be expected to output higher emission levels.

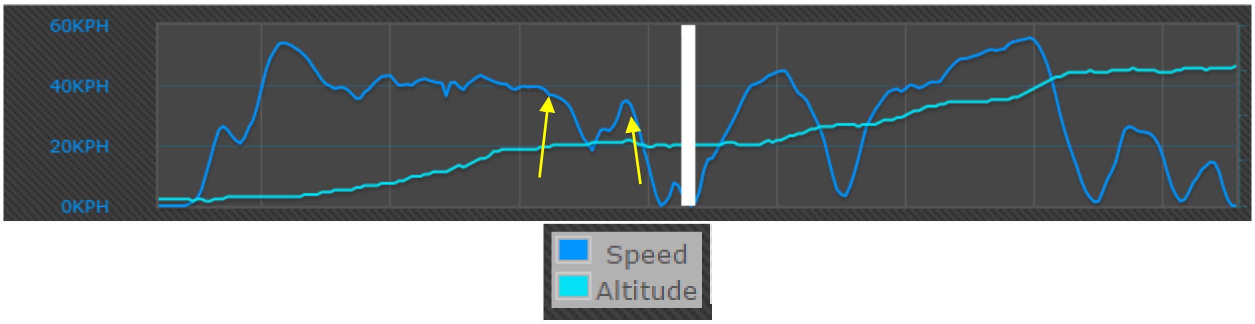

Figure 29: Speed Profile: No Stop at Roundabout

Figure 29 shows the speed profile for Subject 1 during their second run. The speed pattern shown between the two yellow arrows is for a vehicle navigating the roundabout that had no pedestrian, vehicular, or any other reason to stop at the roundabout. The vehicle slows down slightly due to the geometry of the roundabout but it is relatively a gentle deceleration while entering and acceleration while exiting. While traveling through the roundabout the vehicle accelerates for part of it, then the speed is held constant for some time before the vehicle accelerates again and exits the roundabout. The small period of time that the vehicle travels at constant speed indicates that no acceleration or deceleration is happening and that the emission levels during that time period would be relatively smaller than if the vehicle were to continuously accelerate while traveling through the roundabout.

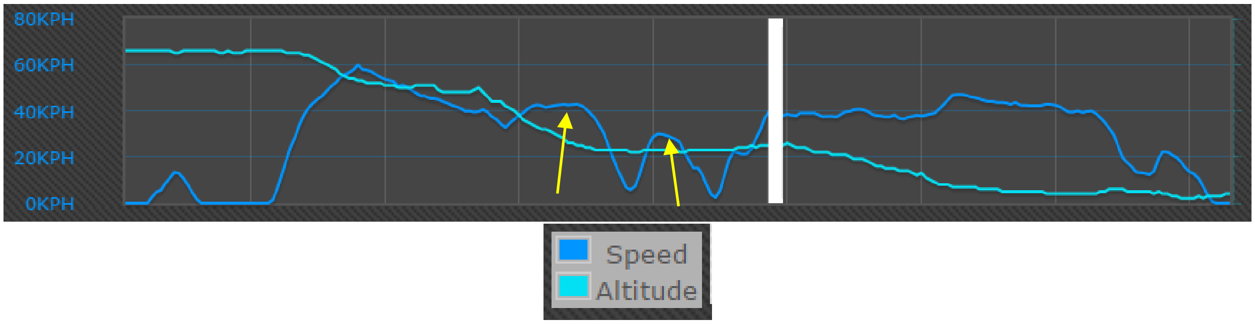

Figure 30: Speed Profile: Yielding for Vehicle: Entrance of the Roundabout

Figure 30 shows the speed profile for Subject 2 during their fourth run. The speed pattern shown between the two yellow arrows is for a vehicle yielding to another vehicle already traveling through the roundabout. The subject vehicle slows down at a constant rate but does not come to a complete stop before accelerating again. It then travels through the roundabout as seen by the pattern that follows, which is similar to the pattern described in Figure 29 for vehicles that do not stop at the roundabout. Based on the logic that more stops indicate higher emission levels, it would be safe to assume that the speed profile in Figure 30 would produce more emissions than the one presented in Figure 29 due to the fact that there are two acceleration/deceleration cycles in Figure 30 compared to one in Figure 29.

