A Comparison of Carbon Dioxide Emissions at a Roundabout and a Signalized Intersection in a Mid-Sized City

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ABSTRACT

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Greenhouse gases (GHG) are increasing in our atmosphere. They have been known to cause changes to our hydrological cycle and manipulate other natural phenomena. Transportation is one of the main causes of this increase. Therefore it is essential to discover ways to reduce GHG caused by the transportation sector. This study aims to determine if roundabouts have lower levels of CO_2 emissions when compared to signalized intersections in the mid-sized city of Belleville, Illinois.

Traffic data were collected on one weekday and one weekend day over two five-minute recording periods in the morning and two in the afternoon. Traffic data were used to calculate average CO_2 emissions at the signalized intersection and the roundabout. Vehicles at the signalized intersection emitted lesser amounts during off peak hours but emitted more CO_2 emissions during peak hours due to increased idle durations whereas vehicles at the roundabout emitted lesser amounts of CO_2 emissions during peak traffic hours and more CO_2 emissions during off peak hours due to the longer driving distances. This pattern occurred on both recording days. Thus, at different recording periods, one intersection experienced lower levels of CO_2 emissions when compared to the other. While these findings are preliminary, they do suggest that roundabouts may be a more environmentally favorable option over traditional signalized intersections even in mid-sized cities.

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CHAPTER I

INTRODUCTION

Over the last few decades, significant climate changes have taken place, many of which have potential negative consequences to human society. The Earth's temperature has increased 1.4 degrees Fahrenheit during the past century, which may cause additional shifts to the Earth's hydrological cycle. We have already begun to see the changes caused by increased global temperatures, such as more frequent floods, droughts, decrease in glacial ice cap, and rising sea levels. The United States Environmental Protection Agency (EPA) believes that humans are the "highly likely" cause of increased global temperature as a result of the large amounts of greenhouse gases (GHG) emitted into the atmosphere. The main GHGs are carbon dioxide, nitrous oxide, methane, and fluorinated gases. These gases act as a blanket around the Earth by holding solar radiation in the atmosphere and not allowing it to bounce back into space, thus significantly increasing the Earth's temperature (U.S. EPA 2011).

There are various causes for increased GHGs in the atmosphere, such as agriculture, commercial and residential uses of energy, industry, and transportation. According to the U.S. EPA (2014), transportation is the second largest cause of GHG emissions into the atmosphere. These emissions come from burning of fossil fuels from cars, trucks, ships, trains, and planes. Over the past two decades, there has been increased fossil fuel burning from these sources, which ultimately has increased GHG levels drastically. It is essential that governments and communities continue to make changes and regulations to these sectors, specifically the transportation sector, in order to significantly decrease GHG emissions.

Statement of the Problem

The United States total GHG emissions increased 7.3 percent in the two decades of 1990 to 2009 (U.S. EPA 2011). Although the percentage may seem small, it is a significant increase to the atmosphere and can cause problems. According to the EPA, transportation contributes 27 percent of GHGs in the Earth's atmosphere yearly. Of the 27 percent, 43 percent is from passenger vehicles (U.S. EPA 2011). Carbon dioxide (CO_2) is 98 percent of the GHGs that are emitted by passenger vehicles. A significant component of the vehicle emissions comes from traffic at intersections. Street intersections cause vehicles to slow, and have stop-and-go movements instead of the ideal cruising speed. Stop-and-go traffic causes increased fuel consumption and high levels of GHG emissions, specifically CO_2 (Coelho et al. 2006). There has been a trend to use roundabouts to reduce vehicle emissions at intersections. Roundabouts are believed to create free-flow traffic and do not have signals that create mandatory idling. As a result, there is less idle time thus less fuel consumption and CO_2 emissions while driving through a roundabout as opposed to a signalized intersection. As GHG levels continue to increase, it is essential to use effective traffic controls to improve traffic flow in order to help decrease or eliminate passenger car emissions impact, as it will significantly decrease the levels of GHG in the Earth's atmosphere.

Although the roundabout is generally believed to contribute to a reduction in emission compared with signalized intersections most studies have so far analyzed larger cities and not mid-sized cities like Belleville, Illinois. Höglund and Niittymäki (1998) indicated in their study that general conclusions for this type of study should not be applied to various research locations, as results will vary due to traffic volume and traffic mechanisms. It was also determined by Höglund and Niittymäki (1998) that traffic responds differently to various traffic mechanisms and traffic volumes. Since there are larger volumes of traffic in larger cities than smaller cities it can be concluded that geographical location can directly affect traffic volume and thus CO_2 emissions. The size of the city may also affect the traffic pattern, which in turn affects the roundabout and signalized intersection performance. Therefore, it is essential that this type of study is conducted at a specific place as results should not be generalized.

The hours chosen to analyze varied throughout each study as well. Some researchers studied peak hours at each intersection and found differences in emissions from morning and evening peak hours, and with different volumes of traffic. (Höglund and Niittymäki 1998; Isebrands and Hallmark 2006; Cerdeira et al. 2007; Mandavilli et al. 2008; Ariniello and Przybyl 2010). Mandavilli's study indicated that the roundabout was more efficient at eliminating emissions for both morning and evening peak hours. The study conducted by Höglund and Niittymäki indicated that the signalized intersection was the best intersection for maximum hour traffic and the roundabout was the best intersection for the middle of the day traffic and low traffic intensity. Therefore, there are various conclusions of which traffic mechanism is more efficient when analyzing different hours of the day and different traffic volumes.

Traffic patterns generally vary between the peak hours on the weekdays and weekend days (Ariniello and Przybyl 2010). This raises the issue of whether the different intersections would perform differently between the weekday and weekend. Existing literature currently lacks the analysis of the comparison of different hours of the day during different recording days, specifically a weekend day. This study provides a first attempt to answer the questions that have yet to be answered.

<u>Purpose of the Study</u>

Roundabouts are known as the safest and most efficient traffic control method. Not only are they known for safety but there have been studies that have shown that roundabouts help reduce GHG emissions and decrease fuel consumption by having less idle time at the intersection (Coelho et al. 2006; Mandavilli et al. 2007; Ariniello amd Przybyl 2010; Correire et al. 2013; Guerrieri et al. 2013). In addition to the studies that indicated that roundabouts help reduce GHG emissions; there have been studies that indicate that there is little to no difference between a signalized intersection and a roundabout when it comes to emissions at the intersection. However, as stated earlier, there have not been studies conducted on medium sized cities. Also, there have been different conclusions regarding the effect of roundabouts in reducing emissions at different hours of the day; and there have not been studies that compare the effect of roundabouts reducing emissions between weekdays and weekend days. The purpose of this study is to examine two different types of transportation traffic control methods at two different intersections to determine which traffic control method allows the least amount of average CO_2 per vehicle. Specifically, this study will compare a signalized intersection and a roundabout in Belleville, Illinois in order to assess which system has a more efficient traffic control mechanism and thus helps reduce carbon dioxide emissions.

The above general research purpose entails the following three specific and related research questions:

1. In which type of intersection do vehicles produce less carbon dioxide emissions per vehicle?

   This question addresses the general issue which compares the performance of a roundabout in conjunction with that of a signalized intersection. This is an issue at the heart of many studies of the roundabout. Based on the general conclusion from many existing studies, the hypothesis is that the roundabout is better at reducing CO_2 emission than the signalized intersection.

2. Do carbon dioxide emissions vary during different hours of the day at each type intersection?

   This question addresses the issue of how different times of the day cause the different intersections to perform differently. Since the traffic pattern varies between the morning and evening peak hours, the effect of different intersections in reducing emissions may also vary. While the first research question raises the issue of which type of intersection is better at emission control, this research question raises the possibility that the performance of different types of intersections in emission control may depend on the time of day, conditioned by traffic conditions. The hypothesis is that the roundabout and the signalized intersection demonstrate different patterns of emissions between morning and evening peak hours. The interest is also in comparing the potential difference between the roundabout and the signalized intersection for different peak hours.

3. Do carbon dioxide emissions vary during different days of the week at each type of intersection?

   This question is a further extension of the second research question and addresses the issue of how different days of the week, such as a weekday and a weekend day, can cause the signalized intersection and roundabout intersections to perform differently. Traffic patterns vary between weekday and weekend days due to changes in work and activity patterns between weekday and weekend days. Thus, the performance of different types of intersections in emission control may also depend on whether it is a weekday or weekend day. The hypothesis is that the signalized intersection and the roundabout experience different travel pattern thus exhibit different levels of emissions between the weekday and weekend day.

Significance of Study

This study contributes to the emission control literature in several important aspects. First, this study was conducted in a mid-sized suburban city which the literature has not studied before. Existing literature exists for larger cities with different traffic patterns and volumes, thus this study will provide a different geographical location and city size that has not be studied before. Second, given that the existing studies arrive at different conclusions regarding the performance of roundabouts in emission control in comparison to the signalized intersections, this study re-visits the issue through a comparison study between a signalized intersection and roundabout. In addition, this study will examine how different times of the day may affect the performance of emission control for both types of intersections, for which the existing studies also had different conclusions. Finally, the existing studies have not addressed the issue of whether weekday and weekend days will make a difference in emission control at the different types of intersections. This study intends to fill the void.

Practical Significance of the Study

The answers provided from the research questions will assist Municipal Departments of Transportation and local officials with implementing the best traffic control method to help decrease CO_2 and other GHG emissions. Since the transportation sector is the second largest contributor of GHG into our atmosphere, significant changes need to be made in order to help reduce current and future negative outcomes due to the increase in levels of GHG, specifically CO_2, in our atmosphere. Roundabouts may be a solution to help reduce CO_2 emissions from the transportation sector. This study will benefit existing literature by using different methods that have not been used in previous studies.

CHAPTER II

LITERATURE REVIEW

The purpose of this literature review is to compare the impact of vehicle traffic controls (signalized intersection) to roundabouts to determine which intersection is the better option at emitting the least amount of CO_2 emissions. In addition to comparing intersections to determine which intersection helps reduce the amount of CO_2 emissions, this literature review will determine what causes differences in CO_2 emissions at the signalized intersection and the roundabout. Previous studies have included analyses of vehicles at roundabout intersections as well as at signalized stoplights and four-way stops.

Research Using aaSIDRA

Modern roundabouts provide many benefits to the cities that use them. Not only are they safer, but they also reduce vehicular emissions, fuel consumption, traffic congestion, and noise pollution by allowing traffic to run smoothly (Mandavilli et al. 2008). Mandavilli et al. conducted a study to investigate modern roundabouts, signalized stoplights and the pollutants cars emitted at these types of intersections. The study consisted of five different locations in two states. Of the five sites, two were previously stop signs before roundabouts were installed. The researcher's video recorded the intersections in two different segments from 0700 to 1300 hours and 1300 to 1900 hours. These two segments were then split into fifteen-minute intervals for close analysis. Next, traffic counts were taken from the recorded data at the intersections. The software used in this study is called aaSIDRA 2.0 (also known as SIDRA). The Australian Road Research Board developed the program to help evaluate intersections such as signalized stoplights, roundabouts, two-way stop control, etc. The input in the software includes road geometry, traffic counts, turning movements, and the speed of vehicles. SIDRA has a four-mode "element model" to estimate fuel consumption, operating cost and pollutant emissions for all traffic facilities. The emissions that are evaluated are CO, CO_2, NO_x, and HC or VOC. The hourly data collected from the video recordings and traffic counts were divided by morning and evening hours and put into SIDRA to be statistically analyzed. Mandavilli et al.'s study indicated that at the roundabout sites, CO_2 emissions were 16 percent and 59 percent less than signalized stoplights for the morning and evening peak hours. The average CO emissions for the roundabout intersection were 21 and 42 percent less than at a signalized stoplight. They concluded that after modern roundabouts were installed instead of stop signs, the CO_2 emissions decreased significantly, as did other GHG emissions and pollutants. In addition, they proved statistically that there was a decrease in delay, queuing, and stopping as compared to a signalized stoplight, which would consequentially decrease GHG emissions (Mandavilli et al. 2008; Correire et al. 2013; Guerrieri et al. 2013).

Coelho et al. (2006) conducted a study using aaSIDRA to help estimate GHG emissions at signalized and non-signalized intersections. As previously stated, the program focuses on the deceleration, idling, acceleration, and cruising behaviors of cars at an intersection. The researchers acknowledge the limitations of aaSIDRA and how it can alter the amounts of emissions calculated. Since the car is accelerating and decelerating again before it can get through the traffic control method, the researchers indicated it is important to include and calculate those emissions as well. Coelho et al. used a methodology that was similar to the methods that were used by aaSIDRA. They used camera-recording devices at signalized and non-signalized intersections to collect data on the "element model" as well as the stop and go actions of each car at an intersection. They divided the stop and go occurrences into long stop and go (LSG) and short stop and go (SSG). In addition, the researchers categorized the cars into three speed profiles: no stop at intersection, one stop, or more than one stop. The different categories helped calculate the emissions more accurately. The researchers found that 43 percent of the vehicles experienced no stops, 36 percent experienced one stop, and 21 percent experienced more than one stop at roundabouts. Coelho et al. (2006) found it is essential that vehicles quickly return to cruising speed at an intersection because that is when the vehicle releases the least amount of emissions. Emissions tend to increase when conflicting traffic and queue time increase, as it does at a signalized stoplight. Roundabouts help ease traffic and queue time, and help maintain cruising speeds, thus further reducing the amount of GHG emissions released into the atmosphere (Coelho et al. 2006).

Ariniello and Przybyl (2010) conducted a study in Colorado that evaluated fifteen intersections, five from three different volume groups: low, moderate, and high. The researchers looked at the peak evening hours for a continuous week. The researchers evaluated roundabout, signalized and non-signalized intersections using the aaSIDRA program. Each intersection in the low volume group was evaluated as a one-lane roundabout, and an all-way stop controlled intersection with single-lane approaches. The moderate group was evaluated as a one-lane roundabout and a traffic signal. The high volume group was evaluated as two-lane roundabout and a traffic signal. The results of each group were averaged and compared to determine fuel reduction and CO_2 emissions annually when comparing the roundabout and stoplight. The results indicated that roundabouts help decrease fuel consumption and CO_2 emissions. For the low volume intersections of 500 vehicles per hour, there were annual reductions of 75 metric tons of CO_2. For high volume intersections of 2,500 to 4,000 vehicles per hour, annual reductions of CO_2 were 150 to 400 metric tons. In addition, Ariniello and Przybyl studied fuel consumption and CO_2 emissions by time of day and analyzed data for when the roundabout was more efficient than signalized and non-signalized stoplights. The highest reduction in low traffic volume was during the peak-hour. For moderate vehicle volume, off peak-hour showed the most reductions in fuel consumption and CO_2 emissions. Lastly, the highest reductions for high vehicle volume intersections were during peak-hour. Ariniello and Przybyl concluded that roundabouts help decrease the levels of CO_2 emissions and decreases fuel consumption at all the different traffic volumes and intersections (Ariniello and Przybyl 2010).

Research Using aaSIDRA and MOBILE

Isebrands and Hallmark (2006) conducted a study in Ames, Iowa that specifically examined signalized intersections that did not have exclusive left or right turn lanes, which ultimately created congestion at the intersection. They evaluated the current intersection, which has left turn lanes as well as one that implemented a roundabout at the intersection. This study analyzed peak morning and evening hours of the day at a roundabout and stoplight. They used the program aaSIDRA to monitor the signalized stoplight and roundabout. In addition, the researchers used the EPA's MOBILE program, which is used to estimate emission rates by predicting gram per mile of emissions of HC, CO, NO_x, CO_2, and Particulate Matter (PM) from cars, trucks, and motorcycles. The results indicated that signalized stoplights had more emissions for every pollutant when compared to a modern roundabout. In some cases the pollutant was 21 to 28 percent higher than the roundabout. CO emissions were 21 percent higher at the signalized stoplight. Emissions at the roundabout were 2 to 5 percent lower than an intersection that added left turn lanes at the stoplight to help with traffic mitigation and idling. (Coelho et al. 2006; Isebrands and Hallmark 2006).

Research Using MOBILE

Cerdeira et al. (2007) studied the impact of traffic on atmospheric pollution on one of Barreiro's highways when comparing traffic lights crossroads (signalized stoplight) and a roundabout. The researchers conducted traffic counts at each of the intersections and classified each car as light-duty vehicles (LDV), heavy-duty diesel vehicles (HDDV), buses (Bus), and motorcycles (MC). The researchers conducted the traffic counts during morning and evening peak hours of 0800 to 1000 in the morning and 1700 to 1900 in the evening. They used the EPA's MOBILE 6.2 software to calculate emission factors of CO, NO_X, and PM. Meteorological data was taken into account in the study by using different meteorological variables such as wind speed and direction, temperature, humidity, and heat flux as these can alter pollutants in the atmosphere. Mobile 6.2 calculated PM from exhaust pipes, brakes, and tires emitted from Light Duty Gasoline Vehicles (LDGV), Light Duty Diesel Vehicles (LDDV), Motorcycles (MC), Heavy-Duty Diesel Vehicles (HDDV), and Buses (Bus). It also calculated CO, NO_X, and PM from the combustion process. Cerdeira et al.'s results indicated there were high amounts of CO and NO_X found in LDGV, and PM was highest in LDDV. Both intersections had high PM_{10} concentration but the signalized stoplight had higher levels of particles due to the waiting, stops, and road slope, which lead to more intense acceleration when compared to the roundabout (Cerdeira et al. 2007).

Research Using "Car-Following" Method

Várhelyi (2002) conducted a study in Sweden that used "car-following" to gather data of the cars' movements to obtain emission levels. The researcher selected 800 cars to follow and mimic their driving patterns as they went through roundabouts and signalized stoplights. The car used to follow the other car's movements was equipped with a computer that registered the driven distance and calculated the time of acceleration, cruising, and deceleration as it passed through all of the intersections. Emissions and fuel were calculated for each car by adding the volume of CO and NO_X emitted; as well as the petrol used per second. The information was based on emission and fuel-consumption factors, created by the Swedish Car-Testing Institute, for the different levels of speed and acceleration. From their data, the researcher found that when replacing a signalized stoplight with a roundabout, CO emissions and fuel consumption decreased significantly. Emission volumes per car decreased 29 percent for CO and fuel consumption decreased 28 percent (Hyden and Várhelyi 2000; Várhelyi 2002).

Research Using INTEGRATION and VISSIM

Ahn et al. (2009) conducted a study that investigated the operational efficiency of a two-way stop control, a roundabout, and a fixed-time traffic signal at an isolated intersection in relation to travel time, fuel consumption, and emissions. In the study, they used two different traffic simulators, INTEGRATION and VISSIM, to replicate realistic driving behaviors and mimic deceleration and acceleration events at a roundabout, stop sign, and signalized intersection. Passenger cars were the only type of vehicle used in this study. The field data collected were the number of lanes, lane stripping, traffic volumes, free-flow speed, saturation flow rate, jam density, and queue length. In order to determine emissions, they used VT-Micro mathematical model estimates. They found that the roundabout produced significant vehicle emissions. Roundabouts were found to increase CO, NO_X, and CO_2 emissions by 344, 456, 95, and 9 percent when a roundabout was operated instead of a stop control; although the intent of the article was not to derive definite fuel consumption or emissions inventories. Ahn et al. (2009) determined that once demand of the intersection (roundabout) increased, the ability to reduce GHG emissions at the intersection diminished as there was more idling time with the vehicles. The researchers also concluded that roundabouts reduce vehicle delays and the queue lengths when there is a low traffic demand level, thus lessening idle time and GHG emissions except when there is significant demand of the intersection (Ahn et al. 2009).

Research Using HUTSIM

Höglund and Niittymäki (1998) analyzed traffic signal systems and a roundabout without traffic signals in Malmö, Sweden. The researchers used computer programs that calculated fuel consumption and emissions, and singular vehicles' driving patterns. The research question they attempted to answer was which intersection is the "best alternative." The Laboratory of Transportation Engineering at Helsinki University of Technology developed the HUTSIM simulation model. It has traffic flow and capacity parameters, such as average delay, amount of stopping vehicles, average travel speed, etc. HUTSIM generates singular vehicle speed profiles such as acceleration, deceleration, stopping time (idling), cruising speed, etc. The researchers studied three different intersections using HUTSIM, existing traffic signal intersection, an improved traffic signal with turning lanes, and a roundabout with two lanes in the circle. All three intersections were simulated for maximum hour traffic, middle of the day, and low traffic intensity. Höglund and Niittymäki's (1998) results indicated that during the maximum hour traffic the best alternative is the improved signalized stoplight. The roundabout intersection was the best alternative for the middle of the day traffic, except for the average speed. Again, the roundabout intersection was the best alternative for low traffic intensity, except for fuel consumption and NO_X emissions. The researchers indicated that the drivers interact differently at each intersection because of the depending flow intensity and vehicle composition flow; therefore, it is difficult to predict the results. In conclusion, results are site specific and it is difficult to generalize obtained results. Although roundabouts were the best alternative for two different cases, the researchers decided that studies should be done for each specific case with a certain street and intersection configuration (Höglund and Niittymäki 1998).

Research Using "CAL3QHC"

Lima et al. (2013) studied the impact of substitution of a traffic light for a modern roundabout on carbon monoxide concentrations in Brazil. They used CAL3QHC, which is a dispersion model, and only considered passenger vehicles as emitting sources. Meteorological parameters were taken into consideration by analyzing eight different wind directions when compared to moving and queued vehicles. The researchers collected traffic flow values for each link obtained during 40 minutes and converted to the period of one hour. The CAL3QHC model calculates emissions factors for a composite vehicle on the free flow speed and on queues. For the two intersections where CO concentration was estimated, simulations were conducted on eight wind directions. Lima et al. (2013) discovered that wind direction did not have significant effect on the maximum values at the two intersections. Maximum concentrations of CO at the roundabout were less than a third of the values of the traffic light intersection. The high contribution of CO concentrations is from queue and idling vehicles. In conclusion, roundabouts showed to have lower CO emissions, but the researchers stated that a better estimate would require adjustments in their methodology. Estimated emissions directly affect the study, therefore the researchers would rather have on-road emission to be more accurate (Lima et al. 2013).

<u>Research Using Mathematical Modeling to Calculate Emissions</u>

High density and traffic congestion in urban areas are causes of significant air pollution in major cities. Emission factors are influenced by driving patterns such as speed and degree of acceleration and deceleration. Mutasem et al. (2000) investigated different intersections and their impacts on air quality. The methodology was a five-step process that was strictly focused on air quality. First, they defined the standards that were desired for air quality. Second, different levels of pollutants were developed from the baseline amounts by using mathematical modeling. Third, they calculated future levels of emissions by using mathematical equations. Next, they compared future levels with applicable standards and baseline conditions, and discovered the potential impact of the emissions. Lastly, they recommended emission mitigation measures to improve air quality to achieve the regulator standards (Mutasem et al. 2000). Their emissions factor assessment concluded that the emissions increased significantly at lower average speeds.

The researchers found that emissions decrease when there is free flow traffic and higher speeds. The article stated that pollutant emissions factors are five to ten times higher in situations involving stop-and-go traffic due to the acceleration and decelerations process. If cruising speed increased, it can reduce emissions significantly. Therefore, roundabouts are important assets to the process of emissions mitigation because they eliminate the stop-and-go traffic and allow drivers to accelerate and decelerate less than they would at stoplights (Mutasem et al. 2000).

Kozak et al. (2013) performed traffic analyses for the Rondo Rataje roundabout in Poznan, Poland. Specifically, they investigated the entries and exits of the roundabout of various types of vehicles such as passenger cars, heavy-duty trucks, delivery trucks, motorcycles, and buses. They conducted various simulations based on traffic data in the roundabout during morning rush hours. The results indicate that passenger cars cause the main source of emissions of CO, CO_2, and HC. Data also showed that NO_x and PM emissions are from passenger and heavy-duty vehicles. In conclusion, Kozak et al. states that roundabouts do have environmental impacts and have significant levels of emissions (Kozak et al. 2013).

<u>Research Using "Actual On-Road" Methods</u>

Hallmark et al. (2011) conducted a study in Minnesota that gathered actual on-road emissions. The researchers examined two roundabouts, one signalized stoplight, and a stop sign to determine which traffic control mechanism emitted more pollutants. The researchers' methodology used actual on-road data to assess pollutants instead of mathematical assessments to determine the emissions at different intersections. They used a portable emissions measurement system (PEMS) to collect their data. The researchers tested two different drivers, as driving behavior is known to alter emissions (Dabbas 2004; Hallmark et al. 2011). Each of the drivers drove the same routes which involved driving through the different controlled intersections. They studied the drivers during morning and evening peak hours. The PEMS measured HC, CO, CO_2, O_2, and NO_X emissions. Hallmark et al. (2014) found that roundabouts had fewer emissions than four-way-stops. Emissions were 9 percent and 12 percent higher for the two drivers at a four-way-stop than at the roundabout. On one of the routes used, the data showed that CO_2 emissions were 21 percent and 13 percent higher for the two drivers at the signalized stoplight rather than at the roundabout. Therefore, Hallmark et al. determined that roundabouts are in fact useful when trying to reduce GHG emissions and other pollutants at an intersection (Hallmark et al. 2011; Hallmark and Mudgal 2011)

Reddy et al. (2006) studied vehicles in India that were interrupted and uninterrupted by traffic control methods to determine which emitted more air pollutants. Interrupted modes were vehicles stopped by signals, whereas uninterrupted modes were vehicles that traveled smoothly without stoppages. The researchers divided the vehicles into three different categories: two wheelers, three wheelers, and four wheelers. A tailpipe gas analyzer was connected to each type of vehicle to determine pollutants released. For each of the different vehicles, it was evident that interrupted flow conditions generally had higher tailpipe emissions than uninterrupted vehicles. There was an 11 to 18 percent reduction in emissions when the vehicle was uninterrupted. This leads to the conclusion that free flow traffic controls, such as a roundabout, are essential to be able to reduce GHG emissions (Reddy et al. 2006).