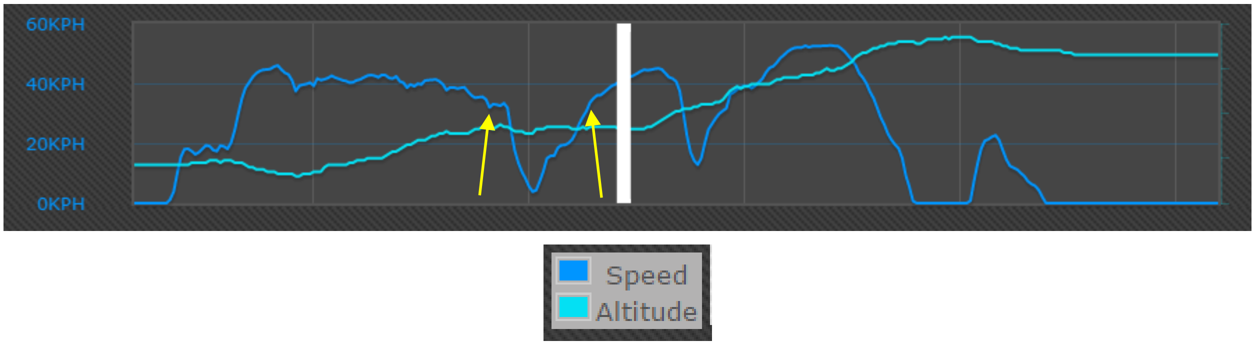

Figure 31: Speed Profile: Yielding to Pedestrian at Entrance of Roundabout

Figure 31 shows the speed profile for Subject 9 during their ninth run. The speed pattern shown between the two yellow arrows is for a vehicle yielding to a single pedestrian at the crosswalk located at the entrance of the roundabout. The vehicle decelerates at a higher rate than the deceleration rate utilized by the vehicles in the previous two figures but the acceleration is similar to those vehicles. The sharper deceleration rate indicates that emissions were being produced at a higher level during that stop than in the previous two examples though the time spent in acceleration seems like it would have produced similar emission levels. In combination with having to stop when yielding to a vehicle at the entrance it is likely that the emissions produced would be even higher.

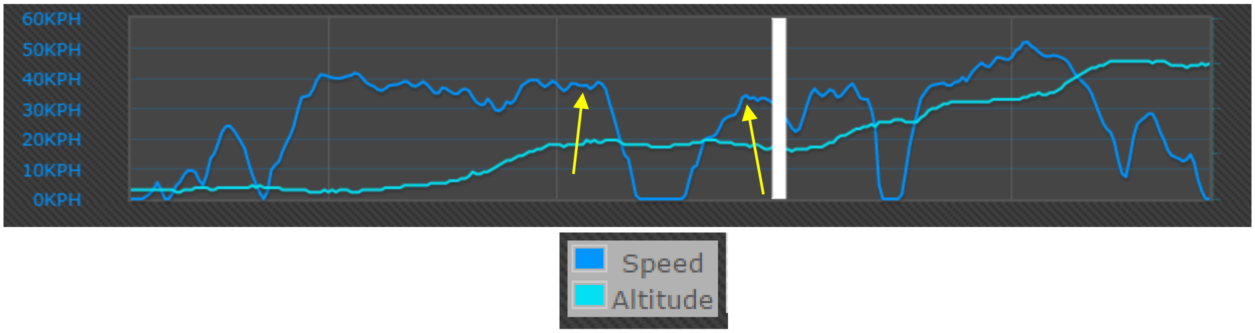

Figure 32: Speed Profile: Stopped for Multiple Pedestrians Entrance of the Roundabout

Figure 32 shows the speed profile for Subject 2 during their first run. The speed pattern shown between the two yellow arrows is for a vehicle yielding to multiple pedestrians at the crosswalk located at the entrance of the roundabout. The vehicle decelerates at a rate similar to the one utilized by vehicles in Figures 29, 30, and 31 but the difference is that Subject 2 actually reaches a speed of zero and remains there for some time while the pedestrians pass. The time spent idling is wasteful but the emission levels during this time are small compared to when the vehicle is in accelerating or decelerating driving mode. Again if this scenario was in combination with the others mentioned the emission levels would be even higher throughout the roundabout.