Research on Traffic Patterns and Emissions

Perry and Owens (2011) conducted a study that analyzed the weekday and weekend variability and long-term trends in traffic as well as emissions for the Charlotte North Carolina Metropolitan area during the 1990's. This study examined hourly traffic from three different streets in Charlotte and the emissions caused from traffic from 1990 to 1997. This study found that the weekday patterns showed two speak that corresponded with AM and PM peak hours. Figure 1 showed that the AM peak hours occurred for a shorter duration (3 to 4 hours) than the PM peak hours (4 to 5 hours). The weekend days (Saturday and Sunday) were different from the weekday pattern showing that traffic volumes were lower than weekday volumes with highest volumes during the midday (only one peak hour). NO_x and CO levels were the highest during the morning peak hours and were lower on the weekend days. The ambient ozone levels were higher from 8:00 AM to 2:00 PM and decreased into the late evening and morning hours. There was not variability between the weekday and weekend days. Results indicated that the NO_x emissions caused by the nearby power plant were the lowest of anytime during the week on Monday and emissions increased sharply by midnight reaching mid-week emission levels. The end of the week emissions started decrease starting on Fridays. Therefore there were variations in traffic pattern and emissions when comparing different weekdays and weekend days as well as years (Perry and Owens 2011).

Conclusion

In conclusion, the literature indicates that roundabouts have many sustainable benefits that signalized stoplights and other intersection traffic controls do not have. Roundabouts are safe, help with the reduction of vehicular emissions, fuel consumption, traffic congestion, and noise pollution. They reduce crashes by 72 percent, and 87 percent of these prevented crashes would be fatal or cause injury (Hallmark and Mudgal 2011). Of the many studies and various methodologies used to research GHG emissions at roundabouts, signalized stoplights and stop signs, most of these indicated that roundabouts reduce emissions significantly. Although results vary among studies conducted, many researchers indicated that roundabouts reduce GHG emissions by at least 10 percent (Ahn et al. 2009; Hallmark et al. 2011; Hallmark and Mudgal 2011; Reddy et al. 2006). When vehicles can maintain cruising speeds, emissions, fuel consumption, and traffic congestion are commonly at their lowest. Therefore, roundabouts are beneficial to the cities that implement them in more ways than lowering GHG emissions.

The research I conducted fits into current literature by examining and comparing CO_2 emissions at stoplight and roundabout intersections. I collected traffic counts from each intersection and used a fuel consumption formula as well as a CO_2 emissions formula from aaSIDRA to calculate manually the GHG emissions. The goal of my research is to demonstrate roundabouts reduce GHGs, specifically CO_2 emissions in a local setting.

CHAPTER III

DATA AND METHODS

The Emissions Model

The literature review shows that the most current computer programs are aaSIDRA, the Environmental Protection Agency's (EPA) MOBILE 6.2, and other various computer programs (Coelho et al. 2006; Isebrands and Hallmark 2006; Mandavilli et al. 2008; Ariniello and Przybyl 2010), which are used to calculate emissions. These types of programs are used because it is known that CO_2 emissions vary based on the driving pattern of deceleration, idling, and acceleration. In addition to driving pattern, in depth details are used for each vehicle such as, speed, tire size, car torque, year of the vehicle, fuel type, etc. In addition, in MOBILE 6.2 computer simulation software, the location, road conditions, season, and time of day are also contributing factors. This comprehensive model of emissions can be expressed as:

Emissions= F(driving pattern, speed, vehicle characteristics, road conditions, climate) [1]

The methods chosen for this study follow the general spirit of the above model but simplify its implementation due to limited availability of information necessary for the comprehensive model. Specifically, the emission model used in this study is

Emission= F(driving pattern, speed, idle duration) [2]

The terms such as vehicle characteristics, road conditions, and climate are eliminated due to a lack of data for these variables. It can also be assumed that these variables do not vary within a city and thus are the same at both data collection sites used in this study.

In the simplified emission model [2], emissions are determined by driving pattern and vehicle speed. CO_2 emissions vary based on different speeds that vehicles are driving in the intersection thus, speed data were analyzed in this study. Researchers have found that CO_2 emissions increase significantly at lower speeds and when located in stop-and-go traffic. Emissions decrease at higher speeds and free flow traffics, which would show that roundabouts are more efficient (Mutasem et al. 2000; Reddy et al. 2006). Therefore, it can be hypothesized that a roundabout can reduce stop-and-go driving pattern as well as generate higher speed, compared with a regular intersection. Thus, a roundabout generates fewer emissions. This hypothesis is illustrated in Figure 1 below. In the figure, the actual speed pattern on how vehicles drive through a roundabout and intersection without idle time is the black line. The actual speed is higher at the roundabout than at the signalized intersection. Average idle speed, if it occurs at the roundabout, is significantly shorter duration than when idling occurs at the signalized intersection. The average speed for both intersections is labeled with the blue line. The average speed at the roundabout is higher (MPH) than the average at the signalized intersection. This suggests that the roundabout is more efficient and leads to lower amounts of CO_2 than the signalized intersection because of the higher traveled speed.

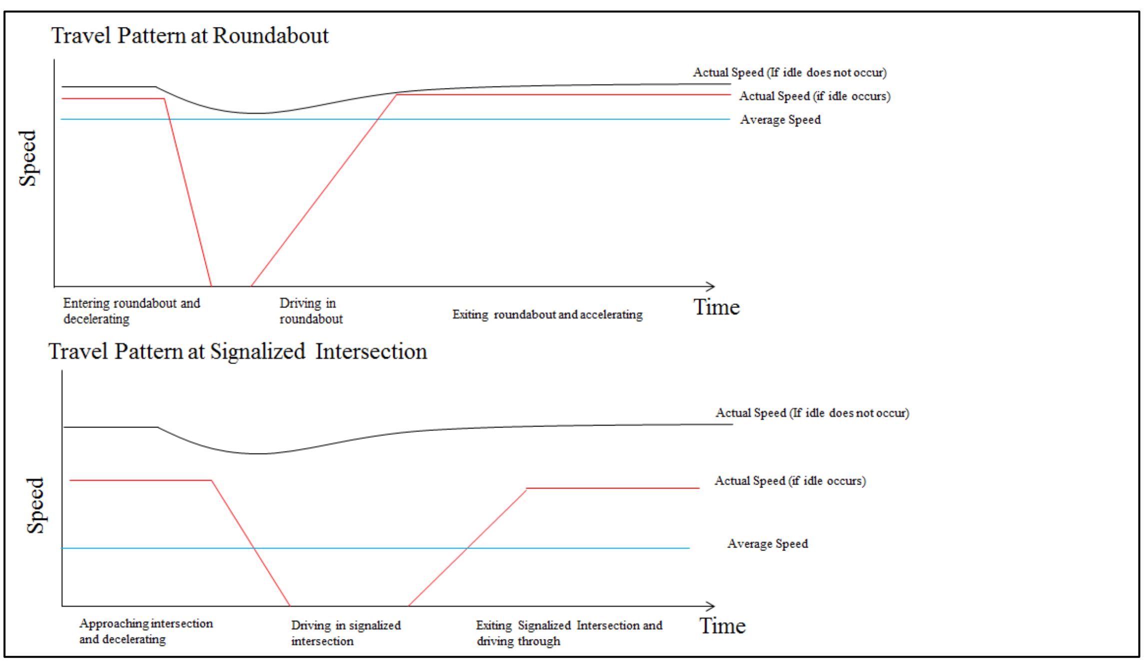

Figure 1: Travel Pattern of the Roundabout and Signalized Intersection. The actual speed traveled is in black for both graphs. The average speed is blue for both graphs. The average speed (if idling occurs) is red for the Roundabout and Signalized Intersection. Source: Author

The emission model of the study informs the methods used in this study, which include the following steps. First, data needs to be collected in order to determine the driving pattern such as stop-and-go pattern and vehicle speed for each vehicle that passes through the roundabout and the intersection. Second, from individual driving patterns and speeds, the average idle time and average vehicle speed for all vehicles going through the roundabout and the intersection at a particular time can be calculated. Third, the t-test of two independent samples will be performed to evaluate whether the average idle time and average vehicle speed are significantly different between the roundabout and the signalized intersection. Fourth, fuel consumption and CO_2 emissions are calculated using the empirical relationship between the vehicle speed and fuel consumption, and between the vehicle speed and CO_2 emissions. Figure 2 below is a flowchart that provides a general overview these steps. These steps will be discussed in depth following the following sections.

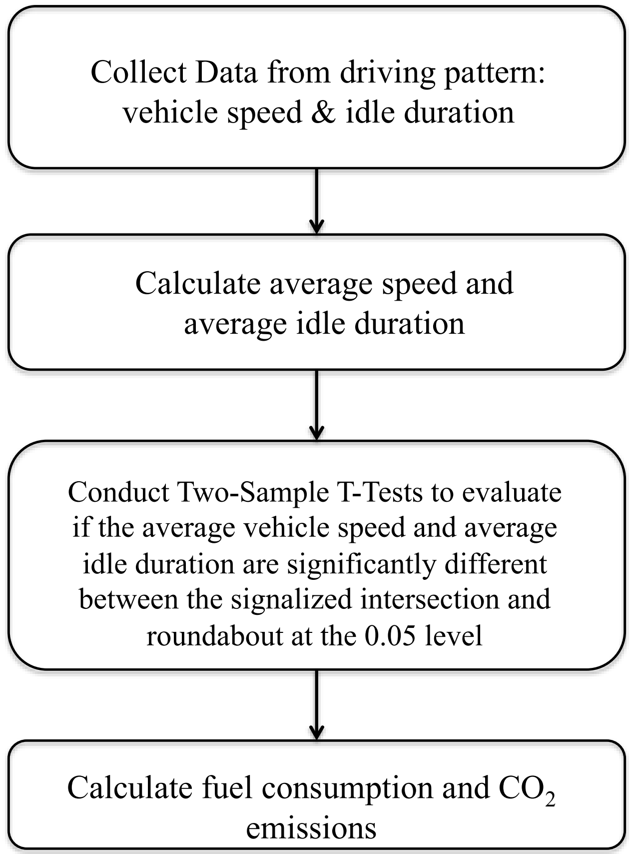

Figure 2: Methods Flow Chart. This chart shows the steps in order to calculate CO_2 emissions at the roundabout and the signalized intersection.

Study Site

Belleville, Illinois was chosen as the research location because the city has shown interest in finding ways to reduce Greenhouse Gases (GHGs), specifically carbon dioxide (CO_2) and ways to help reduce their contribution to climate change. They have already started to implement roundabouts throughout the town and are continuing to construct more. Höglund and Niittymäki (1998) indicated that studies should be done for each street and intersection configuration because it can be difficult and misleading to generalize results for different locations. Therefore, this study is site specific and will be beneficial to the City of Belleville.

Data were collected at a roundabout and signalized intersection in Belleville, Illinois (Figure 3). Belleville is located in St. Louis metropolitan area, in southwestern Illinois. As estimated by the United States Census Bureau in 2013, Belleville has a population of 42,895 (U.S. Census 2014).

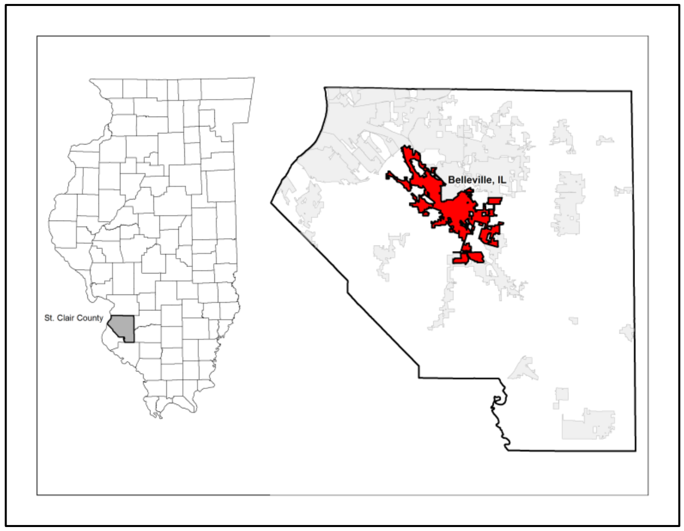

Figure 3: Map of St. Clair County and Belleville, Illinois. Source: City of Belleville

The roundabout is located on Illinois Route 159 and Main Street in the center of downtown, also known as "Town's Square." The signalized intersection is located at 17th Street and Main Street. Illinois Route 159 runs North-South and 17th and Main Street runs East-West. Main Street and Illinois Route 159 intersect to create the roundabout intersection. The signalized intersection is located thirteen blocks to the west of the roundabout. Both streets are located in downtown Belleville and have relatively high and similar traffic counts, which allows for equal comparison. Figure 4 below shows the aerial view of the signalized intersection on the left hand side of the picture outlined in red and the roundabout intersection on the right hand side outlined in blue.

Figure 4: Aerial View of the Signalized Intersection and Roundabout. Source: ESRI ArcGIS.

Figure 5a below is a zoomed in aerial view of the roundabout intersection and Figure 5b is the recording view for the roundabout intersection.

Figure 5a: Aerial View of the Roundabout. Source: ESRI ArcGIS.

Figure 5b: Recording View at the Roundabout. Source: Author.

Figure 6a is a zoomed in aerial view of the signalized intersection and 6b is the data recording view for the signalized intersection.

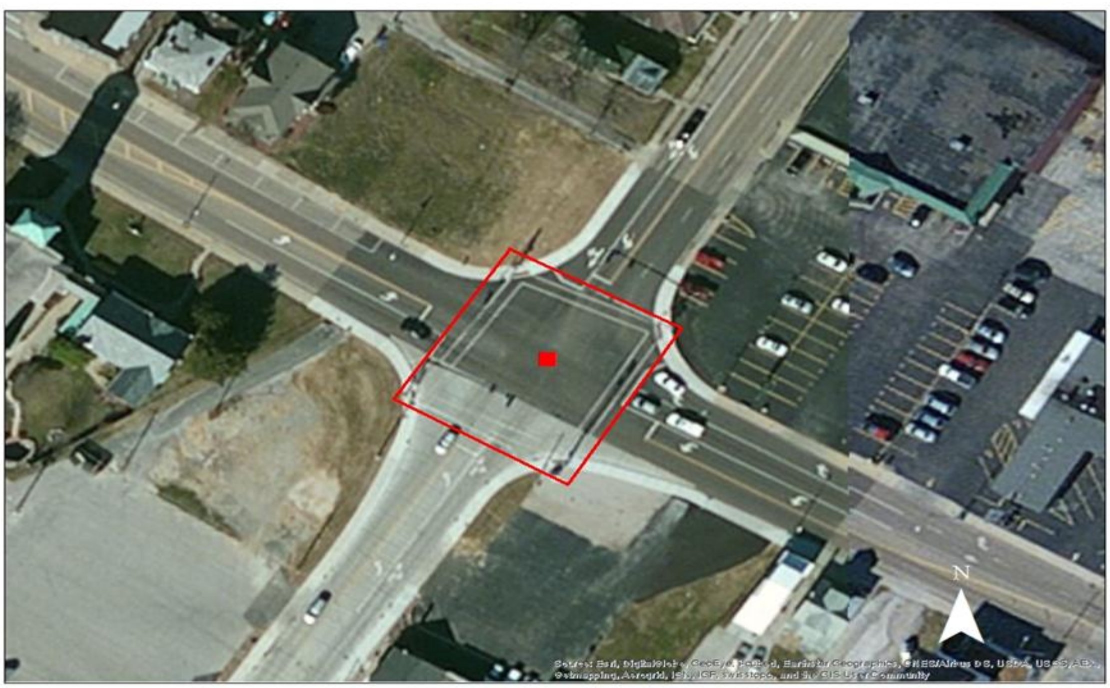

Figure 6a: Aerial View of the Signalized Intersection. Source: ESRI ArcGIS.

Figure 6b: Recording View of the Signalized Intersection. Source: Author.

<u>Data Collection</u>

Part 1: Video Data Collection

Data was collected at both intersections by using two video recorders, which ran concurrently. The roundabout intersection was recorded from a nearby building in order to obtain an aerial view of the intersection. The video recorder was placed on a tripod on the second floor of the building. The signalized intersection was recorded from a nearby parking lot with a view of the intersection. The research held the video recorder to record all time periods. There were two five-minute segments recorded during the morning hours of 0715 and 0815 as well as two five-minute segments during the evening hours of 1615 and 1815 on both Thursday, May 29 (weekday [WD]) and Saturday, May 31 (weekend day [WE]) of 2014. The video recordings were viewed digitally on a television screen and laptop. The benefit of having recorded data was that it could be retrieved and reviewed at any time.

Part 2: Visual Data Collection

Data was visually collected from the video recordings. Traffic counts were extracted as well as the duration each vehicle spent in the intersection for the morning and evening five-minute recording segments. In order to determine traffic counts and the duration of time each vehicle spent in the intersection, each intersection had to be defined. At the signalized intersection, there are crosswalks on each leg of the intersection. The crosswalks were used to determine when each vehicle entered and exited the intersection. At each entrance point of the roundabout, there are slow down arrows painted on the road surface. Once the vehicle crossed the arrows, it was determined to be in the intersection. When the vehicle passed the yellow-stripped median, which divided the different traffic lanes, a vehicle was determined to be out of the intersection.

In addition to the duration spent within each intersection, idle time was collected for all vehicles at both intersections. Vehicles were considered idling at the roundabout if they were waiting to enter the defined intersection (i.e. the slowdown arrows). Vehicles were considered idling at the signalized intersection if they were stopped outside of the boundaries (crosswalks) waiting to enter. Figure 7a below is an aerial view of the idle area at the signalized intersection. Figure 7b below is an aerial view of the idle area at the roundabout. In each picture, there are two white boxes; each vehicle was considered idling if it was stopped between the boxes on the road. These boxes were created based on what could be seen in the recording view.

Figure 7a: Aerial View of the Idle Area at the Signalized Intersection. Source: ESRI ArcGIS.

Figure 7b: Aerial View of the Idle Area at the Roundabout. Source: ESRI ArcGIS.

A Microsoft Excel spreadsheet was created to use as a checklist to help organize the extracted primary data. Columns headings were created to indicate the duration of the car in the intersection or idle time, type of car, and which exit was used to leave the intersection. In order to determine the duration within in the intersection and idle time, a stopwatch was used. This technique was used for all five-minute recorded segments at each intersection.

Two-sample T-Tests

The average speed and idle time from all recording periods and days at the signalized intersection and roundabout were compared in Two-Sample T-Tests. There were 40 two-sample t-tests since the tests compares average speeds for the same intersection at different times of the day, or at the same time on different days; or between different intersections at the same time, or different times of a day, or at the same time on different days.

The null hypothesis used when comparing the signalized intersection to roundabout data was that average speeds are not significantly different at the roundabout intersection and the signalized intersection. The alternative hypothesis was that average speeds were significantly higher at the roundabout than at the signalized intersection. In order to reject the null hypothesis, there would have to be a significance level of p=0.05 or less (i.e. p is smaller than 0.05). In conducting the two sample t-tests, the Levene's test is also performed over the equality of variance between two samples being compared. If the "Levene's test of Equality of Variances" is significant at the p= 0.05 level, the null hypothesis that the two samples have equal variance was rejected and the test that is based on the non-equal variance was used indstead. The Levene's test is applied to all t-tests in the study. These hypotheses were used for all eight t-test run with speed data for each recording time on May 29 and May 31.

When comparing different recording periods at the same intersection on the same day the null hypothesis was that the average speeds during both recording periods are not significantly different. The alternative hypothesis is a one tailed test implying that the average speed at one intersection is higher than at the other one.

When comparing the same recording period on different recording days at the same intersection the null hypothesis was that the average speeds during both recording periods are not significantly different. The alternative hypothesis is again a one tailed test implying that the average speed at one intersection is higher than at the other one.

In addition, 40 t-tests of two samples were run in order to calculate the average idle time and to determine if idle time is significantly different ($p=0.05$) at each intersection and recording period. Similarly to speed data, null and alternative were created. T-tests were run comparing different recording times within the same day at each intersection as well as same recording times of different days. When idle time was compared at the signalized intersection and roundabout the null hypothesis was that the average idle time at each intersection was not significantly different between the two intersections, while the alternative hypothesis was that the average idle time was significantly longer at the signalized intersection than at the roundabout.

When comparing different recording periods on the same recording day the null hypothesis was that the average idle time for both recording periods are not significantly different from each other while the alternative hypothesis was that the average idle time for both recording periods on the same recording day were significantly different. When comparing the same recording period on different recording days the null hypothesis was that the average idle time for both recording periods were not significantly different from each other. The alternative hypothesis was that the average idle times for both recording periods were significantly different.

Calculation of Fuel Consumption and CO_2 Emissions

A series of calculations were conducted to determine the fuel consumption and CO_2 emissions of each vehicle at the roundabout and signalized intersection. Fuel consumption and CO_2 amounts vary depending on the speed at which each car was traveling; consequently the speed of all vehicles had to be calculated. The formula, $\frac{d}{t} = r$, was used to determine the speed all vehicles traveled through both intersections. The symbols in the formula above stand for the following; d is distance, t is time, and r is the rate that it traveled. The distance each vehicle had traveled was divided by the amount of time in the intersection. The exit distances for both intersections were measured using ArcGIS measuring tools. These distances were calculated from the point of entrance to the point of exit for each exit option. Table 1 below shows the exit distances at each intersection from the point of entrance to point of exit for the first, second, and third exit at the roundabout and left, straight, or right at the signalized intersection.

Intersection	Distance (ft)	Roundabout	Distance (ft)
Right	42.0	First Exit	95.0
Straight	100.0	Second Exit	212.0
Left	92.5	Third Exit	317.0

Table 1: Signalized Intersection and Roundabout Exit Distances

All vehicles were then divided by which exit was used as each distance varied in order to determine the speed. The average speed was calculated based on all vehicles that traveled through an intersection for a specific recording time. I used a two-sample t-test in order to determine the average speed and determine whether the speeds were significantly different ($p = 0.05$) between each intersection during all recording times. Once the average speed for each intersection was determined, the fuel consumption and CO_2 emissions were calculated using the average speed.

The burning of fossil fuels is essentially what creates CO_2 and other GHG thus in order to calculate CO_2 emissions, it was essential to first determine the amount of fuel consumed by all vehicles at each intersection. Since fuel consumption varies depending on the speed each car is traveling, the Wisconsin Transportation Economic Analysis Guidelines (2014), provided a table with miles per gallon (MPG) and gallons per mile (gal/mi) values for speeds of five miles per hour (MPH) to 80 MPH. Table 2 below shows the Operating Speed vs. Fuel Economy rates that were used in calculating fuel consumption and CO_2 emissions for this study (Wisconsin Transportation 2014).

Operating Speed vs. Fuel Economy for Autos and Trucks				
Speed (mph)	Auto MPG*	Truck MPG**	Auto Gal/Mile	Truck Gal/Mile
0	0.00	0.00	∞	∞
5	11.50	2.89	0.0866	0.346
10	19.30	4.83	0.0518	0.207
15	24.60	6.14	0.0407	0.163
20	28.00	6.99	0.0358	0.143
25	30.00	7.50	0.0333	0.133
30	31.10	7.79	0.0321	0.128
35	31.70	7.93	0.0315	0.126
40	31.90	7.98	0.0313	0.125
45	32.00	7.99	0.0313	0.125
50	31.90	7.96	0.0314	0.126
55	31.60	7.89	0.0317	0.127
60	30.90	7.74	0.0323	0.129
65	29.80	7.44	0.0336	0.134
70	27.70	6.92	0.0361	0.145
75	24.20	6.06	0.0413	0.165
80	19.00	4.74	0.0528	0.211

Table 2: Operating Speed vs. Economy for Autos and Trucks. Source: Wisconsin Transportation (2014)

These values were converted from gal/mi to milliliters (mL) per mile and the corresponding value was then applied to the average speed at each intersection to determine the amount of fuel consumed in mL per mile. If there was a vehicle that traveled at a speed not indicated in Table 2, their speeds were plotted on a fitted graph, provided by the Wisconsin Transportation Analysis Guidelines, to get the estimated MPG. Once the MPG was found, fuel consumption calculations were conducted to find the fuel consumption in gal/mi values. They were then converted into milliliters per mile. Figure 8 was used in order to calculate MPG for the corresponding MPH that was not provided by the Wisconsin Transportation Analysis Guidelines. Table 3 below was created for vehicles whose speeds were not included in the guidelines.

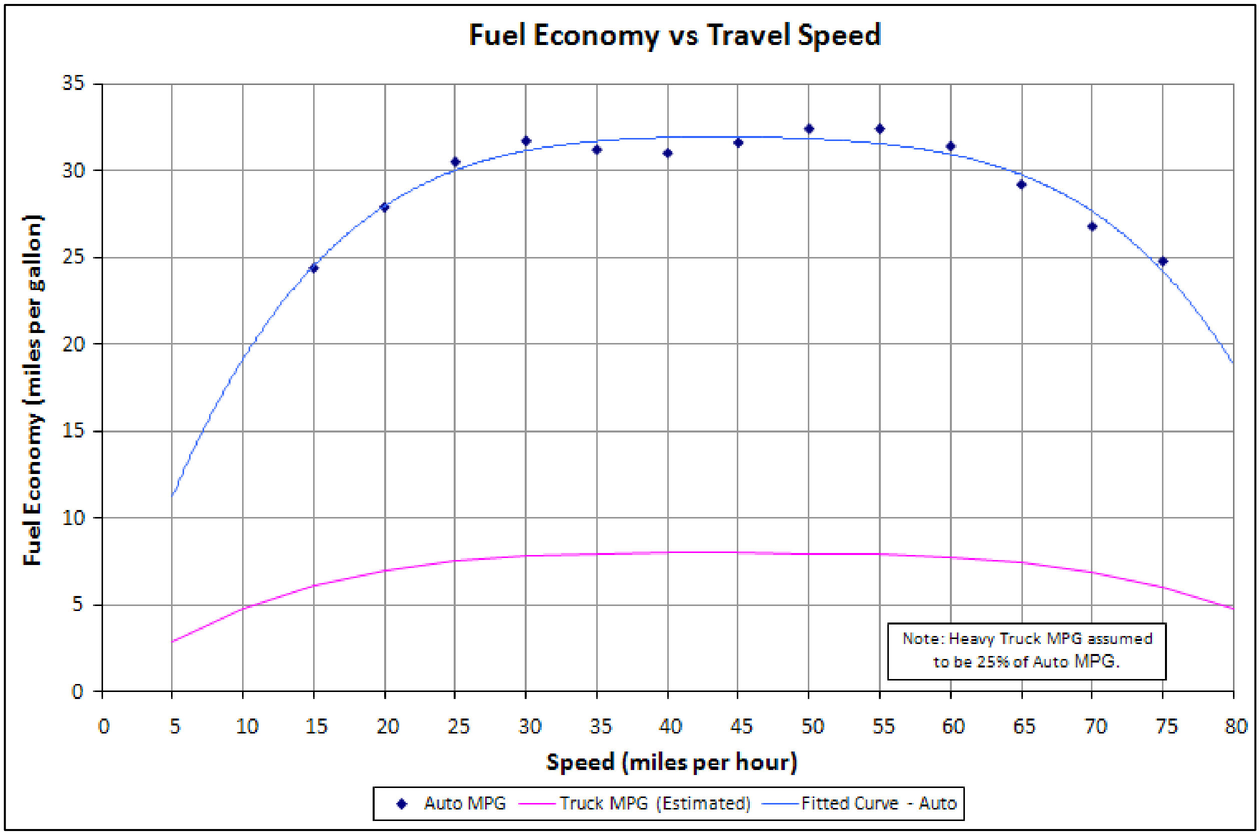

Figure 8: Fuel Economy vs. Travel Speed Graph. Source: Wisconsin Transportation 2014.

MPH	MPG	gal/mi	MPH	MPG	gal/mi
3	8.2	0.1220	**28**	31.0	0.0323
5	11.5	0.0867	**29**	31.0	0.0323
6	12.5	0.0800	**30**	31.1	0.0321
7	13.0	0.0769	**31**	31.3	0.0319
8	15.0	0.0667	**32**	31.4	0.0318
9	17.5	0.0571	**33**	31.6	0.0316
10	19.3	0.0518	**34**	31.6	0.0316
11	20.0	0.0500	**35**	31.7	0.0315
12	21.0	0.0476	**36**	31.7	0.0315
13	22.9	0.0437	**37**	31.8	0.0314
14	24.0	0.0417	**38**	31.8	0.0314
15	25.8	0.0388	**39**	31.8	0.0314
16	26.9	0.0372	**40**	31.9	0.0313
17	27.2	0.0368	**41**	31.9	0.0313
18	27.3	0.0366	**42**	31.9	0.0313
19	27.8	0.0360	**43**	32.0	0.0313
20	28.0	0.0357	**44**	32.0	0.0313
21	28.5	0.0351	**45**	32.0	0.0313
22	29.0	0.0345	**46**	32.0	0.0313
23	29.3	0.0341	**47**	31.9	0.0313
24	29.8	0.0336	**48**	31.9	0.0313
25	30.0	0.0333	**49**	31.9	0.0313
26	30.6	0.0327	**50**	31.9	0.0313
27	30.9	0.0324			

Table 3: Additional MPH to MPG Calculations.

The average speed was used instead of calculating each vehicles fuel consumption and CO_2 emissions to reduce the amount of error created by calculation. If fuel consumption and CO_2 emissions were calculated for all vehicles there would be more room for error as the amount of calculations increases significantly. Akçelik and Besley (2003) indicated that there is 2.5 grams (g) of CO_2 per milliliter. Thus, 2.5 g was multiplied by the average fuel consumption in mL per mile in order to determine the average amount of CO_2 grams per mile. Then, the average distance traveled during the specific recording period (in miles), at each intersection was multiplied by the CO_2 emissions in grams per mile in order to obtain grams of CO_2.

The distance traveled at roundabout is significantly longer than at the signalized intersection, which ultimately would lead to more CO_2 emissions emitted at the roundabout. In order to account for the difference in distance traveled, a distance adjustment was used to create a more accurate comparison. From the center of the signalized intersection to the boundary, it is 50 feet. From the center of the roundabout to the boundary is 72 feet. In order to make the distance traveled at the signalized intersection close to the roundabout, a total of 44 feet, 22 feet for each side of the signalized intersection, was added to the average distance traveled at the signalized intersection for each recording time in order to make a better comparison of CO_2 emissions at each intersection. Figure 9 below indicates how the distance adjustment was calculated.

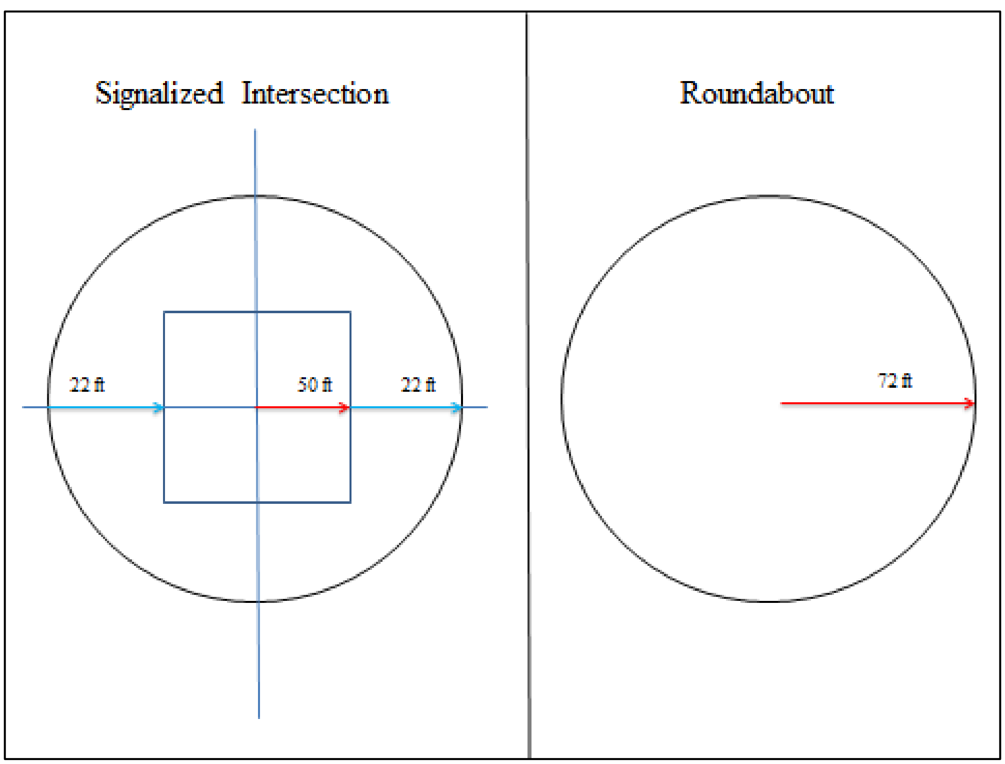

Figure 9: Distance Adjustment of the Signalized Intersection. An adjustment was used for a more accurate comparison between intersections. Source: Author.

Idle time at each intersection was used to calculate additional fuel consumption and CO_2 emissions. Akçelik and Besley (2003) provided an average idle fuel consumption rate of 1350 mL/h, which had to be converted into mL/sec (0.375 mL/sec). This value was multiplied by the average time (in seconds) each vehicle idled at each intersection during the different recording times. After the fuel consumption in milliliters was calculated, the same CO_2 emissions value of 2.5 g/mL was applied to each average fuel consumption values of the different recording times to get the amount of CO_2 emissions in grams.

T-Test CO_2 Emissions Calculations

If the t-test results indicated that it was not significant, it could be assumed that the average speed or the average idle time during both recording periods are of equal variance; or in other words, are the same. As a result, the average speeds or average idle times used in the t-tests were then used to create an average speed or average idle time between the two recording periods in order to calculate CO_2 emissions. Once the average speed or idle time of the averages from the t-tests was determined, the new average was used in order to calculate fuel consumption and CO_2 the same way it was calculated for t-tests that were significant.

Limitations

While conducting the literature review, it was evident that there are varying approaches to conducting this type study. Many researchers used traffic count data to determine CO_2 emissions (Höglund and Niittymäki 1998; Isebrands and Hallmark 2006; Cerdeira et al. 2007; Ahn et al. 2009; Ariniello and Przybyl 2010). In addition to traffic count data, these researchers also analyzed the manners of driving at each type of intersections, specifically examining deceleration, acceleration, and idle time. Unfortunately, I did not have access to necessary computer programs, such as aaSIDRA, to analyze the driving patterns and calculate fuel consumption and emissions. This is a limitation of this study as some studies suggest that driving patterns can significantly alter the amount of fuel consumption and vehicular emissions. In order to monitor driving behavior, I would need a large aerial view of both intersections to be able to see the driving patterns, which I was unable to obtain. In addition, I was not able to gather *in situ* CO_2 emissions. Alternatively, these emission levels were estimated based on calculations provided by Wisconsin Transportation Economic Analysis Guidelines and aaSIDRA. It would be ideal to be able to gather CO_2 levels at each intersection, but I did have access to a tool that could provide those services.

In addition, since the original methodology of this thesis used combined aspects of calculating emissions from two different sources it must be noted that this can lead to conversion differences because of the different standards of the different researchers, which ultimately leads to inaccuracy with calculations.

CHAPTER IV

RESULTS

Introduction

The objectives of this study were to analyze average and compare CO_2 emissions at a roundabout and signalized intersection. There were three main research questions asked to fulfill these objectives, which were (1) In which type of intersection do vehicles produce less carbon dioxide emissions? (2) Do carbon dioxide emissions vary during different hours of the day at each type of intersection? (3) Do carbon dioxide emissions vary during different days of the week at each type of intersection? To answer these questions, data were collected at the different intersections, and sample average driving speeds and idle times were collected and tested for significance. In addition, the CO_2 emissions are calculated based on the test results and conversion factors. This chapter reports these empirical results.

Average Driving Speeds and Average Idle Times

Data were collected by recording traffic at the signalized intersection and at the roundabout simultaneously for all recording times and recording days. After traffic was recorded, the duration each vehicle was in each intersection as well as idle time of each vehicle that idled was extracted. The duration of driving time in each intersection was used in order to calculate the average speed at the signalized intersection and roundabout to determine CO_2 emissions. The idle time was extracted to account for additional CO_2 emissions at each intersection.

Table 4 below indicates the number of vehicles that drove through each intersection and the average miles per hour (MPH) for each five-minute recording period. Table 5 below indicates how many vehicles idled and the duration of idle time during data collection for all recording periods and days at both intersections.

Date	Time	Number of Vehicles (Signal/Roundabout)	Mean Speed (MPH)
5/29/2014	0715	155/195	17.655/19.707
	0815	110/180	14.328/18.556
	1615	133/170	17.012/18.097
	1715	118/142	16.984/17.966
5/31/2014	0715	32/49	17.306/19.040
	0815	48/73	18.039/18.604
	1615	93/103	16.310/18.224
	1715	78/112	16.707/18.373

Table 4: Vehicle Amounts and Mean Speeds at both Intersections. The table provides the total amount of vehicles that drove through each intersection for all recording times. The average MPH is also indicated for the signalized intersection and roundabout for both recording days and all recording times.

Date	Time	Number of Vehicles (Signal/Roundabout)	Mean Idle Time
5/29/2014	0715	155/195	2.738/0.413
	0815	110/180	7.864/0.429
	1615	133/170	5.768/0.772
	1715	118/142	7.967/0.331
5/31/2014	0715	32/49	2.135/0.386
	0815	48/73	3.665/0.200
	1615	93/103	6.767/0.523
	1715	78/112	4.490/0.191

Table 5: Vehicle Amounts and Mean Idle Time at both Intersections. The table provides the total amount of vehicles that drove through each intersection for all recording times. The average idle time is also indicated for the signalized intersection and roundabout for both recording days and all recording times.

Figure 10 below indicates the average speeds at each intersection for each recording period during the May 29 recording day. Figure 11 indicates the average speeds for both intersections for all recording periods on May 31.

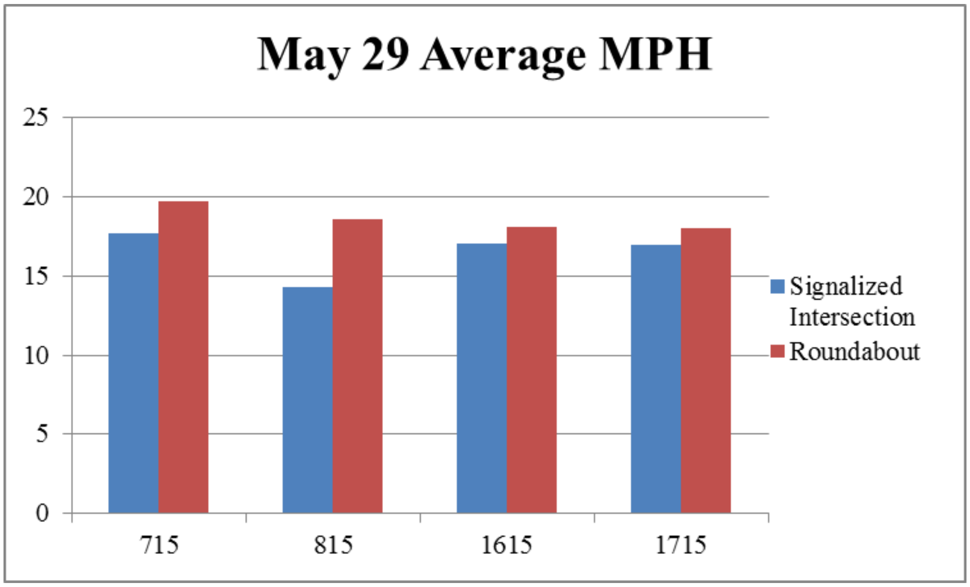

Figure 10: Average Speed for All Recording Periods at both Intersections on May 29.

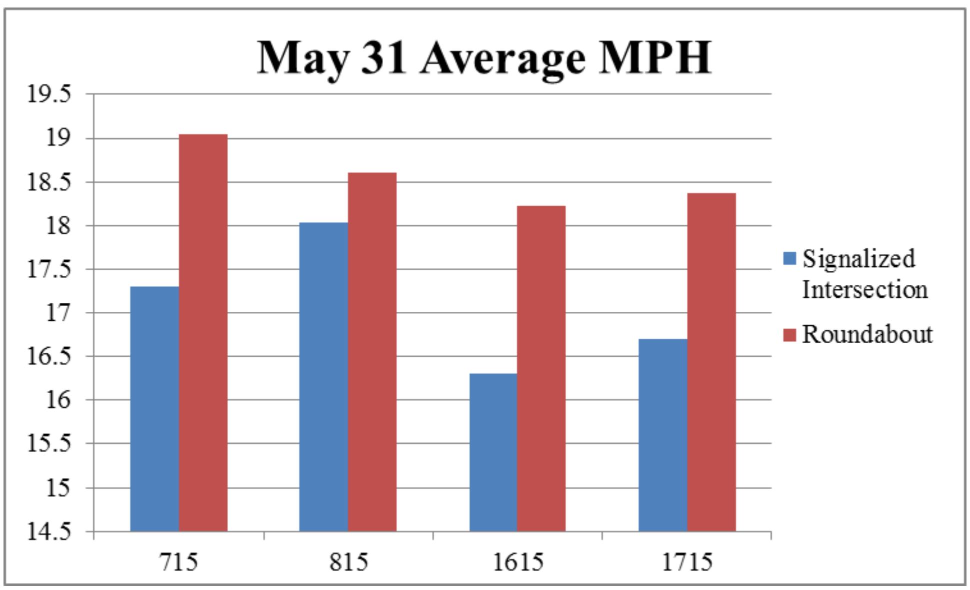

Figure 11: Average Speed for All Recording Periods at both Intersections on May 31.

Figure 12 indicates the average idle time at the signalized intersection and roundabout on May 29. Figure 13 below displays the average idle time at the signalized intersection and the roundabout for all recording periods on May 31.

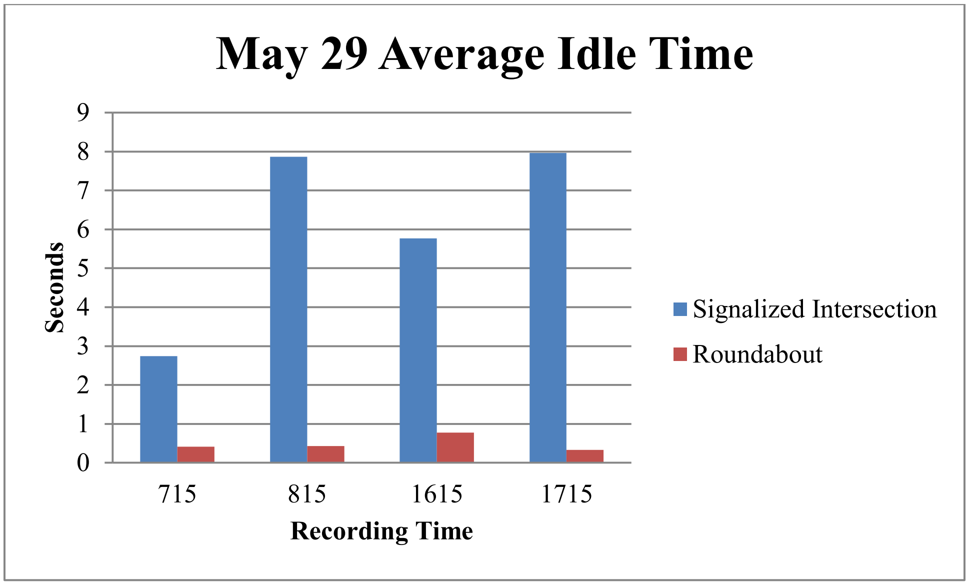

Figure 12: Average Idle Time for All Recording Periods at both Intersections on May 29.

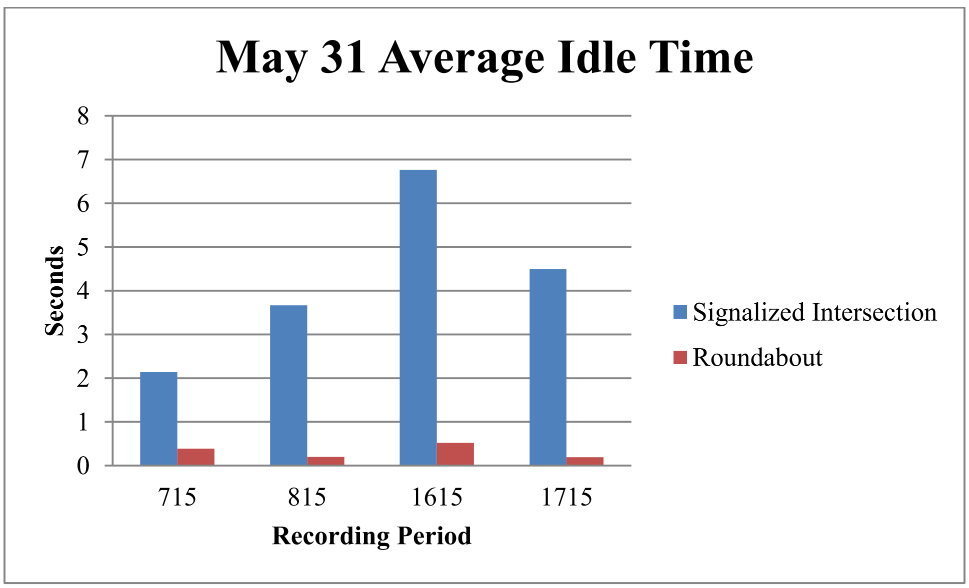

Figure 13: Average Idle Time for All Recording Periods at both Intersections on May 31.

Two-Sample T-Test Results

In this study, the emission is the result two factors: driving speed within an intersection and idle time at the intersection. Thus, the difference in these two factors at the different intersections, and at different times and days of the same intersection may have significant impact on the emissions. Since the data collected represent only samples of average speeds and idle times, the significance test is conducted to evaluate whether the population average speeds and idle times are significantly different between different intersections, and between different times and days at the same intersection. To this purpose, two-sample t-tests, also known as Independent Samples t-tests, were conducted using SPSS. Speed and idle time data were analyzed by comparing the signalized intersection data to the roundabout data for all recording periods and recording days. The two-sample t-tests were also used to compare different recording periods on the same day at both intersection and to compare the same recording periods on different recording days at both intersections. These t-tests were used in order to answer all research questions.

Two-Sample T-Tests Speed Data (Signalized Intersection to Roundabout)

To address Research Question 1, there were eight two-sample t-tests run with speed data. These eight t-tests were used to compare the same recording period at the signalized intersection and roundabout for both recording days. Of the eight t-tests that were run, five were significant and three were not significant. Table 6 below indicates the significant and non-significant t-tests results for speed data on May 29. In Table 7 indicates the significant and non-significant t-test results for speed data on May 31.

Time	Intersection	Number of Vehicles	Mean Speeds	Levene's Test p-value	df	one tailed p-value
0715	Signalized vs. Roundabout	155 vs. 195	17.654 vs. 19.707	0.000*	348	0.000*
0815	Signalized vs. Roundabout	110 vs. 180	14.327 vs. 18.555	0.036*	207	0.000*
1615	Signalized vs. Roundabout	133 vs. 170	17.011 vs. 18.096	0.000*	192	0.040*
1715	Signalized vs. Roundabout	118 vs. 142	16.984 vs. 17.966	0.000*	187	0.086

Table 6: May 29 T-Test Results of Speed for both Intersections. Two-Sample t-test results for mean speeds for observations on May 29 at the signalized intersection and roundabout. *Significant at 0.05 level.

Time	Intersection	Number of Vehicles	Mean Speeds	Levene's Test p-value	df	one tailed p-value
0715	Signalized vs. Roundabout	32 vs. 49	17.306 vs. 19.040	0.001*	44	0.137
0815	Signalized vs. Roundabout	48 vs. 73	18.038 vs. 18.604	0.000*	64	0.304
1615	Signalized vs. Roundabout	93 vs.103	16.399 vs. 18.224	0.000*	127	0.009*
1715	Signalized vs. Roundabout	78 vs. 112	16.707 vs. 18.372	0.000*	119	0.025*

Table 7: May 31 T-Test Results of Speed for both Intersections. Two-Sample t-test results for mean speeds for observations on May 31 at the signalized intersection and roundabout. *Significant at the 0.05 level.

The five significant t-tests will be discussed below. The two sample t-tests run with SPSS provided the Levene's Test to test whether the variance of two populations are the same based on the two samples. It also provides the two sample t-test under either assumption. As a result, if the Levene's Test for Equality of Variances were not significant, then the equal variances were assumed. Otherwise, the equal variances were not assumed, as indicated with an asterisk (*) in the reporting tables. The last column of the reporting tables lists the result consistent with the Levene's test. That is, if the Levene's Test is not significant, it reports the two sample test assuming the same variance of the two population average speeds. On the other hand, if the Levene's Test is significant, it reports the two sample test assuming the different variance of the two population average speeds. The null hypothesis is that two population average speeds are not significantly different from each other. The alternative hypothesis is that the average speed at the roundabout is higher than that at the signalized intersection. Significant values ($p < 0.05$) are noted in bold. These general conditions are reflected in Tables 6 and 7 on the test on average speeds. They are also reflected in all tables reporting the two sample t-test results later in the text. It is apparent that, of the eight pairs of relationships tested, only in three pairs is the roundabout average speed not significantly faster than the signalized intersection at the 0.05 level, including May

29 at 1715, and May 31 at 0715 and 0815. In all other five pairs, the roundabout average speed is significantly faster than that at the signalized intersection at the 0.05 level.