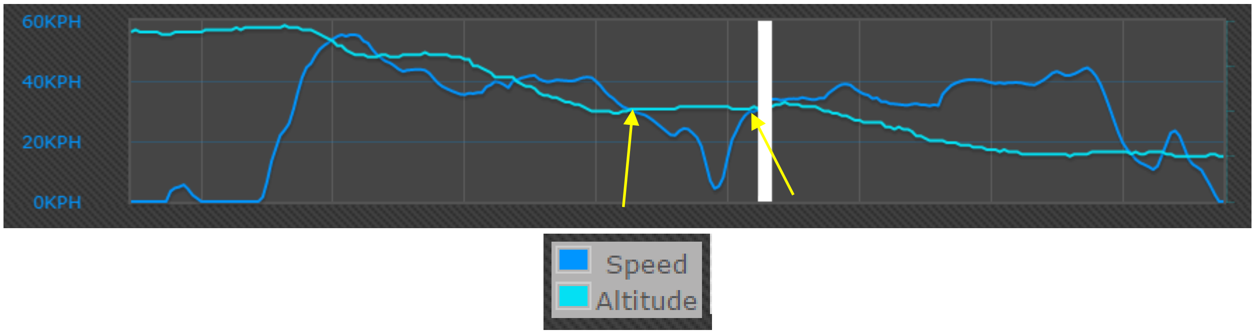

Figure 33: Speed Profile: Yielding to Pedestrian at Exit of Roundabout

Figure 33 shows the speed profile for Subject 2 during their fourth run. The speed pattern shown between the two yellow arrows is for a vehicle yielding to a single pedestrian at the crosswalk located at the exit of the roundabout. The pattern is very similar to the one seen in Figure 31, which is the profile for stopping for a single pedestrian at the entrance of the roundabout.

Figure 34: Speed Profile: Queued at Roundabout Pedestrians and Traffic Level High

Figure 34 shows the speed profile for Subject 6 during their seventh run. The speed pattern shown between the two yellow arrows is for a vehicle in a queue leading to the roundabout. The pattern is more erratic with multiple acceleration/deceleration cycles. The time spent in high acceleration and deceleration rates is considerably larger than in the other figures presented before implying a potentially higher production of CO_2 emissions.

Summary of Findings

The emission data from the i2D device did not produce any pattern in relation to high emission events and number of pedestrians at roundabouts. Most of the high emission events either happened for a different reason than pedestrians or did not occur at the roundabout. There was also no correlation between the total number of stops and the average or total CO_2 produced during a run, which is contrary to what the literature tells us. In the future more subjects need to be used to get a larger database from which to make conclusions.

The speed profiles from the device showed some insights into how high levels of pedestrians may affect emission levels at a roundabout. The speed file in Figures 29-34 all show different aspects of a vehicle trajectory throughout a roundabout and the reasons one might have to stop or slow down along that trajectory. If the vehicle and pedestrian volumes at a roundabout where high enough one might see a combination of the speed profiles shown in Figures 29-34 and also multiple acceleration/deceleration cycles which would produce significantly higher emission levels compared to a vehicle that does not have to stop at all while traveling through the roundabout as shown in Figure 29.

CHAPTER 9

RESEARCH CONTRIBUTIONS AND RECOMMENDATIONS

In chapter of this thesis a number of research contribution were outlined:

- Determining critical gap at a double single-lane roundabout.
- SSAM analysis and accuracy determination for two types of roundabouts: a) single-lane and b) double single-lane.
- Exploring the relationship between pedestrian crossing volumes and vehicle emissions at roundabouts.
- Emission level comparison of roundabouts and signalized intersections and stop-controlled intersections.

This chapter will discuss the extent to which these contributions were achieved and will propose recommendation for future research to improve the findings.

Research Contribution 1

- Determining critical gap at a double single-lane roundabout.

The critical gap of the Atkins Corner double single-lane roundabout was determined using two methods. The first was the Raff Method which determined that the critical gap range decreased from 6 to 6.5 seconds in the before conditions, which was two stop sign controlled intersections, to 2.5 to 4.5 seconds in the after conditions, which was the double single-lane roundabout. This is a considerable decrease in the size of the critical gap and indicates that knowing this value would be beneficial when developing accurate micro-simulation models. The second method was the Cumulative Acceptance Method. This method produced results that were mixed. In the before conditions the critical gap was determined to range from 4 to 4.25

seconds. The after conditions showed that the critical gap decreased to 3.5 seconds for the West Bay Road approach in the evening peak and to 3.75 seconds for the Bay Road approach in the morning peak. However, in the morning peak at the West Bay Road approach the critical gap increased to 5.5 seconds and in the evening at the Bay Road approach it increased to 6.5 seconds. Though this method did not have consistent results it still indicates that the critical gap can vary dramatically under slightly different conditions and therefore, should be assessed if trying to develop accurate micro-simulation models.