May 29 (WD) Two-Sample T-Tests for Speed Data (Signalized to Signalized; Roundabout to Roundabout)

In order to answer Research Question 2 (do carbon dioxide emissions vary during different hours of the day at each type of intersection?), twelve t-tests were run to compare different recording periods on May 29 at the signalized intersection and at the roundabout. The general conditions regarding the Levene's Test is the same as discussed previously, and the t-test results listed are also consistent with the Levene's Test, as discussed previously. The alternative hypothesis is that average speed of one recording period is higher than the other. As can be seen in Table 8, of the 6 pairs of relationships tested on May 29 for the signalized intersection, three pairs show significant difference in average speed between different times at the 0.05 level of the day, between 0715 and 0815, between 0715 and 1715, and between 0815 and 1615, respectively.

Time	Intersection	Number of Vehicles	Mean Speeds	Levene's Test p-value	df	one tailed p-value
0715 vs. 0815	Signalized vs. Signalized	115 vs. 110	17.654 vs. 14.327	0.029*	261	0.000*
1615 vs. 1715	Signalized vs. Signalized	133 vs. 118	17.011 vs. 16.983	0.429	249	0.486
0715 vs. 1615	Signalized vs. Signalized	155 vs. 133	17.654 vs. 17.011	0.629	286	0.216
0815 vs. 1715	Signalized vs. Signalized	110 vs. 118	14.327 vs. 16.983	0.008*	223	0.000*
0715 vs 1715	Signalized vs. Signalized	155 vs. 118	17.654 vs. 16.983	0.812	271	0.220
0815 vs. 1615	Signalized vs. Signalized	110 vs. 133	14.327 vs. 17.011	0.047*	240	0.000*

Table 8: May 29 T-Test Results of Speed for Signal Comparison. Two-Sample t-test results for mean speeds for observations on May 29 at the Signalized Intersection. *Significant at the 0.05 level.

Similarly, there were six t-tests run for the roundabout comparison on May 29. Of the six t-tests, three were significant and three were not significant. Table 9 below indicates the t-test results of roundabout comparison on May 29. As can be seen in Table 9, of the 6 pairs of relationships tested on May 29 for the Roundabout, three pairs show significant difference in average speed between different times at the 0.05 level of the day, between 0715 and 0815, between 0715 and 1615, and between 0715 and 17:15, respectively.

Time	Intersection	Number of Vehicles	Mean Speeds	Levene's Test p-value	df	one tailed p-value
0715 vs. 0815	Roudabout vs. Roundabout	195 vs. 180	19.707 vs. 18.555	0.489	373	0.006*
1615 vs. 1715	Roudabout vs. Roundabout	170 vs. 142	18.096 vs. 17.965	0.048*	275	0.383
0715 vs. 1615	Roudabout vs. Roundabout	195 vs. 170	19.707 vs. 18.096	0.448	363	0.000*
0815 vs. 1715	Roudabout vs. Roundabout	180 vs. 142	18.555 vs. 17.965	0.744	320	0.128
0715 vs 1715	Roudabout vs. Roundabout	195 vs. 142	19.707 vs. 17.965	0.204	335	0.000*
0815 vs. 1615	Roudabout vs. Roundabout	180 vs. 170	18.555 vs. 18.096	0.221	348	0.159

Table 9: May 29 T-Test Results of Speed for Roundabout Comparison. Two-Sample t-test results for mean speeds for observations on May 29 at the roundabout. *Significant at the 0.05 level.

May 31 (WE) Two-Sample T-Tests for Speed Data (Signalized to Signalized; Roundabout to Roundabout)

Similarly, in order to answer Research Question 2 (do carbon dioxide emissions vary during different hours of the day at each type of intersection?), twelve two-sample t-tests were conducted to compare different recording periods on May 31 at the signalized intersection (Table 10) and roundabout (Table 11). The alternative hypothesis was that one of the average speeds is significantly higher than the other. All twelve t-tests were not significant.

Time	Intersection	Number of Vehicles	Mean Speeds	Levene's Test p-value	df	one tailed p-value
0715 vs. 0815	Signalized vs. Signalized	32 vs. 48	17.306 vs. 18.038	0.394	78	0.333
1615 vs. 1715	Signalized vs. Signalized	93 vs. 78	16.399 vs. 16.707	0.513	169	0.380
0715 vs. 1615	Signalized vs. Signalized	32 vs. 93	17.306 vs. 16.399	0.204	123	0.267
0815 vs. 1715	Signalized vs. Signalized	48 vs. 78	18.038 vs. 16.707	0.362	124	0.137
0715 vs 1715	Signalized vs. Signalized	32 vs. 78	17.306 vs. 16.707	0.087	108	0.340
0815 vs. 1615	Signalized vs. Signalized	48 vs. 93	18.038 vs 16.399	0.715	139	0.090

Table 10: May 31 T-Test Results of Speed for Signal Comparison. Two-sample t-test results for mean speeds for observations on May 31 at the Signalized Intersection. *Significant at the 0.05 level.

Time	Intersection	Number of Vehicles	Mean Speeds	Levene's Test p-value	df	one tailed p-value
0715 vs. 0815	Roundabout vs. Roundabout	49 vs. 73	19.040 vs.18.604	0.032	88	0.288
1615 vs. 1715	Roundabout vs. Roundabout	103 vs. 112	18.224 vs. 18.372	0.021	209	0.380
0715 vs. 1615	Roundabout vs. Roundabout	49 vs. 103	19.040 vs. 18.224	0.003	71	0.130
0815 vs. 1715	Roundabout vs. Roundabout	73 vs. 112	18.604 vs. 18.372	0.120	183	0.345
0715 vs 1715	Roundabout vs. Roundabout	49 vs. 112	19.040 vs. 18.372	0.271	159	0.175
0815 vs. 1615	Roundabout vs. Roundabout	73 vs.103	18.604 vs. 18.224	0.738	174	0.231

Table 11: May 31 T-Test Results of Speed for Roundabout Comparison. Two-Sample t-test results for mean speeds for observations on May 31 at the roundabout. *Significant at the 0.05 level.

May 29 (WD) and 31(WE) Comparison of Two-Sample T-Tests Speed Data (Signalized to Signalized; Roundabout to Roundabout)

In order to answer Research Question 3, (do carbon dioxide emissions vary during different days of the week at each type of intersection?), t-tests were run comparing the same recording periods on May 29 to May 31. The Levene's Test for equal variance assumption is the same as discussed previously. The alternative hypothesis is that one of the average speeds is higher than the other. A total of eight t-tests were run. Four t-tests were run using the signalized intersection data (Table 12) and four t-tests were run using the roundabout data (Table 13). At the signalized intersection, one test was significant and three t-tests were not significant. At the roundabout, all t-tests were not significant. Table 12 below indicates the t-tests results for the May 29 to May 31 comparison.

Time	Intersection	Number of Vehicles	Mean Speeds	Levene's Test p-value	df	one tailed p-value
May 29 vs. May 31 - 0715	Signalized vs. Signalized	155 vs. 32	17.654 vs. 17.306	0.226	185	0.405
May 29 vs. May 31 - 0815	Signalized vs. Signalized	110 vs. 48	14.327 vs. 18.038	0.021*	156	0.000*
May 29 vs. May 31 - 1615	Signalized vs. Signalized	133 vs. 93	17.011 vs. 16.399	0.529	224	0.245
May 29 vs. May 31 - 1715	Signalized vs. Signalized	118 vs. 78	16.983 vs. 16.707	0.429	194	0.387

Table 12: May 29 and 31 T-Test Results of Speed for Signal Comparison. Two-Sample t-test results for mean speeds for observations on May 29 and 31 at the Signalized Intersection. *Significant at the 0.05 level.

Time	Intersection	Number of Vehicles	Mean Speeds	Levene's Test p-value	df	one tailed p-value
May 29 vs. May 31 - 0715	Roundabout vs. Roundabout	195 vs. 49	19.707 vs. 19.040	0.054	66	0.173
May 29 vs. May 31 - 0815	Roundabout vs. Roundabout	180 vs. 73	18.555 vs. 18.604	0.316	251	0.470
May 29 vs. May 31 - 1615	Roundabout vs. Roundabout	170 vs. 103	18.096 vs. 18.244	0.463	271	0.380
May 29 vs. May 31 - 1715	Roundabout vs. Roundabout	142 vs. 112	17.965 vs. 18.372	0.529	224	0.245

Table 13: May 29 and 31 T-Test of Speed for Roundabout Comparison. Two-sample t-test results for mean speeds for observations on May 29 and 31 at the roundabout. *Significant at the 0.05 level.

May 29 (WD) and 31(WE) Two-Sample T-test Idle Data (Signalized Intersection to Roundabout)

In addition to speed data two-sample t-tests, the same types of tests were used for the vehicles idle time at each intersection. Eight two-sample t-tests were run comparing idle time at the signalized intersection and roundabout for each recording period. Again, the Levene's Test is conducted for the equal variance assumption of the two populations. If the assumption is not supported, the t-test result under the non-equal variance assumption is used. The null hypothesis is that two populations idle times are not significantly different from each other; the alternative hypothesis was that idle time at the signalized intersection is significantly longer than that at the roundabout. Significant values ($p < 0.05$) are noted in bold. As can be seen in Tables 14 and 15, all eight pairs of relationships tested demonstrate significance difference at the 0.05 level.

Time	Intersection	Number of Vehicles	Mean Idle Time	Levene's Test p-value	df	one tailed p-value
0715	Signalized vs. Roundabout	155 vs. 195	2.738 vs. 0.413	0.000*	161	0.000*
0815	Signalized vs. Roundabout	110 vs. 180	7.864 vs. 0.429	0.000*	111	0.000*
1615	Signalized vs. Roundabout	133 vs. 170	5.768 vs. 0.770	0.000*	138	0.000*
1715	Signalized vs. Roundabout	118 vs. 142	7.967 vs. 0.331	0.000*	119	0.000*

Table 14: May 29 T-Test Results of Idle Time for both Intersections. Two-sample t-test results for mean idle time (in seconds) at both intersections for observations on May 29. *Significant at the 0.05 level.

Time	Intersection	Number of Vehicles	Mean Idle Time	Levene's Test p-value	df	one tailed p-value
0715	Signalized vs. Roundabout	32 vs. 49	2.135 vs. 0.386	0.000*	37	0.017*
0815	Signalized vs. Roundabout	48 vs. 73	3.665 vs. 0.200	0.000*	48	0.000*
1615	Signalized vs. Roundabout	93 vs.103	6.767 vs. 0.523	0.000*	96	0.000*
1715	Signalized vs. Roundabout	78 vs. 112	4.490 vs. 0.191	0.000*	78	0.000*

Table 15: May 31 T-Test Results of Idle Time for both Intersections. Two-sample t-test results for mean idle time (in seconds) at both intersections for observations on May 31. *Significant at the 0.05 level.

May 29 (WD) Two-Sample T-Test Idle Data (Signalized to Signalized; Roundabout to Roundabout)

Similarly, in order to answer Research Question 2 (do carbon dioxide emissions vary during different hours of the day at each type of intersection?), twelve t-tests were run to compare idle data for different recording periods on May 29 at the signalized intersection and at the roundabout. The alternative hypothesis was that idle time at one intersection was longer than the other. Of the twelve t-tests, six were significant and six were not significant. Three were significant during the May 29 signalized intersection comparisons (Table 16) and three were significant during the May 29 roundabout comparisons (Table 17).

Time	Intersection	Number of Vehicles	Mean Idle Times	Levene's Test p-value	df	one tailed p-value
0715 vs. 0815	Signalized vs. Signalized	115 vs. 110	2.738 vs. 7.864	0.000*	263	0.000*
1615 vs. 1715	Signalized vs. Signalized	133 vs. 118	5.768 vs. 7.967	0.044*	249	0.109
0715 vs. 1615	Signalized vs. Signalized	155 vs. 133	2.738 vs. 5.768	0.000*	286	0.008*
0815 vs. 1715	Signalized vs. Signalized	110 vs. 118	7.864 vs. 7.967	0.760	226	0.479
0715 vs 1715	Signalized vs. Signalized	155 vs. 118	2.738 vs. 7.967	0.000*	271	0.000*
0815 vs. 1615	Signalized vs. Signalized	110 vs. 133	7.864 vs. 5.768	0.024*	241	0.126

Table 16: May 29 T-Test Results of Idle Time for Signal Comparison. Two-Sample t-test results for mean idle time for May 29 at the signalized intersection. *Significant at the 0.05 level.

Time	Intersection	Number of Vehicles	Mean Idle Times	Levene's Test p-value	df	one tailed p-value
0715 vs. 0815	Roudabout vs. Roundabout	195 vs. 180	0.413 vs. 0.429	0.82	372	0.460
1615 vs. 1715	Roudabout vs. Roundabout	170 vs. 142	0.771 vs. 0.033	0.000*	289	0.021*
0715 vs. 1615	Roudabout vs. Roundabout	195 vs. 170	0.413 vs. 0.771	0.000*	272	0.035*
0815 vs. 1715	Roudabout vs. Roundabout	180 vs. 142	0.429 vs. 0.331	0.299	319	0.292
0715 vs 1715	Roudabout vs. Roundabout	195 vs. 142	0.413 vs. 0.331	0.302	335	0.294
0815 vs. 1615	Roudabout vs. Roundabout	180 vs. 170	0.429 vs. 0.771	0.002*	321	0.056*

Table 17: May 29 T-Test Results of Idle Time for Roundabout Comparison. Two-sample t-test results for mean idle time for May 29 at the roundabout. *Significant at the 0.05 level.

May 31 (WE) Two-Sample T-Test Idle Data (Signalized to Signalized; Roundabout to Roundabout)

In order to answer Research Question 2 (do carbon dioxide emissions vary during different hours of the day at each type of intersection?), twelve t-tests were run to compare idle data for different recording periods on May 31 at the signalized intersection and at the roundabout. Of the twelve t-tests, six were significant and six were not significant. There were three significant and three not significant t-tests at the signalized intersection. The results to the May 31 recording period comparisons at the signalized intersection are located in Table 18 below.

Time	Intersection	Number of Vehicles	Mean Idle Times	Levene's Test p-value	df	one tailed p-value
0715 vs. 0815	Signalized vs. Signalized	32 vs. 48	2.135 vs. 3.665	0.047*	78	0.113
1615 vs. 1715	Signalized vs. Signalized	93 vs. 78	6.767 vs. 4.490	0.049*	168	0.090
0715 vs. 1615	Signalized vs. Signalized	32 vs. 93	2.135 vs.6.767	0.000*	122	0.015*
0815 vs. 1715	Signalized vs. Signalized	48 vs. 78	3.665 vs. 4.490	0.113	124	0.314
0715 vs 1715	Signalized vs. Signalized	32 vs. 78	2.135 vs. 4.490	0.008*	108	0.049*
0815 vs. 1615	Signalized vs. Signalized	48 vs. 93	3.665 vs. 6.767	0.000*	136	0.024*

Table 18: May 31 T-Test Results of Idle Time for Signal Comparison. Two-sample t-test results for mean idle time for May 31 at the signalized intersection. *Significant at the 0.05 level.

Time	Intersection	Number of Vehicles	Mean Idle Times	Levene's Test p-value	df	one tailed p-value
0715 vs. 0815	Roundabout vs. Roundabout	49 vs. 73	0.386 vs.0.200	0.108	120	0.217
1615 vs. 1715	Roundabout vs. Roundabout	103 vs. 112	0.523 vs. 0.191	0.001*	161	0.052*
0715 vs. 1615	Roundabout vs. Roundabout	49 vs. 103	0.386 vs. 0.523	0.428	150	0.326
0815 vs. 1715	Roundabout vs. Roundabout	73 vs. 112	0.200 vs. 0.191	0.942	183	0.475
0715 vs 1715	Roundabout vs. Roundabout	49 vs. 112	0.386 vs. 0.191	0.068	159	0.180
0815 vs. 1615	Roundabout vs. Roundabout	73 vs.103	0.200 vs. 0.523	0.007*	166	0.066

Table 19: May 31 T-Test Results of Idle Time for Roundabout Comparison. Two-sample t-test results for mean idle time for May 31 at the roundabout. *Significant at the 0.05 level.

May 29 (WD) and 31 (WE) Comparison of Two-Sample T-Test Idle Data (Signalized to Signalized; Roundabout to Roundabout)

Similarly, in order to answer Research Question 3, (do carbon dioxide emissions vary during different days of the week at each type of intersection?), t-tests were run comparing the same recording periods on May 29 to May 31 with idle data. There were eight t-tests run, two of the t-tests was significant while six were non-significant (Table 20 and Table 21). Four t-tests were run using the signalized intersection data and four t-tests were run using the roundabout data. Two of the four t-tests at the signalized intersection were significant.

Time	Intersection	Number of Vehicles	Mean Idle Times	Levene's Test p-value	df	one tailed p-value
May 29 vs. May 31 - 0715	Signalized vs. Signalized	155 vs. 32	2.738 vs. 2.135	0.234	185	0.339
May 29 vs. May 31 - 0815	Signalized vs. Signalized	110 vs. 48	7.864 vs. 3.665	0.000*	156	0.035*
May 29 vs. May 31 - 1615	Signalized vs. Signalized	133 vs. 93	5.765 vs. 6.767	0.866	224	0.279
May 29 vs. May 31 - 1715	Signalized vs. Signalized	118 vs. 78	7.967 vs. 4.490	0.001*	194	0.028*

Table 20: May 29 and 31 T-Test Results of Idle Time for Signal Comparison. Two-sample t-test results for mean idle time for observations on May 29 and May 31 at the signalized intersection. *Significant at the 0.05 level.

Time	Intersection	Number of Vehicles	Mean Idle Times	Levene's Test p-value	df	one tailed p-value
May 29 vs. May 31 - 0715	Roundabout vs. Roundabout	195 vs. 49	0.4315 vs. 0.3869	0.935	242	0.453
May 29 vs. May 31 - 0815	Roundabout vs. Roundabout	180 vs.73	0.4274 vs. 0.2005	0.047*	251	0.149
May 29 vs. May 31 - 1615	Roundabout vs. Roundabout	170 vs. 103	0.7764 vs. 0.5234	0.065	250	0.154
May 29 vs. May 31 - 1715	Roundabout vs. Roundabout	142 vs. 112	0.3312 vs. 0.1911	0.100	252	0.188

Table 21: May 29 and 31 T-Test Results of Idle Time for Roundabout Comparison**.** Two-sample t-test results for mean idle time for observations on May 29 and May 31 at the roundabout. *Significant at the 0.05 level.

Fuel Consumption and CO_2 Emissions Calculation Results

Fuel Consumption and CO_2 Emissions Calculations for Speed Data (Signalized to Roundabout)

In order to address Research Question 1 (in which type of intersection do vehicles produce less carbon dioxide emissions?), fuel consumption and CO_2 emissions were calculated using the average speed and idle time from corresponding t-tests for the signalized intersection and roundabout comparisons. Table 22 below indicates the calculations for fuel consumption and CO_2 emissions of speed data on the May 29 and May 31 signalized intersection to roundabout comparison.

Time_Date	Intersection	Average Speed (MPH)	Fuel Consumption (gal/mi)	Fuel Consumption (mL/mi)	CO2 Emissions (g/mi)	CO2 Emissions (g)
0715_29	Intersection	17.655	0.039	146.117	365.292	9.360
	Roundabout	19.707	0.036	136.275	340.687	13.675
0815_29	Intersection	14.328	0.042	157.852	394.629	9.818
	Roundabout	18.556	0.037	139.303	348.258	14.155
1615_29	Intersection	17.012	0.039	146.117	365.292	9.188
	Roundabout	18.096	0.037	139.303	348.258	13.787
1715_29	Intersection	17.475	0.039	146.117	365.292	9.214
	Roundabout	17.475	0.039	146.117	365.292	14.066
0715_31	Intersection	18.173	0.037	139.303	348.258	8.719
	Roundabout	18.173	0.037	139.303	348.258	13.256
0815_31	Intersection	18.322	0.037	139.303	348.258	9.076
	Roundabout	18.322	0.037	139.303	348.258	13.842
1615_31	Intersection	16.400	0.037	140.817	352.043	9.047
	Roundabout	18.224	0.037	139.303	348.258	13.927
1715_31	Intersection	16.707	0.037	140.817	352.043	9.022
	Roundabout	18.373	0.037	139.303	348.258	13.601

Table 22: May 29 and 31 Fuel Consumption and CO_2 Emissions of Speed at both Intersections. The values in blue indicate non-significant t-tests.

During the 0715 recording period on May 29 comparisons of speed data at the signalized intersection and roundabout, the average amount of fuel consumption at the signalized intersection was 146.116 mL/mi and was 136.274 mL/mi at the roundabout. The average amount of CO_2 emissions for the signalized intersection was 9.360 g while the roundabout had 13.675 g of CO_2. During the 0815 recording period, the average fuel consumption at the signalized intersection was 157.851 mL/mi and was 139.303 mL/mi at the roundabout. The average CO_2 emissions at the signalized intersection during the 0815 recording period was 9.817 g and was 14.154 g of CO_2.

During the 1615 recording period on May 29 at the signalized intersection, the average fuel consumption was 146.116 mL/mi and was 139.303 mL/mi at the roundabout. The average CO_2 at the signalized intersection was 9.187 g and was 13.786 g at the roundabout. The t-test results for the 1715 recording period were not significant therefore an average speed between the signalized intersection and the roundabout was used to calculate fuel consumption and CO_2. The average fuel consumption during the 1715 recording period was 146.116 mL/mi. At the signalized intersection, there was an average of 9.214 g of CO_2 and at the roundabout there was 14.066 g.

The t-tests results indicated that the 0715 recording period on May 31 comparing the signalized intersection and roundabout were not significantly different; therefore an average speed between both intersections was used to calculate fuel consumption and CO_2 emissions. The average fuel consumption was 139.303 mL/mi. The average CO_2 emission at the signalized intersection was 8.718 g and was 13.256 at the roundabout.

The t-test results indicated that the 0815 recording period on May 31 comparing the signalized intersection and roundabout were not significantly different; therefore an average speed between both intersections was used to calculate fuel consumption and CO_2 emissions.

The average fuel consumption was 139.303 mL/mi. The average CO_2 emission at the signalized intersection was 9.076 g and was 13.842 g at the roundabout.

During the 1615 recording period on May 31 at the signalized intersection, the average fuel consumption was 140.817 mL/mi and was 139.303 mL/mi at the roundabout. The average CO_2 emission at the signalized intersection was 9.046 g and was 13.927 at the roundabout. During the 1715 recording period on May 31 at the signalized intersection, the average fuel consumption was 140.817 mL/mi and was 139.303 mL/mi at the roundabout. The average CO_2 emission at the signalized intersection was 9.022 g and was 13.601 at the roundabout. The calculations of average fuel consumption and average CO_2 emissions from idling at the signalized intersection and roundabout on May 29 and May 31 will be indicated in Table 23 below.

Time_Date	Intersection	Average Idle Time(sec)	Fuel Consumption (mL)	CO2 Emissions (g)
0715_29	**Intersection**	2.738	1.027	2.567
	Roundabout	0.414	0.155	0.388
0815_29	**Intersection**	7.864	2.949	7.373
	Roundabout	0.430	0.161	0.403
1615_29	**Intersection**	5.768	2.163	5.408
	Roundabout	0.772	0.289	0.724
1715_29	**Intersection**	7.967	2.988	7.469
	Roundabout	0.331	0.124	0.311
0715_31	**Intersection**	2.135	0.801	2.002
	Roundabout	0.387	0.145	0.363
0815_31	**Intersection**	3.665	1.374	3.436
	Roundabout	0.201	0.075	0.188
1615_31	**Intersection**	6.767	2.538	6.344
	Roundabout	0.523	0.196	0.491
1715_31	**Intersection**	4.491	1.684	4.210
	Roundabout	0.191	0.072	0.179

Table 23: May 29 and 31 Fuel Consumption and CO_2 Emissions from Idle Time at both Intersections.

The average fuel consumption during the 0715 recording period on May 29 at the signalized intersection was 1.026 mL and was 0.155 mL at the roundabout. The average CO_2 emission at the signalized intersection was 2.566 g and was 0.387 g at the roundabout. During the 0815 recording period, the average fuel consumption at the signalized intersection was 2.949 mL and was 0.161 mL at the roundabout. The average CO_2 emissions at the signalized intersection during the 0815 recording period was 7.372 g and was 0.402 g at the roundabout.

During the 1615 recording period on May 29, the average fuel consumption at the signalized intersection was 2.163 mL and was 0.289 mL at the roundabout. The average CO_2 emission at the signalized intersection was 5.407 g and was 0.723 g at the roundabout. During the 1715 recording period at the signalized intersection, the average fuel consumption was 2.987 mL and was 0.124 mL at the roundabout. The average CO_2 emission at the signalized intersection was 7.469 g and was 0.310 g at the roundabout.

The total emissions at the signalized intersection and the roundabout for all recording times and days as well as the percentage of contribution of emissions from driving and idling are indicated in Table 24 below.

Time_Date	Intersection	Total Emissions (g)	Contribution from Driving	Contribution from Idling
0715_29	**Intersection**	11.927	78%	22%
	Roundabout	14.063	97%	3%
0815_29	**Intersection**	17.190	57%	43%
	Roundabout	14.558	97%	3%
1615_29	**Intersection**	14.595	63%	37%
	Roundabout	14.510	95%	5%
1715_29	**Intersection**	16.683	55%	45%
	Roundabout	14.377	98%	2%
0715_31	**Intersection**	10.720	81%	19%
	Roundabout	13.619	97%	3%
0815_31	**Intersection**	12.512	73%	27%
	Roundabout	14.030	99%	1%
1615_31	**Intersection**	15.391	59%	41%
	Roundabout	14.418	97%	3%
1715_31	**Intersection**	13.232	68%	32%
	Roundabout	13.781	99%	1%

Table 24: May 29 and 31 Average Total CO_2 for both Intersections. The table also indicates the percentage of contribution of driving and idling to CO_2 emissions.

The total CO_2 emissions during the 0715 recording period on May 29 at the signalized intersection, there was an average total of 11.927 g of CO_2 while it was 14.063 g at the roundabout. At the signalized intersection 78 percent of CO_2 emissions came from driving while 22 percent came from idling. At the roundabout 97 percent of CO_2 emissions came from driving while 3 percent came from idling.

During the 0815 recording period on May 29 at the signalized intersection an average total of 17.190 g of CO_2 was emitted while 14.558 g was emitted at the roundabout. At the signalized intersection, 57 percent of emissions were from driving while 43 percent was from idling. At the roundabout 97 percent of emissions were from driving and 3 percent were from idling.

During the 1615 recording period on May 29 at the signalized intersection there was an average total of 14.595 g of CO_2 emitted and there was an average total of 14.510 g at the roundabout. At the signalized intersection, 63 percent of emissions came from driving while 37 percent was from idling. At the roundabout, 95 percent of CO_2 emissions came from driving while 5 percent came from idling.

During the 1715 recording period on May 29 at the signalized intersection there was an average total of 16.683 g of CO_2 emitted and there was 14.377 g emitted at the roundabout. At the signalized intersection, 55 percent of CO_2 emissions came from driving while 45 percent came from idling. At the roundabout, 98 percent of emissions came from driving and 2 percent came from idling.

During the 0715 recording period on May 31 at the signalized intersection there was an average total of 10.720 g of CO_2 emitted and there was 13.619 g at the roundabout. At the signalized intersection, 81 percent of CO_2 emissions came from driving while 19 percent came from idling. At the roundabout, 97 percent of CO_2 emissions came from driving while 3 percent came from idling.

During the 0815 recording period on May 31 at the signalized intersection there was an average total of 12.512 g of CO_2 emitted and there was 14.030 g at the roundabout. At the signalized intersection, 73 percent of CO_2 emissions came from driving while 27 percent came from idling. At the roundabout, 99 percent of CO_2 emissions came from driving while 1 percent came from idling.

During the 1615 recording period on May 31 at the signalized intersection there was an average total of 15.391 g of CO_2 emitted and there was 14.418 g at the roundabout. At the signalized intersection, 59 percent of CO_2 emissions came from driving while 41 percent came from idling. At the roundabout, 97 percent of CO_2 emissions came from driving while 3 percent came from idling.

During the 1715 recording period on May 31 at the signalized intersection there was an average total of 13.232 g of CO_2 emitted and there was 13.781 g at the roundabout. At the signalized intersection, 68 percent of CO_2 emissions came from driving while 32 percent came from idling. At the roundabout, 99 percent of CO_2 emissions came from driving while 1 percent came from idling.

May 29 (WD) Fuel Consumption and CO_2 Calculations for Speed Data (Signalized to Signalized; Roundabout to Roundabout)

In order to address Research Question 2, (do carbon dioxide emissions vary during different hours of the day at each type intersection?), fuel consumption and CO_2 emissions were calculated based on the t-tests data comparing different recording times on the same recording day at both intersections. Table 25 below entails fuel consumption and CO_2 emissions calculations from recording period comparisons at the signalized intersection on May 29. The results of the fuel consumption and CO_2 emissions calculations for the signalized intersection recording period comparisons will be discussed below.

During the 0715 recording period on May 29, the average amount of fuel consumption was 146.116 mL/mi and was 157.852 mL/mi during the 0815 recording period. The average amount of CO_2 emissions during the 0715 recording period was 9.360 g while the average during the 0815 recording period was 9.818 g of CO_2.

Time_Date	Intersection	Average Speed (MPH)	Fuel Consumption (gal/mi)	Fuel Consumption (mL/mi)	CO2 Emissions (g/mi)	CO2 Emissions (g)
7:15_29	Intersection	17.655	0.039	146.117	365.292	9.360
8:15_29	Intersection	14.328	0.042	157.852	394.629	9.818
16:15_29	Intersection	17.243	0.039	146.117	365.292	9.190
17:15_29	Intersection	17.243	0.039	146.117	365.292	9.214
7:15_29	Intersection	17.333	0.039	146.117	365.292	9.360
16:15_29	Intersection	17.333	0.039	146.117	365.292	9.190
7:15_29	Intersection	17.564	0.039	146.117	365.292	9.360
17:15_29	Intersection	17.564	0.039	146.117	365.292	9.214
8:15_29	Intersection	14.328	0.042	157.852	394.629	9.818
16:15_29	Intersection	17.012	0.039	146.117	365.292	9.188
8:15_29	Intersection	14.328	0.042	157.852	394.629	9.818
17:15_29	Intersection	17.475	0.039	146.117	365.292	9.214

Table 25: May 29 Fuel Consumption and CO_2 from Speed for Signal. This table indicates emissions from the signalized intersection recording period comparisons. The values in blue indicate non-significant t-tests.

The 1615 to 1715 t-test was considered not significant; therefore an average speed was determined between both recording periods and was used to calculate fuel consumption and CO_2 emissions. The average amount of fuel consumption was 146.117 mL/mi. The average amount of CO_2 emissions during the 1615 recording period was 9.190 g while the average during the 1715 recording period was 9.214 g of CO_2.

During the 0715 recording period on May 29, the average amount of fuel consumption was 146.116 mL/mi and was 146.116 mL/mi during the 1615 recording period. The average amount of CO_2 emissions during the 0715 recording period was 9.360 g while the average during the 1615 recording period was 9.190 g of CO_2.

The 0715 to 1715 t-test was considered not significant; therefore an average speed was determined between both recording periods and was used to calculate fuel consumption and CO_2 emissions. The average amount of fuel consumption was 146.116 mL/mi. The average amount of CO_2 emissions during the 0715 recording period was 9.360 g while the average during the 1715 recording period was 9.214 g of CO_2.

During the 0815 recording period on May 29, the average amount of fuel consumption was 157.852 mL/mi and was 146.117 mL/mi during the 1615 recording period. The average amount of CO_2 emissions during the 0815 recording period was 9.818 g while the average during the 1615 recording period was 9.188 g of CO_2.

During the 0815 recording period on May 29, the average amount of fuel consumption was 157.852 mL/mi and was 146.117 mL/mi during the 1715 recording period. The average amount of CO_2 emissions during the 0815 recording period was 9.818 g while the average during the 1715 recording period was 9.214 g of CO_2. In Table 26 below, the average idle fuel consumption and CO_2 emissions are indicated for the signalized intersection recording period comparisons on May 29.

Time_Date	Intersection	Average Idle Time (sec)	Fuel Consumption (mL)	CO2 Emissions (g)
7:15_29	**Intersection**	2.738	1.027	2.567
8:15_29	**Intersection**	7.864	2.949	7.373
16:15_29	**Intersection**	6.867	2.575	6.438
17:15_29	**Intersection**	6.867	2.575	6.438
7:15_29	**Intersection**	2.738	1.027	2.567
16:15_29	**Intersection**	5.768	2.163	5.408
7:15_29	**Intersection**	2.738	1.027	2.567
17:15_29	**Intersection**	7.968	2.988	7.470
8:15_29	**Intersection**	6.782	2.543	6.358
16:15_29	**Intersection**	6.782	2.543	6.358
8:15_29	**Intersection**	7.915	2.968	7.420
17:15_29	**Intersection**	7.915	2.968	7.420

Table 26: May 29 Fuel Consumption and CO_2 from Idle Time for Signal. The values in blue indicate non-significant t-tests.

The average fuel consumption during the 0715 recording period on May 29 was 1.027 mL and was 2.949 mL during the 0815 recording period. The average CO_2 emissions during the 0715 recording period was 2.567 g and was 7.373 g during the 0815 recording period.

The t-tests for the 1615 to 1715 comparison indicated that the two samples were not significantly different; therefore an average idle time between two samples was used in order to calculate fuel consumption and CO_2 emissions. The average fuel consumption was 2.575 mL for both recording periods. The average CO_2 emission for both recording periods was 6.438 g.

The average fuel consumption during the 0715 recording period on May 29 was 1.027 mL and was 2.163 mL during the 1615 recording period. The average CO_2 emissions during the 0715 recording period was 2.567 g and was 5.408 g during the 1615 recording period.

The average fuel consumption during the 0715 recording period on May 29 was 1.027 mL and was 2.988 mL during the 1715 recording period. The average CO_2 emissions during the 0715 recording period was 2.567 g and was 7.470 g during the 1715 recording period.

The t-tests for the 0815 to 1615 comparison indicated that the two samples idle times were not significantly different; therefore an average idle time between two samples was used in order to calculate fuel consumption and CO_2 emissions. The average fuel consumption was 2.543 mL for both recording periods. The average CO_2 emission for both recording periods was 6.358 g.

The t-tests for the 0815 to 1715 comparison indicated that the two samples idle times were not significantly different; therefore an average idle time between two samples was used in order to calculate fuel consumption and CO_2 emissions. The average fuel consumption was 2.968 mL for both recording periods. The average CO_2 during both recording periods was 7.420 g.

The total CO_2 emission from speed and idle data from each recording period on May 29 at the signalized intersection and the contribution of CO_2 emissions from each is indicated in Table 27 below.

Time_Date	Intersection	Total Emissions (g)	Contribution from Driving	Contribution from Idling
7:15_29	**Intersection**	11.927	78%	22%
8:15_29	**Intersection**	17.190	57%	43%
16:15_29	**Intersection**	15.627	59%	41%
17:15_29	**Intersection**	15.652	59%	41%
7:15_29	**Intersection**	11.927	78%	22%
16:15_29	**Intersection**	14.597	63%	37%
7:15_29	**Intersection**	11.927	78%	22%
17:15_29	**Intersection**	16.684	55%	45%
8:15_29	**Intersection**	16.176	61%	39%
16:15_29	**Intersection**	15.546	59%	41%
8:15_29	**Intersection**	17.238	57%	43%
17:15_29	**Intersection**	16.634	55%	45%

Table 27: May 29 Average Total CO_2 for Signal Comparison. This table indicates emissions from speed and idle time data at the signalized intersection. The table also indicates the percentage of contribution of driving. and idling to CO_2 emissions.

During the 0715 recording period on May 29 at the signalized intersection there was an average total of 11.927 g of CO_2 emitted and there was 17.190 g during the 0815 recording period. During the 0715 recording period, 78 percent of CO_2 emissions came from driving while 22 percent came from idling. During the 0815 recording period, 57 percent of CO_2 emissions came from driving while 43 percent came from idling.

During the 1615 recording period on May 29 at the signalized intersection there was an average total of 15.627 g of CO_2 emitted and there was 15.652 g during the 1715 recording period. During the 1615 recording period, 59 percent of CO_2 emissions came from driving while 41 percent came from idling. During the 1715 recording period, 59 percent of CO_2 emissions came from driving while 41 percent came from idling.

During the 0715 recording period on May 29 at the signalized intersection there was an average total of 11.927 g of CO_2 emitted and there was 14.597 g during the 1615 recording period. During the 0715 recording period, 78 percent of CO_2 emissions came from driving while 22 percent came from idling. During the 1615 recording period, 63 percent of CO_2 emissions came from driving while 37 percent came from idling.

During the 0715 recording period on May 29 at the signalized intersection there was an average total of 11.927 g of CO_2 emitted and there was 16.684 g during the 1715 recording period. During the 0715 recording period, 78 percent of CO_2 emissions came from driving while 22 percent came from idling. During the 1715 recording period, 55 percent of CO_2 emissions came from driving while 45 percent came from idling.

During the 0815 recording period on May 29 at the signalized intersection there was an average total of 16.176 g of CO_2 emitted and there was 15.546 g during the 1615 recording period. During the 0815 recording period, 61 percent of CO_2 emissions came from driving while 39 percent came from idling. During the 1615 recording period, 59 percent of CO_2 emissions came from driving while 41 percent came from idling.

During the 0815 recording period on May 29 at the signalized intersection there was an average total of 17.238 g of CO_2 emitted and there was 16.634 g during the 1715 recording period. During the 0815 recording period, 57 percent of CO_2 emissions came from driving while 43 percent came from idling. During the 1715 recording period, 55 percent of CO_2 emissions came from driving while 45 percent came from idling.

In order to address Research Question 2, (do carbon dioxide emissions vary during different hours of the day at each type intersection?), fuel consumption and CO_2 emissions were calculated based on the t-tests data comparing different recording times on the same recording day at both intersections. Table 28 below entails fuel consumption and CO_2 emissions calculations from recording period comparisons at the roundabout on May 29. These results will be discussed below.

Time_Date	Intersection	Average Speed(MPH)	Fuel Consumption (gal/mi)	Fuel Consumption (mL/mi)	CO2 Emissions (g/mi)	CO2 Emissions (g)
7:15_29	**Roundabout**	19.707	0.036	136.275	340.687	13.675
8:15_29	**Roundabout**	18.556	0.037	139.303	348.258	14.155
16:15_29	**Roundabout**	18.031	0.037	139.303	348.258	13.708
17:15_29	**Roundabout**	18.031	0.037	139.303	348.258	13.410
7:15_29	**Roundabout**	19.707	0.036	136.275	340.687	13.675
16:15_29	**Roundabout**	18.096	0.037	139.303	348.258	13.787
7:15_29	**Roundabout**	19.707	0.036	136.275	340.687	13.675
17:15_29	**Roundabout**	17.475	0.039	146.117	365.292	14.066
8:15_29	**Roundabout**	18.325	0.037	139.303	348.258	14.074
16:15_29	**Roundabout**	18.325	0.037	139.303	348.258	13.708
8:15_29	**Roundabout**	18.015	0.037	139.303	348.258	14.074
17:15_29	**Roundabout**	18.015	0.037	139.303	348.258	13.410

Table 28: May 29 Fuel Consumption and CO_2 from Speed for Roundabout. The values in blue indicate non-significant t-tests.

The average fuel consumption during the 0715 recording period on May 29 at the roundabout was 136.275 mL/mi and was 139.303 mL/mi during the 0815 recording period. The average CO_2 emission was 13.675 g during the 0715 recoding period and 14.155 g during the 0815 recording period.

The 1615 to 1715 t-test was considered not significant; therefore an average speed was determined between both recording periods and was used to calculate fuel consumption and CO_2 emissions. The average amount of fuel consumption was 139.303 mL/mi during both recording periods. The average amount of CO_2 emissions during the 1615 recording period was 13.708 g while the average during the 1715 recording period was 13.410 g of CO_2.

The average fuel consumption during the 0715 recording period on May 29 at the roundabout was 136.274 mL/mi and was 139.303 mL/mi during the 1615 recording period. The average CO_2 emission was 13.675 g during the 0715 recording period and 13.786 g during the 1615 recording period.

The average fuel consumption during the 0715 recording period on May 29 at the roundabout was 136.274 mL/mi and was 146.116 mL/mi during the 1715 recording period. The average CO_2 emission was 13.675 g during the 0715 and 14.066 g during the 0815 recording period.

The 0815 to 1615 t-test was considered not significant; therefore an average speed was determined between both recording periods and was used to calculate fuel consumption and CO_2 emissions. The average amount of fuel consumption was 139.303 mL/mi during both recording periods. The average amount of CO_2 emissions during the 0815 recording period was 14.074 g while the average during the 1615 recording period was 13.708 g of CO_2.

The 0815 to 1715 t-test was considered not significant; therefore an average speed was determined between both recording periods and was used to calculate fuel consumption and CO_2 emissions. The average amount of fuel consumption was 139.303 mL/mi during both recording periods. The average amount of CO_2 emissions during the 0815 recording period was 14.074 g while the average during the 1715 recording period was 13.410 g of CO_2. In Table 29 below, the average idle fuel consumption and CO_2 emissions are indicated for the roundabout recording period comparisons on May 29.

Time_Date	Intersection	Average Idle Time(sec)	Fuel Consumption (mL)	CO2 Emissions (g)
7:15_29	**Roundabout**	0.422	0.158	0.395
8:15_29	**Roundabout**	0.422	0.158	0.395
16:15_29	**Roundabout**	0.771	0.289	0.723
17:15_29	**Roundabout**	0.331	0.124	0.311
7:15_29	**Roundabout**	0.414	0.155	0.388
16:15_29	**Roundabout**	0.772	0.289	0.724
7:15_29	**Roundabout**	0.372	0.140	0.349
17:15_29	**Roundabout**	0.372	0.140	0.349
8:15_29	**Roundabout**	0.430	0.161	0.403
16:15_29	**Roundabout**	0.772	0.289	0.724
8:15_29	**Roundabout**	0.381	0.143	0.357
17:15_29	**Roundabout**	0.381	0.143	0.357

Table 29: May 29 Fuel Consumption and CO_2 from Idle Time for Roundabout. The calculations in blue indicate non-significant t-tests.

The t-tests for the 0715 to 0815 comparison indicated that the two samples idle times were not significantly different; therefore an average idle time between two samples was used in order to calculate fuel consumption and CO_2 emissions. The average fuel consumption was 0.158 mL during the 0715 and 0815 recording period. The average CO_2 emission during both recording periods was 0.395 g.

The average idle time fuel consumption during the 1615 recording period on May 29 was 0.289 mL and was 0.124 mL during the 1715 recording period. The average CO_2

emission during the 1615 recording period was 0.723 g and was 0.310 g during the 1715 recording period.

The average idle time fuel consumption during the 0715 recording period on May 29 was 0.155 mL and was 0.289 mL during the 1615 recording period. The average CO_2 emission during the 0715 recording period was 0.387 g and was 0.723 g during the 1715 recording period.

The t-tests for the 0715 to 1715 comparison indicated that the two samples idle times were not significantly different; therefore an average idle time between two samples was used in order to calculate fuel consumption and CO_2 emissions. The average fuel consumption was 0.139 mL during the 0715 and 1715 recording period. The average CO_2 emission during both recording periods was 0.349 g.

The average fuel consumption during the 0815 recording period on May 29 was 0.161 mL and 0.289 mL during the 1615 recording period. The average CO_2 emissions during the 0815 recording period was 0.402 g and was 0.723 g during the 1615 recording period.

The t-tests for the 0815 to 1715 comparison indicated that the two samples idle times were not significantly different; therefore an average idle time between two samples was used in order to calculate fuel consumption and CO_2 emissions. The average fuel consumption was 0.142 mL during the 0815 and 1715 recording period. The average CO_2 emission during both recording periods was 0.356 g.

Table 30 below indicates the total average CO_2 emissions between the speed and idle time data for all the recording period comparisons on May 29 at the roundabout.

Time_Date	Intersection	Total Emissions (g)	Contribution from Driving	Contribution from Idling
7:15_29	**Roundabout**	14.070	97%	3%
8:15_29	**Roundabout**	14.550	97%	3%
16:15_29	**Roundabout**	14.431	95%	5%
17:15_29	**Roundabout**	13.721	98%	2%
7:15_29	**Roundabout**	14.063	97%	3%
16:15_29	**Roundabout**	14.510	95%	5%
7:15_29	**Roundabout**	14.024	98%	2%
17:15_29	**Roundabout**	14.415	98%	2%
8:15_29	**Roundabout**	14.477	97%	3%
16:15_29	**Roundabout**	14.432	95%	5%
8:15_29	**Roundabout**	14.431	98%	2%
17:15_29	**Roundabout**	13.767	97%	3%

Table 30: May 29 Average Total CO_2 for Roundabout Comparison. This table indicates emissions from speed and idle time data at the roundabout. The table also indicates the percentage of contribution of driving and idling to CO_2 emissions.

The average total CO_2 emissions during the 0715 recording period was 14.070 g and was 14.550 g during the 0815 recording period. During the 0715 recording period 97 percent of emissions were from driving and 3 percent was from idling. During the 0815 recording period 97 percent of emissions were from driving and 3 percent was from idling.

The average total CO_2 emissions during the 1615 recording period was 14.431 g and was 13.721 g during the 1715 recording period. During the 1615 recording period 95 percent of emissions were from driving and 5 percent was from idling. During the 1715 recording period 98 percent of emissions were from driving and 2 percent was from idling.

The average total CO_2 emissions during the 0715 recording period was 14.063 g and was 14.510 g during the 1615 recording period. During the 0715 recording period 97 percent of emissions were from driving and 3 percent was from idling. During the 1615 recording period 95 percent of emissions were from driving and 5 percent was from idling.

The average total CO_2 emissions during the 0715 recording period was 14.024 g and was 14.415 g during the 1715 recording period. During the 0715 recording period 98 percent of emissions were from driving and 2 percent was from idling. During the 1715 recording period 98 percent of emissions were from driving and 2 percent was from idling.

The average total CO_2 emissions during the 0815 recording period was 14.477 g and was 14.432 g during the 1615 recording period. During the 0815 recording period 97 percent of emissions were from driving and 3 percent was from idling. During the 1615 recording period 95 percent of emissions were from driving and 5 percent was from idling.

The average total CO_2 emissions during the 0815 recording period was 14.431 g and was 13.767 g during the 0815 recording period. During the 0715 recording period 97 percent of emissions were from driving and 3 percent was from idling. During the 0815 recording period 97 percent of emissions were from driving and 3 percent was from idling.

May 31 (WE) Fuel Consumption and CO_2 Calculations for Speed Data (Signalized to Signalized; Roundabout to Roundabout)

In order to address Research Question 2 (do carbon dioxide emissions vary during different hours of the day at each type of intersection?), fuel consumption and CO_2 emissions were calculated. Table 31 below indicates the values of fuel consumption and CO_2 emissions for the signalized intersection on the May 31.

Time_Date	Intersection	Average Speed(MPH)	Fuel Consumption (gal/mi)	Fuel Consumption (mL/mi)	CO2 Emissions (g/mi)	CO2 Emissions (g)
7:15_31	Intersection	17.672	0.039	146.117	365.292	12.189
8:15_31	Intersection	17.672	0.039	146.117	365.292	12.564
16:15_31	Intersection	16.553	0.037	140.817	352.043	11.981
17:15_31	Intersection	16.553	0.037	140.817	352.043	11.956
7:15_31	Intersection	16.852	0.037	140.817	352.043	11.747
16:15_31	Intersection	16.852	0.037	140.817	352.043	11.981
7:15_31	Intersection	17.006	0.039	146.117	365.292	12.189
17:15_31	Intersection	17.006	0.039	146.117	365.292	12.406
8:15_31	Intersection	17.218	0.039	146.117	365.292	12.564
16:15_31	Intersection	17.218	0.039	146.117	365.292	12.432
8:15_31	Intersection	17.372	0.039	146.117	365.292	9.520
17:15_31	Intersection	17.372	0.039	146.117	365.292	12.406

Table 31: May 31 Fuel Consumption and CO_2 from Speed for Signal. This table indicates emissions from speed data for the signalized intersection comparison. The values in blue indicate non-significant t-tests.

The t-tests results, for all recording period comparisons at the signalized intersection on May 31, indicated that the two samples were not significantly different. Therefore an average speed was determine between the two samples and was used in order to calculate fuel consumption and CO_2 emissions. The average fuel consumption during the 0715 to 0815 comparison was 146.117 mL/mi. The average CO_2 emissions during the 0715 recording period was 12.189 g and was 12.564 g during the 0815 recording period.

The average fuel consumption during the 1615 to 1715 recording period comparison was 140.817 mL/mi. The average CO_2 emissions during the 1615 recording period was 11.981 g and was 11.956 g during the 1715 recording period. The average fuel consumption during the 0715 to 1615 recording period comparison was 140.817 mL/mi. The average CO_2 emission during the 0715 recording period was 11.747 g and was 11.981 g during the 1615 recording period.

The average fuel consumption during the 0715 to 1715 recording period comparison was 146.116 mL/mi. The average CO_2 emission during the 0715 recording period was 12.189 g and was 12.406 g during the 1715 recording period. The average fuel consumption during the 0815 to 1615 recording period comparison was 146.116 mL/mi. The average CO_2 emission during the 0815 recording period was 12.564 g and was 12.432 g during the 1615 recording period. The average fuel consumption during the 0815 to 1715 recording period was 146.116 mL/mi. The average CO_2 emission during the 0815 recording period was 9.520 g and was 12.406 g during the 1715 recording period.

Table 32 below indicates the average fuel consumption and CO_2 emissions for idle time data at the signalized intersection on May 31. The results to these calculations will be discussed below.

Time_Date	Intersection	Average Idle Time(sec)	Fuel Consumption (mL)	CO2 Emissions (g)
7:15_31	Intersection	2.897	1.086	2.716
8:15_31	Intersection	2.897	1.086	2.716
16:15_31	Intersection	5.629	2.111	5.277
17:15_31	Intersection	5.629	2.111	5.277
7:15_31	Intersection	2.135	0.801	2.002
16:15_31	Intersection	6.767	2.538	6.344
7:15_31	Intersection	3.312	1.242	3.105
17:15_31	Intersection	3.312	1.242	3.105
8:15_31	Intersection	3.665	1.374	3.436
16:15_31	Intersection	6.767	2.538	6.344
8:15_31	Intersection	4.077	1.529	3.822
17:15_31	Intersection	4.077	1.529	3.822

Table 32: May 31 Fuel Consumption and CO_2 from Idle Time for Signal. The calculations in blue indicate non-significant t-tests.