It would be prudent to evaluate more roundabouts with various geometric designs, entry volumes, and turning ratios to further understand how the critical gap changes when intersections are converted to double single-lane roundabouts. This would help improve micro-simulation models that are developed as alternative designs for future projects.

Research Contribution 2

- SSAM analysis and accuracy determination for two types of roundabouts: a) single-lane and b) double single-lane.

SSAM proved to be an adequate tool for estimating conflicts at a single-lane roundabout and a double single-lane roundabout as long as the entry volumes are large enough to cause a considerable number of conflicts per hour. The UMass campus single-lane roundabout video data showed similar number, type, and location of conflicts as those estimated by SSAM. Only during the morning peak period at the Atkins Corner double single-lane roundabout SSAM estimated number of conflicts did not match the conflicts obtained from the video data. This is most likely due to the low entry volume experience during the morning peak. The most common location of conflicts were on the entering and exiting legs, which would be expected because this is one of the few places at roundabouts that vehicles can travel on conflicting paths. SSAM and the field data had a similar percent split between rear-end conflicts and lane change conflicts at each roundabout during both peak periods. The percent split was different for each model but there was a trend that more rear-end conflicts occurred than lane change conflicts.

It is suggested that SSAM is to estimate conflicts at a variety of roundabouts with various characteristics to ensure that SSAM continues to prove to be an accurate tool for estimating the number, type, and location of conflicts at roundabouts. Proving that SSAM is an accurate tool for estimating conflicts at roundabouts has implications for evaluating alternative designs developed for future projects before implementing those designs in the field.

Research Contribution 3

- Determining the relationship between pedestrian crossing volumes and vehicle emissions at roundabouts.

The i2D device produced results did not show a correlation between pedestrian related vehicular stops at roundabouts and high emission events. There was also no pattern seen between total number of stops and the total amount of CO_2 produced. This finding contradicts the literature, which shows that more stops lead to higher emission levels. Before these findings can be trusted more data needs to be collected. Only a hand full of times did a pedestrian cause one of the subjects to stop at the roundabout. Conclusions cannot be drawn from such a limited data set.

The speed profiles produced from the Ubipix show that it is likely that drivers will decelerate at a higher rate when stopping for a pedestrian than when stopping or yielding for another vehicle before entering a roundabout. Based on the literature higher rates of acceleration and deceleration lead to higher emission levels. Therefore, the speed profile comparison that was conducted could indicate that pedestrians could potentially lead to significantly higher emission levels at roundabouts. More data needs to be collected using this device to validate the data here as well as more data should be collected at other roundabouts with various geometric and traffic conditions to see if there is a different effect of pedestrians on emission levels or if a pattern emerges.

Research Contribution 4

- Emission level comparison of roundabouts and signalized intersections and stop-controlled intersections.

During the morning peak hour the stop sign controlled intersections experienced 12.7 times the CO and NO_x levels of those experienced at the Atkins Corner double single-lane roundabout. The evening peak period showed that the stop-controlled intersections produced CO and NO_x levels that were 6.3 times larger than the ones seen at the double single-lane roundabout. It is clear for this data that a double single-lane roundabout under these conditions produces lower emission levels than the ones produced from stop sign controlled intersections under the same conditions. This agrees with the findings of previous studies, which showed that CO and NO_x levels decreased when converted to roundabouts (*48,49,51*).

The UMass campus single-lane roundabout data shows an increase in emission levels at the roundabout compared to the signalized intersection. This finding differs from the results found in studies in the literature (*46,48,49*). This may be due to the fact that at roundabout entering queues vehicles often start and stop more than once. By the time the last vehicle in an entering queue reaches the intersection they may have gone through 8 acceleration/deceleration cycles combined with idling in-between. This may cause higher emission levels compared to signalized intersections when entering demands are high. Assuming that the green time is long enough to dissipate the queue (i.e., under saturated conditions), every vehicle will have gone through only one acceleration/deceleration cycle at maximum. Going through one acceleration/deceleration cycle is expected to produce fewer emissions than going through multiple cycles assuming the rate of acceleration/deceleration is comparable. To further prove these finding more data needs to be collected at a variety of intersections under various conditions.

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