The t-test for the 0715 to 0815 recording period indicated that the two samples are not significantly different; therefore an average idle time was determine between the two samples and was used in order to calculate fuel consumption and CO_2 emissions. The average fuel consumption for both recording periods was 1.086 mL. The average CO_2 emission was 2.717 g during both recording periods.

The t-test for the 1615 to 1715 recording period indicated that the two samples are not significantly different; therefore an average idle time was determine between the two samples and was used in order to calculate fuel consumption and CO_2 emissions. The average fuel consumption for both recording periods was 2.111 mL. The average CO_2 emission was 5.277 g during both recording periods.

The average fuel consumption during the 0715 recording period was 0.801 mL and was 2.538 mL during the 1615 recording period. The average CO_2 emission was 2.002 g during the 0715 recording period and was 6.344 g during the 1615 recording period.

The t-test for the 0715 to 1715 recording period indicated that the two samples are not significantly different; therefore an average idle time was determine between the two samples and was used in order to calculate fuel consumption and CO_2 emissions. The average fuel consumption for both recording periods was 1.242 mL. The average CO_2 emission was 3.105 g during both recording periods.

The average fuel consumption during the 0815 recording period was 1.374 mL and was 2.538 mL during the 1615 recording period. The average CO_2 emission was 3.436 g during the 0815 recording period and was 6.344 g during the 1615 recording period.

The t-test for the 0815 to 1715 recording period indicated that the two samples are not significantly different; therefore an average idle time was determine between the two samples and was used in order to calculate fuel consumption and CO_2 emissions. The average fuel consumption for both recording periods was 1.529 mL. The average CO_2 emission was 3.822 g during both recording periods.

The total average CO_2 emissions for the recording period comparisons on May 31 at the signalized intersection are indicated in Table 33 below. The results of the total average fuel consumption and CO_2 emissions will be discussed below.

Time_Date	Intersection	Total Emissions(g)	Contribution from Driving	Contribution from Idling
7:15_31	**Intersection**	14.905	82%	18%
8:15_31	**Intersection**	15.280	82%	18%
16:15_31	**Intersection**	17.257	69%	31%
17:15_31	**Intersection**	17.232	69%	31%
7:15_31	**Intersection**	13.749	85%	15%
16:15_31	**Intersection**	18.325	65%	35%
7:15_31	**Intersection**	15.294	80%	20%
17:15_31	**Intersection**	15.511	80%	20%
8:15_31	**Intersection**	16.000	79%	21%
16:15_31	**Intersection**	18.776	66%	34%
8:15_31	**Intersection**	13.342	71%	29%
17:15_31	**Intersection**	16.228	76%	24%

Table 33: May 31 Average Total CO_2 for Signal Comparison. This table indicates total emissions from speed and idle time data at the signalized intersection. The table also indicates the percentage of contribution of driving and idling to CO_2 emissions.

The average total CO_2 emissions during the 0715 recording period on May 31 was 14.905 g and was 15.280 g during the 0815 recording period. During the 0715 recording period 82 percent of CO_2 emissions were from driving and 18 percent were from idling. During the 0815 recording period, 82 percent of CO_2 emissions were from driving and 18 were from idling. The average total CO_2 emissions during the 1615 recording period on May 31 was 17.257 g and was 17.232 g during the 1715 recording period. During the 1615 recording period 69 percent of CO_2 emissions were from driving and 18 percent were from idling. During the 1715 recording period 69 percent of CO_2 emissions were from driving and 18 percent were from idling.

The average total of CO_2 emissions during the 0715 recording period was 13.749 g and was 18.325 g during the 1615 recording period. During the 0715 recording period 85 percent of CO_2 emissions were from driving and 15 percent was from idling. During the 1615 recording period 65 percent of CO_2 emissions were from driving and 35 percent were from idling. The average total CO_2 emissions during the 0715 recording period was 15.294 g and was 15.511 g during the 1715 recording period. During the 0715 recording period 80 percent of CO_2 emissions were from driving and 20 were from idling. During the 1715 recording period 80 percent of CO_2 emissions were from driving and 20 percent were from idling.

The average total CO_2 emissions during the 0815 recording period was 16.000 g and was 18.776 g during the 1615 recording period. During the 0815 recording period 79 percent of CO_2 emissions were from driving and 21 percent was from idling. During the 1615 recording period, 66 percent of CO_2 emissions were from driving and 34 were from idling. The average total CO_2 emissions during the 0815 recording period was 13.342 g and was 16.228 g during the 1715 recording period. During the 0815 recording period, 71 percent of CO_2 emissions were from driving and 29 were from idling. During the 1715 recording period 76 percent of CO_2 emissions were from driving and 24 were from idling.

In order to address Research Question 2 (do carbon dioxide emissions vary during different hours of the day at each type of intersection?), fuel consumption and CO_2 emissions were calculated. Table 34 below indicates the values of fuel consumption and CO_2 emissions for the roundabout on the May 31. The fuel consumption and CO_2 emissions during the roundabout comparison of recording periods on May 31 will be discussed below.

Time_Date	Intersection	Average Speed(MPH)	Fuel Consumption (gal/mi)	Fuel Consumption (mL/mi)	CO2 Emissions (g/mi)	CO2 Emissions (g)
7:15_31	Roundabout	18.822	0.037	139.303	348.258	13.256
8:15_31	Roundabout	18.822	0.037	139.303	348.258	13.842
16:15_31	Roundabout	18.298	0.037	139.303	348.258	13.927
17:15_31	Roundabout	18.298	0.037	139.303	348.258	13.601
7:15_31	Roundabout	18.632	0.037	139.303	348.258	13.256
16:15_31	Roundabout	18.632	0.037	139.303	348.258	13.927
7:15_31	Roundabout	18.706	0.037	139.303	348.258	13.256
17:15_31	Roundabout	18.706	0.037	139.303	348.258	13.601
8:15_31	Roundabout	18.414	0.037	139.303	348.258	13.842
16:15_31	Roundabout	18.414	0.037	139.303	348.258	13.927
8:15_31	Roundabout	18.488	0.037	139.303	348.258	13.842
17:15_31	Roundabout	18.488	0.037	139.303	348.258	13.601

Table 34: May 31 Fuel Consumption and CO_2 from Speed for Roundabout. The values in blue indicate non-significant t-tests.

The t-tests results for all recording period comparisons at the roundabout on May 31 indicated that the two samples were not significantly different. Therefore an average speed was determine between the two samples and was used in order to calculate fuel consumption and CO_2 emissions. The average fuel consumption for the 0715 to 0815 recording period comparison on May 31 at the roundabout was 139.303 mL/ mi. The average CO_2 emissions during the 0715 recording period was 13.256 g and was 13.842 g during the 0815 recording period.

The average fuel consumption during the 1615 to 1715 recording period on May 31 was 139.303 mL/mi. The average CO_2 emission during the 1615 recording period was 13.927 and was 13.601 g during the 1715 recording period. The average fuel consumption during the 0715 to 1615 recording period was 139.303 mL/mi. The average CO_2 emission during the 0715 recording period was 13.256 g and was 13.927 g during the 1715 recording period.

The average fuel consumption during the 0715 to 1715 recording period was 139.303 mL/mi. The average CO_2 emission during the 0715 recording period was 13.256 g and was 13.601 g during the 1715 recording period. The average fuel consumption during the 0815 to 1615 recording period was 139.303 mL/mi. The average CO_2 emission during 0815 recording period was 13.842 g and was 13.927 g during the 1615 recording period. The average fuel consumption during the 0815 to 1715 recording period comparison was 139.303 mL/mi. The average CO_2 emission during the 0815 recording period was 13.842 g and was 13.601 g during the 1715 recording period.

The results to the fuel consumption and CO_2 emissions calculations for idle time data on May 31 at the roundabout are indicated in Table 35 and will be discussed below.

Time_Date	Intersection	Average Idle Time(sec)	Fuel Consumption (mL)	CO2 Emissions (g)
7:15_31	**Roundabout**	0.294	0.110	0.275
8:15_31	**Roundabout**	0.294	0.110	0.275
16:15_31	**Roundabout**	0.523	0.196	0.491
17:15_31	**Roundabout**	0.191	0.072	0.179
7:15_31	**Roundabout**	0.455	0.171	0.427
16:15_31	**Roundabout**	0.455	0.171	0.427
7:15_31	**Roundabout**	0.289	0.108	0.271
17:15_31	**Roundabout**	0.289	0.108	0.271
8:15_31	**Roundabout**	0.362	0.136	0.339
16:15_31	**Roundabout**	0.362	0.136	0.339
8:15_31	**Roundabout**	0.196	0.073	0.184
17:15_31	**Roundabout**	0.196	0.073	0.184

Table 35: May 31 Fuel Consumption and CO_2 from Idle Time for Roundabout. The calculations in blue indicate non-significant t-tests.

The t-test for the 0715 to 0815 comparison indicated that the two samples were not significantly different. Therefore, an average idle time between both recording periods was used in order to calculate fuel consumption and CO_2 emissions. The average fuel consumption for both recording periods was 0.110 mL. The average CO_2 emission for both recording periods was 0.275 g.

The average fuel consumption during the 1615 recording period was 0.196 mL and was 0.072 mL during the 1715 recording period. The average CO_2 emission during the 1615 recording period was 0.490 g and was 0.179 g during the 1715 recording period.

The t-test for the 0715 to 1615 recording period indicated that the two samples were not significantly different. Therefore, an average idle time between both recording periods was used in order to calculate fuel consumption and CO_2 emissions. The average fuel consumption for both recording periods was 0.171 mL. The average CO_2 emission for both recording periods was 0.427 g.

The t-test for the 0715 to 1715 recording period indicated that the two samples were not significantly different. Therefore, an average idle time between both recording periods was used in order to calculate fuel consumption and CO_2 emissions. The average fuel consumption for both recording periods was 0.108 mL. The average CO_2 emission for both recording periods was 0.271 g.

The t-test for the 0815 to 1615 recording period indicated that the two samples were not significantly different. Therefore, an average idle time between both recording periods was used in order to calculate fuel consumption and CO_2 emissions. The average fuel consumption for both recording periods was 0.136 mL. The average CO_2 emission for both recording periods was 0.339 g.

The t-test for the 0815 to 1715 recording period indicated that the two samples were not significantly different. Therefore, an average idle time between both recording periods was used in order to calculate fuel consumption and CO_2 emissions. The average fuel consumption for both recording periods was 0.073 mL. The average CO_2 emission for both recording periods was 0.184 g.

The total average emissions during the May 31 recording period comparisons are indicated in Table 36 below. The results of fuel consumption and CO_2 emissions calculations will be discussed below.

Time_Date	Intersection	Total Emissions(g)	Contribution from Driving	Contribution from Idling
7:15_31	**Roundabout**	13.532	98%	2%
8:15_31	**Roundabout**	14.117	98%	2%
16:15_31	**Roundabout**	14.418	97%	3%
17:15_31	**Roundabout**	13.781	99%	1%
7:15_31	**Roundabout**	13.683	97%	3%
16:15_31	**Roundabout**	14.354	97%	3%
7:15_31	**Roundabout**	13.527	98%	2%
17:15_31	**Roundabout**	13.872	98%	2%
8:15_31	**Roundabout**	14.181	98%	2%
16:15_31	**Roundabout**	14.267	98%	2%
8:15_31	**Roundabout**	14.026	99%	1%
17:15_31	**Roundabout**	13.785	99%	1%

Table 36: May 31 Average Total CO_2 for Roundabout Comparison. This table indicates speed and idle time data at the roundabout. The table also indicates the percentage of contribution of driving and idling to CO_2 emissions.

The total average CO_2 emissions during the 0715 recording period was 13.532 g and was 14.117 g during the 0815 recoding period on May 31. During the 0715 recoding period 98 percent of CO_2 emissions were from driving and 2 percent were from idling. During the 0815 recording period, 98 percent of CO_2 emissions were from driving and 2 percent were from idling.

The total average CO_2 emissions during the 1615 recording period was 14.418 g and was 13.781 g during the 1715 recoding period on May 31. During the 1615 recoding period 97 percent of CO_2 emissions were from driving and 3 percent were from idling. During the 1715 recording period, 99 percent of CO_2 emissions were from driving and 1 percent was from idling.

The total average CO_2 emissions during the 0715 recording period was 13.683 g and was 14.354 g during the 1615 recoding period on May 31. During the 0715 recoding period 97 percent of CO_2 emissions were from driving and 3 percent were from idling. During the

1615 recording period, 97 percent of CO_2 emissions were from driving and 3 percent were from idling.

The total average CO_2 emissions during the 0715 recording period was 13.527 g and was 13.872 g during the 1715 recoding period on May 31. During the 0715 recoding period 98 percent of CO_2 emissions were from driving and 2 percent were from idling. During the 1715 recording period, 98 percent of CO_2 emissions were from driving and 2 percent were from idling.

The total average CO_2 emissions during the 0815 recording period was 14.181 g and was 14.266 g during the 1615 recoding period on May 31. During the 0815 recoding period 98 percent of CO_2 emissions were from driving and 2 percent were from idling. During the 0815 recording period, 98 percent of CO_2 emissions were from driving and 2 percent were from idling.

The total average CO_2 emissions during the 0815 recording period was 14.025 g and was 13.785 g during the 1715 recoding period on May 31. During the 0815 recoding period 99 percent of CO_2 emissions were from driving and 1 percent was from idling. During the 1715 recording period, 99 percent of CO_2 emissions were from driving and 1 percent was from idling.

May 29 (WD) and 31 (WE) Comparison of Fuel Consumption and CO_2 (Signalized to Signalized; Roundabout to Roundabout)

In order to address Research Question 3, (do carbon dioxide emissions vary during different days of the week?), fuel consumption and CO_2 emissions were calculated using t-tests data comparing the same recording times on May 29 and May 31. The fuel consumption and CO_2 emissions calculations are indicated in Table 37 and will be discussed below.

Time_Date	Intersection	Average Speed(MPH)	Fuel Consumption (gal/mi)	Fuel Consumption (mL/mi)	CO2 Emissions (g/mi)	CO2 Emissions (g)
7:15_29	Intersection	17.480	0.039	146.117	365.292	9.360
7:15_31	Intersection	17.480	0.039	146.117	365.292	12.189
8:15_29	Intersection	14.328	0.042	157.852	394.629	9.818
8:15_31	Intersection	18.322	0.037	139.303	348.258	9.076
16:15_29	Intersection	16.705	0.037	140.817	352.043	8.856
16:15_31	Intersection	16.705	0.037	140.817	352.043	11.981
17:15_29	Intersection	16.845	0.037	140.817	352.043	8.880
17:15_31	Intersection	16.845	0.037	140.817	352.043	11.956

Table 37: May 29 and 31 Fuel Consumption and CO_2 from Speed for Signal Comparison. The values in blue indicate not significant t-tests.

The t-tests for 0715 May 29 to 0715 May 31 indicated that the two samples are not significantly different. Therefore, an average speed was determined between the two samples in order to calculate fuel consumption and CO_2 emissions. The average fuel consumption for both recording periods was 146.117 mL/mi. The average CO_2 emission during the May 29 0715 recording period was 9.360 g and was 12.189 g during the May 31 0715 recording period.

The average fuel consumption during the May 29 0815 recording period was 157.852 mL/mi and was 139.303 mL/mi during the May 31 0815 recording period. The average CO_2 emission during the May 29 0815 recording period was 9.817 g and was 9.076 g during the May 31 0815 recording period.

The t-tests for the May 29 1615 to May 31 1615 indicated that the two samples were not significantly different. Therefore, an average speed was used between the two samples in order to calculate fuel consumption and CO_2 emissions. The average fuel consumption for both recording periods was 140.817 mL/mi. The average CO_2 emission during the May 29 1615 recording period was 8.856 g and was 11.981 g during the May 31 1615 recording period.

The t-tests for the May 29 1715 to May 31 1715 indicated that the two samples were not significantly different. Therefore, an average speed was used between the two samples in order to calculate fuel consumption and CO_2 emissions. The average fuel consumption for both recording periods was 140.817 mL/mi. The average CO_2 emission during the May 29 1615 recording period was 8.880 g and was 11.956 g during the May 31 1615 recording period.

The fuel consumption and CO_2 emissions were calculated with idle time data for the May 29 to May 31 comparisons. The results of these calculations are in Table 38 and will be discussed below.

Time_Date	Intersection	Average Idle Time(sec)	Fuel Consumption (mL)	CO2 Emissions (g)
7:15_29	**Intersection**	2.437	0.914	2.284
7:15_31	**Intersection**	2.437	0.914	2.284
8:15_29	**Intersection**	7.864	2.949	7.373
8:15_31	**Intersection**	3.665	1.374	3.436
16:15_29	**Intersection**	6.268	2.350	5.876
16:15_31	**Intersection**	6.268	2.350	5.876
17:15_29	**Intersection**	7.967	2.988	7.469
17:15_31	**Intersection**	4.490	1.684	4.209

Table 38: May 29 and 31 Fuel Consumption and CO_2 from Idle Time for Signal Comparison. This table indicates fuel consumption and emission for the signalized intersection comparison. The values in blue indicate non-significant t-tests.

The t-test comparing May 29 0715 to May 31 0715 indicated that the two samples were not significantly different. Therefore, an average idle time between both recording periods was used in order to calculate fuel consumption and CO_2 emissions. The average fuel consumption for both recording periods was 0.914 mL. The average CO_2 emission for both recording periods was 2.284 g.

The average fuel consumption during the May 29 0815 recording period was 2.949 mL and was 1.374 mL during the May 31 0815 recording period. The average CO_2 emission during the May 29 recording period was 7.373 g and was 3.436 g during the May 31 recording period.

The t-test comparing May 29 1615 to May 31 1615 indicated that the two samples were not significantly different. Therefore, an average idle time between both recording periods was used in order to calculate fuel consumption and CO_2 emissions. The average fuel consumption for both recording periods was 2.350 mL. The average CO_2 emission for both recording periods was 5.876 g.

The average fuel consumption during the May 29 1715 recording period was 2.988 mL and was 1.684 mL during the May 31 1715 recording period. The average CO_2 emission during the May 29 recording period was 7.469 g and was 4.209 g during the May 31 recording period.

The total average CO_2 emissions for the May 29 to May 31 recording period comparisons are indicated in Table 39 and will be discussed below.

Time_Date	Intersection	Total Emissions(g)	Contribution from Driving	Contribution from Idling
7:15_29	**Intersection**	11.644	80%	20%
7:15_31	**Intersection**	14.474	84%	16%
8:15_29	**Intersection**	17.190	57%	43%
8:15_31	**Intersection**	12.512	73%	27%
16:15_29	**Intersection**	14.732	60%	40%
16:15_31	**Intersection**	17.856	67%	33%
17:15_29	**Intersection**	16.349	54%	46%
17:15_31	**Intersection**	16.165	74%	26%

Table 39: May 29 to 31 Average Total CO_2 for Signal Comparison. This table indicates emissions of speed and idle time data for recording period comparisons at the signalized intersection. This table also indicates the percentage of contribution of CO_2 emissions from driving and idle time

The total average CO_2 emission for May 29 0715 recording period was 11.644 g and was 14.474 g during the May 31 0715 recording period. During the May 29 0715 recording period, 80 percent of CO_2 emissions were from driving and 20 percent of CO_2 emissions were from idling. During the May 31 0715 recording period, 84 percent of CO_2 emissions were from driving and 16 percent were from idling.

The total average CO_2 emission for May 29 0815 recording period was 17.190 g and was 12.512 g during the May 31 0815 recording period. During the May 29 0815 recording period, 57 percent of CO_2 emissions were from driving and 43 percent of CO_2 emissions were from idling. During the May 31 0815 recording period, 73 percent of CO_2 emissions were from driving and 27 percent were from idling.

The total average CO_2 emission for May 29 1615 recording period was 14.732 g and was 17.856 g during the May 31 1615 recording period. During the May 29 1615 recording period, 60 percent of CO_2 emissions were from driving and 40 percent of CO_2 emissions were from idling. During the May 31 1615 recording period, 67 percent of CO_2 emissions were from driving and 33 percent were from idling.

The total average CO_2 emission for May 29 1715 recording period was 16.349 g and was 16.165 g during the May 31 1715 recording period. During the May 29 1715 recording period, 54 percent of CO_2 emissions were from driving and 46 percent of CO_2 emissions were from idling. During the May 31 1715 recording period, 74 percent of CO_2 emissions were from driving and 26 percent were from idling.

In order to address Research Question 3 (do carbon dioxide emissions vary between different days?), fuel consumption and CO_2 emissions were calculated at the roundabout comparing the same recording periods on May 29 to May 31. The fuel consumption and CO_2 emissions calculations for the roundabout are indicated in Table 40, and will be discussed below.

Time_Date	Intersection	Average Speed(MPH)	Fuel Consumption (gal/mi)	Fuel Consumption (mL/mi)	CO2 Emissions (g/mi)	CO2 Emissions (g)
7:15_29	Roundabout	19.356	0.036	136.275	340.687	13.600
7:15_31	Roundabout	19.356	0.036	136.275	340.687	12.046
8:15_29	Roundabout	18.579	0.037	139.303	348.258	14.074
8:15_31	Roundabout	18.579	0.037	139.303	348.258	13.842
16:15_29	Roundabout	18.160	0.037	139.303	348.258	13.708
16:15_31	Roundabout	18.160	0.037	139.303	348.258	13.927
17:15_29	Roundabout	18.168	0.037	139.303	348.258	13.410
17:15_31	Roundabout	18.168	0.037	139.303	348.258	13.601

Table 40: May 29 and 31 Fuel Consumption and CO_2 from Speed for Roundabout Comparison. The values in blue indicate non-significant t-tests.

The t-test for May 29 at 0715 to May 31 at 0715 recording period comparisons indicated that the two samples are not significantly different. Therefore, an average speed between both samples was used in order to calculate fuel consumption and CO_2 emissions. The average fuel consumption for both recording periods was 136.275 mL/mi. The average CO_2 emissions during the May 29 at 0715 recording period was 13.599 g and was 12.046 g during the May 31 at 0715 recording period.

The t-test for May 29 at 0815 to May 31 at 0815 recording period comparisons indicated that the two samples are not significantly different. Therefore, an average speed between both samples was used in order to calculate fuel consumption and CO_2 emissions. The average fuel consumption for both recording periods was 139.303 mL/mi. The average CO_2 emissions during the May 29 at 0815 recording period was 14.074 g and was 13.842 g during the May 31 at 0815 recording period.

The t-test for May 29 at 1615 to May 31 at 1615 recording period comparisons indicated that the two samples are not significantly different. Therefore, an average speed between both samples was used in order to calculate fuel consumption and CO_2 emissions. The average fuel consumption for both recording periods was 139.303 mL/mi. The average CO_2 emissions during the May 29 at 1615 recording period was 13.708 g and was 13.927 g during the May 31 at 1715 recording period.

The t-test for May 29 at 1715 to May 31 at 1715 recording period comparisons indicated that the two samples are not significantly different. Therefore, an average speed between both samples was used in order to calculate fuel consumption and CO_2 emissions. The average fuel consumption for both recording periods was 139.303 mL/mi. The average CO_2 emissions during the May 29 at 1715 recording period was 13.410 g and was 13.601 g during the May 31 at 1715 recording period.

Fuel consumption and CO_2 emissions for idle time data calculations for May 29 to May 31 recording period comparisons is indicated in Table 41. The results to these calculations will be discussed below.

Time_Date	Intersection	Average Idle Time(sec)	Fuel Consumption (mL)	CO2 Emissions (g)
7:15_29	**Roundabout**	0.400	0.150	0.375
7:15_31	**Roundabout**	0.400	0.150	0.375
8:15_29	**Roundabout**	0.315	0.118	0.295
8:15_31	**Roundabout**	0.315	0.118	0.295
16:15_29	**Roundabout**	0.648	0.243	0.607
16:15_31	**Roundabout**	0.648	0.243	0.607
17:15_29	**Roundabout**	0.261	0.098	0.245
17:15_31	**Roundabout**	0.261	0.098	0.245

Table 41: May 29 and 31 Fuel Consumption and CO_2 from Idle Time for Roundabout Comparison. The values in blue indicate non-significant t-tests.

The t-test for May 29 at 0715 to May 31 at 0715 comparison indicated that the two samples are not significantly different. Therefore, an average idle time was used between the two samples in order to calculate fuel consumption and CO_2 emissions. The average fuel consumption for both recording periods was 0.150 mL. The average CO_2 emission for both recording periods was 0.375 g.

The t-test for May 29 0815 to May 31 at 0815 comparison indicated that the two samples are not significantly different. Therefore, an average idle time was used between the two samples in order to calculate fuel consumption and CO_2 emissions. The average fuel consumption for both recording periods was 0.118 mL. The average CO_2 emission for both recording periods was 0.295 g.

The t-test for May 29 at 1615 to May 31 at 1615 comparison indicated that the two samples are not significantly different. Therefore, an average idle time was used between the two samples in order to calculate fuel consumption and CO_2 emissions. The average fuel consumption for both recording periods was 0.243 mL. The average CO_2 emission for both recording periods was 0.607 g.

The t-test for May 29 at 1715 to May 31 at 1715 comparison indicated that the two samples are not significantly different. Therefore, an average idle time was used between the two samples in order to calculate fuel consumption and CO_2 emissions. The average fuel consumption for both recording periods was 0.098 mL. The average CO_2 emission for both recording periods was 0.245 g.

The average total CO_2 emissions results from speed and idle time data comparing the same recording periods on May 29 to May 31 are indicated in Table 42. These results will be discussed below.

Time_Date	Intersection	Total Emissions(g)	Contribution from Driving	Contribution from Idling
7:15_29	**Roundabout**	13.975	97%	3%
7:15_31	**Roundabout**	12.421	97%	3%
8:15_29	**Roundabout**	14.370	98%	2%
8:15_31	**Roundabout**	14.138	98%	2%
16:15_29	**Roundabout**	14.316	96%	4%
16:15_31	**Roundabout**	14.535	96%	4%
17:15_29	**Roundabout**	13.655	98%	2%
17:15_31	**Roundabout**	13.846	98%	2%

Table 42: May 29 and 31 Average Total CO_2 for Roundabout Comparison. This table indicates emissions from speed and idle time data from comparing same recording periods. The table indicates the percentage of contribution of CO_2 emissions from driving and idling.

The average total CO_2 emissions during the May 29 at 0715 recording period was 13.975 g and was 12.421 g during the May 31 at 0715 recording period. During the May 29 0715 recording period, 97 percent of emissions were from driving and 3 percent were from idling. During the May 31 at 0715 recording period, 97 percent of emissions were from driving and 3 percent were from idling.

The average total CO_2 emissions during the May 29 at 0815 recording period was 14.370 g and was 14.138 g during the May 31 at 0815 recording period. During the May 29 at 0815 recording period, 98 percent of emissions were from driving and 2 percent were from idling. During the May 31 at 0815 recording period, 98 percent of emissions were from driving and 2 percent were from idling.

The average total CO_2 emissions during the May 29 at 1615 recording period was 14.316 g and was 14.535 g during the May 31 at 1615 recording period. During the May 29 at 1615 recording period, 96 percent of emissions were from driving and 4 percent were from idling. During the May 31 at 1615 recording period, 96 percent of emissions were from driving and 4 percent were from idling.

The average total CO_2 emissions during the May 29 at 1715 recording period was 13.655 g and was 13.846 g during the May 31 at 1715 recording period. During the May 29 at 1715 recording period, 98 percent of emissions were from driving and 2 percent were from idling. During the May 31 at 1715 recording period, 98 percent of emissions were from driving and 2 percent were from idling.

Summary of Results

The results of this analysis were used to address all Research Questions. Research Question 1, (in which type of intersection do vehicles produce less carbon dioxide emissions?), sixteen t-tests were run comparing speed and idle time data at the signalized intersection and roundabout for both recording days in order to determine which intersection causes vehicles to produce more CO_2 emissions. There were thirteen significant t-tests and three non-significant tests. The average total CO_2 emissions from the calculations indicated that for the three recording period comparisons, the signalized intersection had more CO_2

emissions (May 29 at 0815, 1715; May 31 at 1615). The average total CO_2 emissions indicated that there were three recording period comparisons where the roundabout had more CO_2 emissions (May 29 at 0715; May 31 at 0715, 0815). The average total CO_2 emissions indicated that there were two recording period comparisons where CO_2 emissions were the same (May 29 at 1615; May 31 at 1715).

In order to address Research Question 2, (do carbon dioxide emissions vary during different hours of the day at each type of intersection?), 48 t-tests were run comparing speed and idle time data of each recording period on May 29. The same procedure was done for speed and idle time data on May 31. There were 15 significant t-tests and 33 non-significant t-tests. The total average CO_2 emission at the signalized intersection on May 29 indicated that CO_2 emissions varied for all recording period comparisons except one. The total average CO_2 emissions on May 29 at the roundabout indicated that there were two recording period comparisons where emissions varied and four recording period comparisons where CO_2 emissions did not vary.

The average total CO_2 emissions at the signalized intersection on May 31 indicated that there were four recording period comparisons where emissions varied and two recording period comparisons where emissions did not vary. The average total CO_2 emissions at the roundabout on May 31 indicated that there were four recording period comparisons where emissions varied and two recording periods where emissions did not vary.

To address Research Question 3, (do carbon dioxide emissions vary during different days of the week at each type of intersection?), sixteen t-tests were run comparing speed and idle time data of the same recording periods on the different recordings days. There were three significant t-tests and thirteen non-significant t-tests. The total average CO_2 emissions comparing May 29 to May 31 at the signalized intersection indicated that emissions varied for all recording period comparisons except for one. The total average CO_2 emissions comparing May 29 to May 31 at the roundabout indicated that emissions varied during one recording period and did not vary for three recording periods. An analysis of the results will be conducted in the next chapter.

CHAPTER V

DISCUSSION

Introduction

While Chapter IV reports statistical findings and the results of calculation of fuel consumption and CO_2 emissions, this chapter discusses and interprets these results in the context of the research questions. Specifically, Research Question 1 (in which type of intersection do vehicles produce less carbon dioxide emissions?) addresses the general issues of the performance of a signalized intersection and roundabout at emitting the least amount of CO_2. This study analyzed different hours and different days at both intersections to determine the efficiency of each intersection. The hypothesis is that the roundabout is better at reducing CO_2 emissions when compared to the signalized intersection. Research Question 2 (do carbon dioxide emissions vary during different hours of the day at each type of intersection?) addresses the issue of how different times of the day cause different intersections to perform differently as the traffic patterns vary between morning and afternoon peak hours. Research Question 3 (do carbon dioxide emissions vary during different days of the week at each type of intersection?) addresses how different days of the week, such as a weekday and weekend day can cause the signalized intersection and roundabout intersections to perform differently.

The first three sections address the three research questions in turn, and the last section summarizes the discussion and the findings. Since the three research questions are closely related and integrated, to answer any one question would necessarily involve the two other questions. As a result, instead of addressing the research questions one at a time, the chapter will first discuss the pattern of emissions in steps and then address the research questions all together.

It must be noted that the patterns between the different intersections, recording periods, and recording days that are discussed below are not from actual observed patterns. The patterns are derived from specific numbers within data, as data were not collected for whole days. Therefore, the patterns were not seen specifically but they are suggested by data and literature suggests the specific patterns that are discussed below (Perry and Owens 2011).

May 29 (WD) Analysis

CO_2 emissions from driving were calculated by using the average MPH and the driving distance at the signalized intersection and roundabout for all recording periods multiplied by necessary emission factors associated with speed and distance. Emissions from idling were calculated by using idling time multiplied by the relevant factor. The total CO_2 emissions per vehicle was the sum of the emissions resulted from driving within an intersection and the emissions from idling. Table 43 indicates the total emissions, driving emissions, and idling emissions at both intersections. Table 44 indicates the traffic volume, driving speed, and idle time at each intersection.

	Total CO_2 Emissions (g)		**Driving Emissions (g)**		**Idling Emissions (g)**	
May 29	**Roundabout**	**Intersection**	**Roundabout**	**Intersection**	**Roundabout**	**Intersection**
0715	14.06	11.93	13.67	9.36	0.39	2.57
0815	14.56	17.19	14.15	9.81	0.40	7.37
1615	14.51	14.60	13.79	9.19	0.72	5.40
1715	14.38	16.68	14.07	9.21	0.31	7.47

Table 43: May 29 Total CO_2 Emissions, Driving Emissions, and Idle Emissions for All Recording Periods at both Intersections.

	Traffic volume (Amount of Vehicles)		**Driving Speed (MPH)**		**Idling time (Seconds)**	
May 29	**Roundabout**	**Intersection**	**Roundabout**	**Intersection**	**Roundabout**	**Intersection**
0715	195	155	19.707	17.655	0.413	2.738
0815	180	110	18.556	14.328	0.429	7.864
1615	170	133	18.097	17.012	0.771	5.768
1715	142	118	17.966	16.984	0.331	7.967

Table 44: May 29 Traffic Volume, Driving Speed, and Idle Time for All Recording Periods at both Intersections.

May 29 (WD) Morning Recording Periods (0715 and 0815)

On May 29, during the 0715 recording period the signalize**d** intersection had less total average CO_2 emissions when compared to the roundabout. As shown in Table 43, the average total CO_2 emission at the signalized intersection was 11.927 g and was 14.062 g at the roundabout. From Table 43, of the two components of the total emissions (i.e. driving emissions and idling emissions), driving emissions were higher at the roundabout than at the signalized intersection (13.67 g v. 9.36 g). Although the idling emissions at the roundabout were lower than those at the signalized intersection (0.39 g vs. 2.57 g), the much higher driving emissions caused the higher total emissions at the roundabout than at the signalized intersection. Thus the higher emission per vehicle at the roundabout during 0715 was cause by higher driving emissions.

As analyzed in Chapter IV, the driving emissions were determined by driving distance and the driving speed. During 0715 on May 29, the average driving speed at the roundabout was higher than at the signalized intersection (19.77 MPH vs. 17.66 MPH). Although the higher speed was associated with lower emissions (Table 3 Chapter III), there was much longer driving distance within the roundabout than within the signalized intersection (213 feet vs. 91 feet during 0715 on May 29), which caused the driving emissions to be higher at the roundabout than at the signalized intersection. Even though some adjustments were made to make the driving distances comparable between the two intersections for this study, it still did not alter the fundamental fact that longer driving distance at the roundabout caused the higher driving emissions than at the signalized intersection.

During the 0815 recording period on May 29, the roundabout had less total average CO_2 emissions per vehicle when compared to the signalized intersection. The average total

CO_2 emission at the signalized intersection was 14.56 g and was 17.19 g at the signalized intersection. As seen in Table 43, the roundabout still had higher driving emission than the signalized intersection (14.15 g vs. 9.81 g). However, the idling emissions at the roundabout were much lower than at the signalized intersection (0.40 g vs. 7.37 g). In other words, it was the idling emissions that contributed to the reverse of the total emissions at the two intersections during 0815 on May 29.

While the higher idling emissions during 0815 were the direct cause of the total emission reversion from 0715 to 0815, the underlying reasons were the changing traffic pattern. From Table 44, it can be seen that during the 0715, within the signalized intersection, there was a larger traffic volume, higher driving speed, and shorter idling times than during 0815. This seems to suggest a process of traffic building up at the signalized intersection between 0715 and 0815, the two points in time during the morning peak hours. Because of the traffic build up, the driving speed decreased from 17.66 MPH to 14.33 MPH (an 18.9% decrease), and the traffic volume dropped from 155 to 110 vehicles (a 29% decrease) within the signalized intersection. At the same time, the average idling time changed to 2.74 seconds to 7.86 seconds or nearly 3 times as long.

At the roundabout, while the traffic was also building up from 0715 to 0815, it caused much less change in traffic patterns, compared with at the signalized intersection. For example, traffic volume decreased from 195 to 180 vehicles (an 8.3% decrease), the driving speed decreased from 19.71 MPH to 18.56 MPH (a 5.8% decrease). In addition, the idling time at the roundabout was virtually unchanged from 0715 to 0815. Compared with the signalized intersection, the roundabout seemed to have a more stable capacity in channeling the traffic during different hours. In contrast, the signalized intersection seemed to be better at channeling traffic during lighter traffic hours than during the busier hours. When traffic became heavier, the ability of channeling traffic at the signalized intersection was challenged and which caused the traffic to back up more significantly than at the roundabout. A clear indication was the much longer idling time. As stated earlier, it is the much longer idling time that caused the total emissions to be higher at the signalized intersection than at the roundabout during 0815.

May 29(WD) Afternoon Recording Periods (1615 and 1715)

During the 1615 recording period, the total average CO_2 emissions were approximately the same at the signalized intersection and the roundabout. As shown in Table 43, the average total CO_2 emissions per vehicle at the signalized intersection were 14.595 g and were 14.510 g at the roundabout. From Table 43, of the two components of the total emissions (i.e. driving emissions and idling emission) driving emissions were higher at the roundabout than at the signalized intersection (13.79 g vs. 9.19 g). Although the idling emissions at the roundabout were lower than those at the signalized intersection (0.72 g vs. 5.40 g) the similar average total CO_2 emissions at both intersections was caused from higher driving emissions at the roundabout, which in turn, as the previous discussion has already analyzed concerning the trade-off between driving speed and driving distance, was caused by the longer distances traveled at the roundabout.

During the 1715 recording period, the roundabout had less average total CO_2 emissions per vehicle when compared to the signalized intersection. The average total CO_2 emission at the signalized intersection was 16.68 g and was 14.38 g per vehicle at the roundabout. As indicated in Table 43, the driving emissions were still higher at the roundabout than at the signalized intersection (14.07 g vs. 9.21 g). However idling emissions at the roundabout were significantly lower than at the signalized intersection (0.31 g vs. 7.47

g). The long idle duration at the signalize intersection significantly increased the idling emissions which ultimately resulted in the signalized intersection having higher average total CO_2 emissions than the roundabout.

While the cause of the shift in average total CO_2 emissions between the 1615 and 1715 recording periods was due to significantly increased idle duration at the signalized intersection, the underlying cause was the changing traffic patterns. From Table 44, it can be seen that during the 1615 recording period at the signalized intersection there was lighter traffic volume, higher driving speed, and shorter idle duration than during the 1715 recording period. This seems to suggest that traffic was building up during the 1615 and 1715 recording period. It is the buildup of traffic that caused the decrease in driving speed from 17.01 MPH to 16.98 MPH (a 0.2% decrease) and the traffic volume dropped from 133 to 118 vehicles (an 11% decrease) within the signalized intersection. The traffic buildup also caused an increase of the average idle duration from 5.76 seconds to 7.97 seconds (a 38.4% increase).

As previously discussed during the morning recording periods (0715 and 1815), at the roundabout, the traffic was also building up during the 1615 and 1715 recording periods. This can be seen from a reduced vehicle volume from 170 vehicles to 142 (a 17% decrease), and the reduced driving speed from 18.09 MPH to 17.96 MPH (a 0.71% decrease). While the decrease in driving speed is less than 1% at both the roundabout and the signalized intersection, the pattern of a larger decrease in vehicle volume at the signalized intersection than at the roundabout is similar to the morning traffic pattern. However, while idling duration increased significantly at the signalized intersection, it decreased at the roundabout from 0.77 seconds to 0.33 seconds. This changing pattern not only deviates from the pattern observed in the morning (increasing idle duration), but also it contradicts intuition since traffic buildup would necessarily mean longer idling times. A possible explanation of this unusual pattern is that with a smaller traffic volume within the roundabout, it became easier for vehicles to enter and exit the roundabout which helped cut down the idling times.

It should be noted that the traffic buildup in the afternoon seemed to be much less than in the morning between the two recording periods. This is reflected in the smaller traffic volumes within the both intersections in the afternoon than in the morning, and in the marginal change in the driving speed in the afternoon. A smaller traffic buildup in the afternoon may be due to the possibility that the morning rush hours may happen within a short duration while the afternoon rush hours may last longer periods of time (Perry and Owens 2011). On the other hand, even though the afternoon traffic buildup was not as severe as in the morning, it still caused significant increase in the idling duration at the signalized intersection. As in the morning, it was much longer idle duration at the signalized intersection during the 1715 recording period than caused the roundabout to have lower average total CO_2 emissions during the 1715 recording period.

At different times of the day, during the morning and afternoon recording periods, the specific emissions are not exactly the same. For example, during the 0715 recording period at the signalized intersection total average emissions were 11.93 g and were 17.19 g during the 0815 recording period. While during the 1615 recording period emissions were 14.60 g and 16.68 g during the 1715 recording period. The total average emissions at the roundabout during the 0715 recording period was 14.06 g and was 14.56 g during the 0815 recording period while during the 1615 recording period emission were 14.51 g and 14.38 g during the 1715 recording period. However, the patterns in the morning and afternoon seem to demonstrate similarities. Specifically, in both morning and afternoon recording periods the total emissions were higher at the signalized intersection during the second recording period, which were caused by higher idling emissions as a result of much longer idling duration. On the first glance, the total emissions during the first recording period in the morning were higher at the roundabout than at the signalized intersection, while those during the second recording period were similar at both intersections. It is possible that the similarity of total emissions between both intersections was because the recording period may have simply captured a particular moment in a transition of the signalized intersection switching from more emissions to less and the switch at the roundabout changing from fewer emissions to more emissions during the afternoon recording periods.

May 31 (WE) Analysis

Table 45 indicates the total emissions, driving emissions, and idling emissions at both intersections. Table 46 indicates the traffic volume, driving speed, and idle time at each intersection.

	Total CO_2 Emissions (g)		Driving Emissions (g)		Idling Emissions (g)	
May 31	**Roundabout**	**Intersection**	**Roundabout**	**Intersection**	**Roundabout**	**Intersection**
0715	13.62	10.72	13.26	8.72	0.36	2.00
0815	14.03	12.51	13.84	9.08	0.19	3.44
1615	14.42	15.39	13.93	9.05	0.49	6.34
1715	13.78	13.23	13.60	9.02	0.18	4.20

Table 45: May 31 Total CO_2, Driving Emissions, and Idle Emissions for All Recording Periods at both Intersections.

	Traffic volume (Amount of Vehicles)		Driving Speed (MPH)		Idling time (Seconds)	
May 31	**Roundabout**	**Intersection**	**Roundabout**	**Intersection**	**Roundabout**	**Intersection**
0715	49	32	19.040	17.306	0.386	2.135
0815	73	48	18.604	18.039	0.200	3.665
1615	103	93	18.224	16.310	0.523	6.767
1715	112	78	18.373	16.707	0.919	4.490

Table 46: May 31 Traffic Volume, Driving Speed, and Idle Time for All Recording Periods at both Intersections.

May 31(WE) Recording Periods (0715 and 0815)

On May 31, during the 0715 recording period, the signalized intersection had less total average CO_2 emissions when compared to the roundabout. As shown in Table 45, the average total CO_2 emission per vehicle at the signalized intersection was 10.720 g and was 13.618 g at the roundabout. Table 45 indicates that driving emissions were higher at the roundabout than at the signalized intersection (13.26 g vs. 8.72 g). Although idle emissions at the roundabout were lower than emissions at the signalized intersection (0.36 g vs. 2.00 g), the much higher driving emissions caused the roundabout to have higher total emissions than the signalized intersection. Therefore the higher CO_2 emission per vehicle at the roundabout during the 0715 recording period was caused by higher driving emissions. As analyzed previously, although higher speed at the roundabout was associated with lower emissions (Table 3 Chapter III), the longer driving distance within the roundabout caused higher emissions than the signalized intersection.

Similarly to the 0715 recording period, during the 0815 recording period, the signalized intersection had less total average CO_2 emissions. As shown in Table 45, the average total CO_2 emission per vehicle at the signalized intersection was 14.03 g vs. 12.51 g. Table 46 indicates that driving emissions at the roundabout were still higher than driving emissions at the signalized intersection. Although idle emissions at the roundabout were lower than at the signalized intersection (0.19 g vs. 3.44 g) the higher driving emissions is what caused the roundabout to emit the most amount of CO_2 emissions per vehicle during the 0815 recording period.

Although the pattern of emissions appeared to be similar between 0715 and 0815 on May 31, there were actually gradual buildup of traffic with the consequences of increasing vehicle volume, reduced driving speed, and longer idling duration. Specifically, the signalized intersection traffic volume increased from 32 vehicles to 48 (a 50% increase) and the roundabout traffic volume increased from 49 vehicles to 73 vehicles (a 49% increase). The increase in traffic volume caused idle duration to increase from 2.135 seconds to 3.665 seconds at the signalized intersection (a 76% increase).

May 31(WE) Afternoon Recording Periods (1615 and 1715)

During the 1615 recording period the roundabout had less average total CO_2 emissions than at the signalized intersection. As seen in Table 45, the average total CO_2 emission at the roundabout was 14.418 g and was 15.391 g at the signalized intersection. Table 45 indicates that the roundabout still had higher driving emissions than the signalized intersection (13.93 g vs. 9.05 g). However, the idling emissions at the roundabout were much lower than at the signalized intersection (0.49 g vs. 6.34 g). Therefore it is clear that the longer idle duration at the signalized intersection caused higher idling emissions, which contributed to the higher total emissions at the signalized intersection than at the roundabout.

During the 1715 recording period, the total average CO_2 emissions were approximately the same at the signalized intersection and the roundabout. As shown in Table 45, the average total CO_2 emissions per vehicle at the signalized intersection were 13.23 g and were 13.78 g at the roundabout. From Table 45, of the two components of the total emissions (i.e. driving emissions and idling emission) driving emissions were higher at the roundabout than at the signalized intersection (13.60 g vs. 9.02 g). Although the idling emissions at the roundabout were lower than those at the signalized intersection (0.18 g vs. 4.20 g) the cause of similar average total CO_2 emissions at both intersections was clearly due to shorter duration of idling at the signalized intersection and longer distanced traveled at the roundabout, given the fact that the lower emissions from higher driving speeds cannot offset the higher emissions from the longer driving distance at the roundabout, as previously discussed.

Between the 1615 and 1715 recording periods, there seemed to be a traffic lessening process, in that driving speed became higher in both intersections, vehicle volume became higher in the roundabout, and the idling duration became shorter. The driving speed increased from 16.310 MPH to 16.707 MPH (a 2.4% increase) at the signalized intersection and 18.224 MPH to 18.373 MPH (a 0.08% increase) at the roundabout. Vehicle volume increased from 103 vehicles to 112 (an 8.7% increase) at the roundabout and idle duration at the signalized intersection decreased from 6.767 seconds to 4.490 (a 33.6% decrease) seconds. Given the increasing driving speed and lessening idling time, vehicle volume within the signalized intersection can be taken as evidence that there was a traffic lessening process. As discussed previously, under lighter traffic volume, the signalized intersection can channel traffic more smoothly than under heavier traffic. Thus, it is this lessening of traffic that may have caused the idling time to reduce significantly which in turn reduced the idling emissions at the signalized intersection and caused the total emissions to be similar between the two intersections.

As mention previously, from 0715 to 0815 on May 31, traffic was building up into the afternoon recording periods. During the 1615 recording period the signalized intersection had the highest traffic volume and longest idle duration when compared to the roundabout (6.767 seconds vs. 0.523 seconds). This seems to suggest that the traffic volume was building up over the morning recording periods into the 1615 recording period in the afternoon. At the high traffic hour recorded during 1615, the total emissions at the signalized intersection rose above those at the roundabout (15.93 g vs. 14.42 g). After the high traffic hour during 1615, a declining traffic volume (93 vehicles to 78 vehicles), which was a 16.1% decrease, caused the total emissions at the signalized intersection to became lower allowing for approximately the same emissions at both intersections.

May 29 (WD) to May 31 (WE) Analysis

CO_2 emissions between the signalized intersection and roundabout varied between the May 29 and May 31 recording days. The variation in emissions was due to very different traffic patterns that affected traffic volume, driving speed, and idle duration. During the May 29 recording day, a weekday, it seemed that the signalized intersection experienced higher total emissions at the peak traffic hours, both in the morning and afternoon. The opposite is true for the roundabout with higher total emissions at the non-peak traffic hours in both morning and afternoon (Figure 14). This changing pattern of total emissions seemed closely associated with the weekday traffic pattern with a peak traffic hour in the morning and afternoon. In general, during the non-peak traffic hours, the signalized intersection can channel traffic with no significant difficulties. The shorter idle duration leads to lower idling emissions and thus lower total emissions. At the same time, the roundabout generates higher driving distances, which led to higher driving emissions and thus higher total emissions. On the other hand, during the peak traffic hours, the signalized intersection was under pressure to channel heavier traffic and idle duration became significantly longer than during non-peak traffic hours, which caused the idling emissions to rise and the total emissions to surpass those at the roundabout. The roundabout emissions stayed relatively the same throughout the recording period throughout the recording day (Figure 15). Since there were two peak traffic hours during the weekday, such total emissions switched twice in one day, as shown in the two recording periods on May 29.

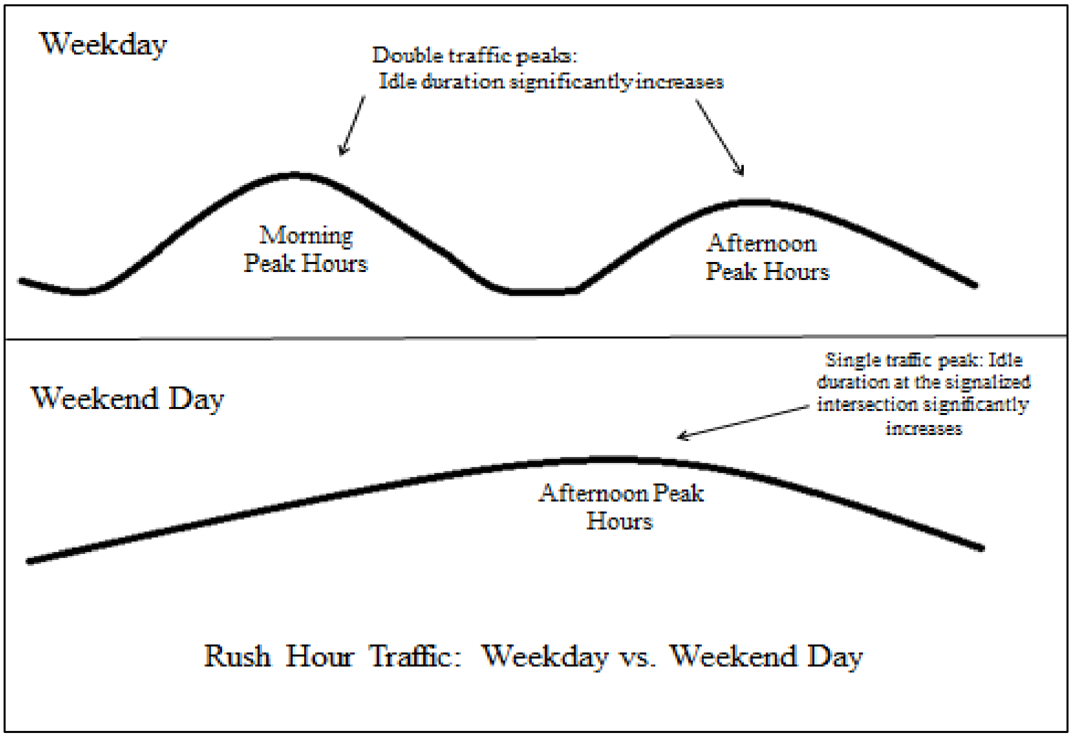

Figure 14: Weekday and Weekend Day Peak Hour Demonstration. This demonstration shows at the when the idle duration at the intersection significantly increased. The weekday recording day had two peak hours while the weekend day had only one peak hour.

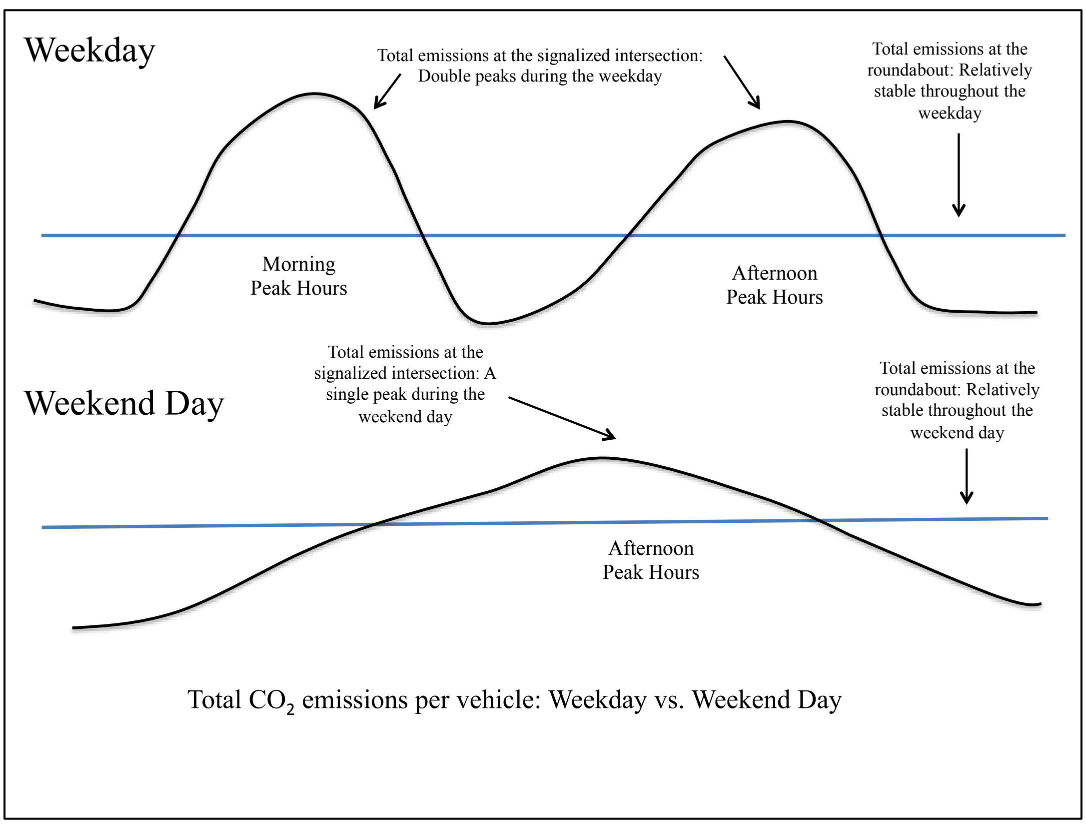

Figure 15: Emissions of Weekday and Weekend Day Peak Hours Demonstration. This demonstration shows emissions at the roundabout stayed relatively the same throughout the week day and weekend day. When peak hour occurred at the signalized intersection, the roundabout emitted the least amount of emissions.

On May 31, the weekend day, the pattern remains that the higher total emissions occurred during the non-peak traffic hour at the roundabout but during the peak traffic hour at the signalized intersection. The only difference is that there was only one peak traffic period (Figure 14). During the one peak traffic period, the signalized intersection generated a longer idling duration, leading to higher idling emissions and thus higher total emissions than at the roundabout. The total average CO_2 emissions at the roundabout stayed relatively the same throughout the recording day on May 31. For all other times when there was non-peak hour traffic, the roundabout generated higher total emissions due to longer driving distance (Figure 15).

It appeared that a key for a switch from the roundabout to the signalized intersection as the higher emissions intersection is the relative weight of idling emissions in comparison with the driving emissions. It was found that the total emissions at the signalized intersection became higher than at the roundabout when the contribution of emissions from idling was over 40 percent. On both recording days there were three instances where the roundabout had less total CO_2 emissions than the signalized intersection (0815 and 1715 on May 29 and 1615 on May 31). During these recording periods, the percent of CO_2 emissions from idling were between 41 percent and 45 percent. It can be concluded that the total emissions at the signalized intersection lower when the contribution of idle time is less than 41 percent, largely as a result of less idle time at the intersection. Therefore, it depends on the idle duration at the signalized intersection if the signalized intersection more efficient or less efficient at emitting fewer amounts of CO_2 emissions when compared to the roundabout. In Table 47 below, indicates a summary of the main results that were discussed in this chapter.

Date	Time	Intersection	Total Emissions (g)	Speed Data T-Test	Idle Time T-Test
May 29 (WD)	0715	Signalized	11.927	Significant	Significant
		Roundabout	14.063		
	0815	Signalized	17.190	Significant	Significant
		Roundabout	14.558		
	1615	Signalized	14.595	Significant	Significant
		Roundabout	14.510		
	1715	Signalized	16.683	Not Significant	Significant
		Roundabout	14.377		
May 31 (WE)	0715	Signalized	10.720	Not Significant	Significant
		Roundabout	13.619		
	0815	Signalized	12.512	Not Significant	Significant
		Roundabout	14.030		
	1615	Signalized	15.391	Significant	Significant
		Roundabout	14.418		
	1715	Signalized	13.232	Significant	Significant
		Roundabout	13.781		

Table 47: Results Summary Table. This table indicates the total emissions, and if the two-sample t-tests for speed and idle data were significant or not significant when comparing the signalized intersection to the roundabout for all recording period and recording days.

Addressing Research Questions

Based on the above analysis, the three research questions can now be addressed. For Research Question 1 it is clear that neither an intersection demonstrates lower emissions at all times and under all circumstances. It is possible that there would be a significant difference between the signalized intersection and roundabout with heavier volumes of traffic occurring at each type of intersection. The signalized intersection was the most efficient at emitting the least amount of CO_2 emissions during the 0715 on May 29 and during 0715 and 0815 recording periods on May 31. The roundabout was the most efficient at emitting the least amount of CO_2 emissions during the 0815 and 1715 recording periods on May 29 and the 1615 recording period on May 31. Both intersections had similar emissions during the 1615 and 1715 recording periods.

As for Research Question 2, CO_2 emissions did vary in the different recording periods. The general pattern seemed to be that during the non-peak traffic hours, the signalized intersection could channel traffic with no significant difficulties. The short idle duration led to lower idling emissions and thus lower total emissions than at the roundabout, which generated higher driving distances leading to higher driving emissions and thus the higher total emissions. During the peak traffic hours, the signalized intersection was not able to channel heavier traffic and idle duration, which, caused the idling emissions to rise, and the total emissions to surpass those at the roundabout.

As for Research Question 3, the pattern of CO_2 emissions did vary between May 29 and May 31, or between weekday and weekend day. On both days, the higher total emissions occurred during the non-peak traffic hours at the roundabout but during the peak traffic hour at the signalized intersection. However, on May 29 (WD) there were two peak hours, one morning and one afternoon. Thus during these two peak traffic hours, the signalized intersection generated higher total emissions. For the rest of the day when non-peak hour traffic occurred, the roundabout generated higher total emissions due to longer driving distances. On May 31 (WE), the weekend day, there was only one peak traffic hour in the early afternoon when the signalized intersection generated higher total emissions. For the rest of the day when there was non-peak hour traffic, the roundabout generated higher total emissions.

After analyzing the results of this study, it was found that the emissions model used previously was revised as the results indicated that the average speed at each intersection was not what set the signalized intersection and the roundabout apart. What caused differences between each intersection were the longer driving distances at the roundabout and longer idle duration at each signalized intersection. The revised model will be indicated with the number three below.

Emissions = F (driving pattern, speed, idle duration)

[2]

Emissions = F (driving pattern, driving distance, and idle duration)

[3]

When the signalized intersection was more efficient than the roundabout, the higher emissions at the roundabout were due to longer driving distances at the roundabout even though a distance adjustment was implemented. When the roundabout was more efficient than the signalized intersection, the higher emissions are due to the longer idle duration at the signalized intersection. Therefore, longer driving distances at the roundabout and longer idle duration at the signalized intersection are the two components that allowed for the variation in efficiency of emitting the least amount of CO_2 emissions between both intersections.

The results from this study have similarities when compared to existing literature of the research topic overall. This study found that idle duration at the signalized intersection during increased traffic during the peak traffic hours set apart the signalized intersection from the roundabout. When traffic volume increased, the signalized intersection was no longer able to emit fewer CO_2 emissions when compared to the roundabout (Coelho et al. 2006; Ahn et al. 2009). Also, results from this study indicated that the roundabout was the better option when compared to the signalized intersection during the peak hours. During the peak hours the signalized intersection emitted more emissions due to increased idling, which did not occur at the roundabout. Ariniello and Przybyl studied fuel consumption and CO_2 emissions by time of day and analyzed data for when the roundabout was more efficient than signalized and non-signalized stoplights for the different traffic volumes. Ariniello and Przybyl also indicated that for low and high traffic volumes, the roundabout has the highest reduction in emissions during the peak hours (Ariniello and Przybyl 2010). Therefore, this study and existing literature have determined that the roundabout is more efficient at emitting the least amount of emissions during peak hours than the signalized intersection. Ariniello and Przybly indicated that emissions varied between different hours of the day, which was directly shown in the results of this study.

The results of this study also showed different conclusions than existing literature. It was found that when the percentage of emissions from idling exceeded 41 percent at the signalized intersection, it was no longer more efficient than the roundabout. Höglund and Niittymäki indicated that the signalized intersection was the best alternative intersection during maximum hour traffic while the results of this study indicated that during the peak hours where traffic volume was higher, the signalized intersection was not more efficient than the roundabout and caused higher emissions due to the increased idle duration. Therefore, the results of this study indicated similarities and differences when compared to the results of existing literature.

In conclusion, neither intersection was the most efficient at emitting the least amount of CO_2 under all circumstances. There were three instances where the signalized intersection and the less amount of CO_2 per vehicle while there were also three instances where the roundabout had the least amount of CO_2 emissions per vehicle. In addition, there were two instances where the CO_2 emissions were approximately the same at both intersections. CO_2 emissions did vary between the different recording periods and different recording days. The changes in emissions during the different recordings periods were due to the peak hours that occurred which were caused by the changing traffic pattern. When comparing May 29 (WD) and May 31 (WE), the weekday has two peak hours while the weekend day only has one peak hour.

CHAPTER VI

CONCLUSION

This study investigated the CO_2 emissions levels at intersections with two types of traffic control methods in order to determine which type experiences lower levels of CO_2 per vehicle. Specifically, this study compares a signalized intersection and a roundabout in Belleville, Illinois in order to assess which system has a more efficient traffic control mechanism and thus helps to reduce carbon dioxide emissions. In order to analyze emissions at the roundabout and the signalized intersection, three research questions were asked: (1) Is the average vehicle speed and idle time significantly different at each intersection?; (2) In which type of intersection, do vehicles produce less carbon dioxide emissions?; (3) Do carbon dioxide emissions vary during different hours of the day and different days of the week at each type of intersection?

Findings

This study found that neither intersection was more efficient at lowering emissions per vehicle under all circumstances. CO_2 emissions varied between different times of the day and between the weekday and weekend day. The signalized intersection generated lower total emissions per vehicle than the roundabout during off-peak hours. This is the result of short idling time and lower idling emissions at the signalized intersection and long driving distance and higher driving emissions at the roundabout. On the other hand, the roundabout produced lower total emissions per vehicle than at the signalized intersection during peak hours. During peak hours, increased traffic volume led to a significant increase in idle duration and additional CO_2 emissions at the signalized intersection. In essence, the peak hours versus the off-peak hours are an indication in changes in traffic volume and thus, CO_2 emissions. The above pattern helps determine the emission variation throughout the day, and is also closely related to the difference in emissions between the weekday and the weekend day.

During the weekday, there were clearly morning and afternoon peak hours. Thus it was observed that twice in the day during the peak hours the total emissions per vehicle at the signalized intersection surpassed that at the roundabout. On the weekend day, there appeared to be only one peak hour. Thus it was observed only one time in the day during the peak hours the total emissions per vehicle at the signalized intersection surpassed that at the roundabout.

Most literature indicated that the roundabout significantly reduced emissions when compared to the signalized intersection (Hyden and Várhelyi 2000; Várhelyi 2002; Mandavilli et al. 2008; Correire et al. 2013; Guerrieri et al. 2013) while it was found in this study that there were times when the roundabout experienced lower emissions than the signalized intersection (i.e. peak hours) and when the signalized intersection was more efficient than the roundabout (i.e. off-peak hours). Therefore, it could not be concluded that roundabout was the better alternative of a traffic mechanism when compared to the signalized intersection for this study for all days and times.

Although one intersection was not efficient under all circumstances for this study, recommendations to the City of Belleville can be made. As the results of this study indicated, the roundabout is better at lowering emissions during peak hours. Therefore, cities that are facing growing populations and thus increasing traffic, roundabouts may be appropriate, even for mid-sized cities like Belleville, Illinois. The future expansion of roundabouts should be evaluated according to the trend of population growth. The U.S. Census data indicates that the population of Belleville increased from 2000 to 2010, which may be the reason for the implementation of roundabout within their city. The U.S. Census data also indicates that the population of Belleville since 2010 has shown a decreasing trend; therefore the future population growth is uncertain. If Belleville decides to replace signalized intersections with roundabouts, it will cost a large amount of money and land in order to do so. Additionally, this study only analyzed the emissions factor of roundabouts and not the traffic control management. As the study indicated, the traffic volumes directly affected the average total emissions therefore this aspect should also be analyzed before the consistent implementation of roundabouts in a mid-sized city like Belleville, IL Overall, Belleville should be cautious with their implementations of roundabouts within the city and should analyze each potential intersection.

Contributions

The study contributes to existing literature in several important ways. Most studies which compare emissions at signalized and roundabout intersections focus on large cities. Since city size may affect traffic patterns and the emission patterns, conclusions drawn from larger cities may not apply to cities of smaller sizes. This study contributes to the literature by examining a medium-sized suburban city, Belleville, Illinois. The literature also draws different conclusions regarding during what hours throughout the day roundabouts are better at reducing the emissions compared to signalized intersections. In addition, the issue of how the weekday emission patter differs from the weekend pattern has not been adequately addressed in other studies. This study reassesses the issue of emissions at different hours of the day and also compares the weekday and weekend emission patterns.

Another contribution is methodological, in most studies traffic counts were used along with other methods such as, computer programs like aaSIDRA or MOBILE6, to calculate emissions at each type of intersection. Computer software provides emission simulations with great accuracy. A drawback is that the researcher needs to provide a great deal of detailed information such as quality of roads, time (season, months, etc.), the vehicle model, age of the vehicle, driving speed, etc. in order to obtain accurate computer simulations. These types of information may not be readily available and are expensive and time-consuming to generate, which necessarily results in a long study cycle. This study used traffic count data and duration in the intersection to calculate the speed of each vehicle, the average time traveling through the intersection, and idling time for each recording period. These data were then used to calculate fuel consumption and CO_2 emissions. This method may not generate results as accurate as computer simulation. However, it requires a smaller amount of data input, it was easy to implement, generated quick results. For studies that examine the general pattern at the preliminary stage of investigation, it may have its own advantages.

Limitations

Similar to all research, there were limitations to this study. There were many researchers that used traffic count data to determine CO_2 emissions as this study did (Höglund and Niittymäki 1998; Isebrands and Hallmark 2006; Cerdeira et al. 2007; Ahn et al. 2009; Ariniello and Przybyl 2010) but in addition to traffic count data, these researchers also analyzed more hours of traffic count data, the manners of driving at each type of intersections, specifically examining deceleration, acceleration, and idle time. Due to logistical restraints, such as access to necessary computer programs that most researchers used, such as aaSIDRA, analysis of the driving patterns and to calculation of fuel consumption and CO_2 emissions were not possible. Also, it is possible if more recording periods and recording days were used, that data and results could have varied. These are also limitations to this study as some studies suggest that driving patterns can significantly alter the amount of fuel consumption and vehicular emissions.

I was not able to gather *in situ* CO_2 emissions like other studies accomplished (Reddy et al. 2006; Hallmark et al. 2011). Alternatively, my emission levels were estimated based on calculations provided by Wisconsin Transportation Economic Analysis Guidelines and aaSIDRA. It would be ideal to be able to gather CO_2 levels at each intersection, but access to these tools was not possible. In addition, since the original methodology of this thesis used combined aspects of calculating emissions from two different sources it must be noted that this can lead to conversion differences because of the different standards of the different researchers, which ultimately leads to inaccuracy with calculations.

Future Research

For future research regarding this study, it would be easier if computer programs like aaSIDRA were accessible in order to calculate fuel consumption and emissions. This program would also allow the analysis of driving patterns, which are said to alter fuel consumption and emissions while approaching and going through an intersection (Várhelyi 2002; Coelho et al. 2006). If computer programs like this were to be used, it would give a better idea of exact fuel consumption and CO_2 emissions at each intersection rather than using averages.

In addition to using computer programs, addition or longer recording periods would be useful. This study was limited to five-minute segments, which did not allow for large sample sizes. An increase in recording periods, duration of recording period, and recording days would allow for a better analysis of traffic count data. Also, the location of the video recorders could have been placed in a better location to allow more visibility. Since the visibility of the video recorders was limited, it did not allow for the analysis of driving patterns of vehicles as they approached and exited each intersection.

Conclusion

As the climate on Earth continues to change, it is essential to discover ways to decrease the severity of what is to come. GHG emissions are hazardous to our climate and are increasing drastically in our atmosphere (U.S. EPA 2014). As the transportation sector is the second largest cause of emissions into the atmosphere it is essential to implement the best traffic control methods in order to reduce emission in this sector. This study was inconclusive of which type of intersection, signalized intersection or roundabout, emits the least amount of emissions. The results indicated that signalized intersection causes higher emissions than the roundabout due to idle duration when heavy traffic volumes are present during peak hours and the roundabout has higher emissions during off-peak hours due to longer driving distances through the intersection. Since this area of study is site specific, it is essential to conduct this study in different geographical locations in varying sized urban locations to further address the issue of which intersection types experience lower GHG emissions, specifically CO_2, to help mitigate the effects of transportation on our changing climate.

REFERENCES

Ahn, K., Nopadon K., and H. Rakha. 2009. "Energy and Environmental Assessment of High-speed Roundabouts." *Transportation Research Record*, no. 2123: 54-65.

Akçelik, R., and M. Besley. 2003. "Operating Cost, Fuel Consumption, and Emission Models in aaSIDRA and aaMOTION." In *25th Conference of Australian Institutes of Transport Research (CAITR 2003)*, pp. 1-15.

Ariniello, A., and B. Przybyl. 2010. "Roundabouts and Sustainable Design." In *Green Streets and Highways 2010: An Interactive Conference on the State of the Art and How to Achieve Sustainable Outcomes*. 82-93. Denver, Colorado.

Cerdeira, R., C. Louro, L. Coelho, J. Garcia, C. Gouveia, P.J. Coelho, and T. Bertrand. 2007. "Traffic Pollutant Emissions in Barreiro City." In *Air Pollution XV: WIT Transactions on Ecology and the Environment,* 311-320.

Coelho, M. C., T. L. Farias, and N. M. Rouphail. 2006. "Effect of Roundabout Operations on Pollutant Emissions." *Transportation Research Part D: Transport and Environment* 11, no. 5: 333-343.

Correire, F., G. Rizzo, and M. Guerrieri. 2013. "Estimation of Air Pollutant Emissions in 'turbo' and Conventional Roundabouts." *Applied Mechanics and Materials*, no. 394: 597-604.

Dabbas, W. M. 2004. "A Critical Look at the Relationships Between Urban Transport Systems and Vehicle Emissions." In 29th *Australasian Transportation Research Forum*, 1-15. Sydney, Australia.

Guerrieri, M., F. Corriere, G. Parla, D. Di Vincenzo, and A. Messineo. 2013. "Reducing Air Pollutants Through Road Innovative Intersections." *Applied Mechanics and Materials,* no. 459: 563-568.

Hallmark, S., B. Wang, A. Mudgal, and H. Isebrands. 2011. "On-Road Evaluation of Emissions Impact of Roundabouts." *Journal of the Transportation Research Board* 2265, no.1: 226-233.

Hallmark, S., and A. Mudgal. 2011. "Comparison of Emissions at Roundabouts Compared to Traditional Traffic Control." In *Proceedings of the 2011 Annual Meeting of the Air and Waste Management Association*. 415-420. Orlando, Florida.

Höglund, P.G., and J. Niittymäki.1998. "Traffic Signal or Roundabout? Intersection Design and Air Pollution." In *Proceedings of the International Conference on Urban Transport and the Environment for the 21st Century,* 329-337.

Hyden, C., and A. Varhelyi. 2000. "The Effects on Safety, Time Consumption, and Environment or Large-scale Use of Roundabouts in an Urban Area: A case study." *Accident Analysis and Prevention*, no. 32: 11-23.

Isebrands, H., and S. Hallmark. 2006. “Assessing the Air Quality Benefits of Roundabouts.” In 2006 Air and Waste Management Association Annual Meeting, New Orleans, LA.

Kozak, M., D. Nijak, K. Kozak, J. Merkisz, and A. Merkisz-Guranowska. 2013. “The analysis of the Environmental Impact of Road Traffic in a Transport Node on the Example of the Rondo Rataje Roundabout in Poznan.” *Urban Transport XIX* 130: 473-484.

Lima, E., B. Bertoncini, and M. Gimenes. 2013. “Simulation of the Impact on Carbon Monoxide Concentration Resulting from Replacing a Signalized Intersection with a Roundabout.” *International Journal of Environment and Pollution* 52, no. 3: 141-154.

Mandavilli, S., M. J. Rys, and E. R. Russell. 2008. “Environmental Impact of Modern Roundabouts.” *International Journal of Industrial Ergonomics* 38, no. 2: 135-42.

Mutasem, E.F., Najm, M.A., and H. Sbayti. 2000. “Air Quality Assessment at Congested Urban intersection.” In *Department of Civil and Environmental Engineering Report*. American University of Bierut.

Perry, J. L., P. M. Owens. 2011. “Weekday/Weekend Variability and Long-Term Trends in Traffic, CO, NOy, and Ozone for the Charlotte Metropolitan Area During the 1990’s.” Proceedings of the Air and Waste Management Associations’ 94th Annual Conference and Exhibition, Orlando, FL.

Reddy, V., R. Sivanandan, and S.P. Anusha. 2006. "Evaluation of Signal Interruptions on Vehicular Emissions." *Indian Institute of Technology, Department of Civil Engineering* 26, no. 4: 363-386.

Várhelyi, A. 2002. "The Effects of Small Roundabouts on Emissions and Fuel Consumption: A Case Study." *Transportation Research Part D: Transport and Environment* 7, no. 1: 65-71.

U.S. Census. 2014. "State and Country Quick Facts. Belleville, Illinois. Population Estimate 2013" U.S. Census Bureau, 2013. http://quickfacts.census.gov/qfd/states/17/1704845.html.

U.S. EPA. 2011. National Air Quality and Emissions Report, 2011. United States of America Environmental Protection Agency. Research Triangle Park; NC.

U.S. EPA. 2014. Climate Change: Basic Information. United States of American Environmental Protection Agency.

Wisconsin Transportation. 2014. "Effect of Operating Speed on Fuel Consumption." Wisconsin Transportation Economic Analysis Guidelines. Madison, WI. http://www.wisdot.info/economics/index.php?title=Financial_Assumptions_and_Parameters