Accelerating Roundabout Implementation in the United States – Volume III of VII

Assessment of the Environmental Characteristics of Roundabouts

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U.S. Department of Transportation
Federal Highway Administration

Safe Roads for a Safer Future
Investment in roadway safety saves lives

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

FOREWORD

Since the Federal Highway Administration (FHWA) published the first *Roundabouts Informational Guide* in 2000, the estimated number of roundabouts in the United States has grown from fewer than one hundred to several thousand. Roundabouts remain a high priority for FHWA due to their proven ability to reduce severe crashes by an average of 80 percent. They are featured as one of the Office of Safety *Proven Safety Countermeasures* and were included in the *Every Day Counts 2* campaign for Intersection & Interchange Geometrics.

As roundabouts became more common across a wide range of traffic conditions, specific questions emerged on how to further tailor certain aspects of their design to better meet the needs of a growing number and diversity of stakeholders. The substantial work performed for this project – *Accelerating Roundabout Implementation in the United States* – sought to address several of the most pressing issues of National significance, including enhancing safety, improving operational efficiency, considering environmental effects, accommodating freight movement and providing pedestrian accessibility. This work represents yet another notable step forward in advancing roundabouts in the United States.

The electronic versions of each of the seven report volumes that document this project are available on the Office of Safety website at http://safety.fhwa.dot.gov/.

Michael S. Griffith
Director
Office of Safety Technologies

NOTICE

QUALITY ASSURANCE STATEMENT

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16. Abstract

This volume is third in a series of seven. The other volumes in the series are: Volume I – Evaluation of Rectangular Rapid-Flashing Beacons at Multilane Roundabouts, Volume II – Assessment of Roundabout Capacity Models for the Highway Capacity Manual Final Report, Volume IV – A Review of Fatal and Severe Injury Crashes at Roundabouts, Volume V – Evaluation of Geometric Parameters that Affect Truck Maneuvering and Stability, Volume VI – Investigation of Crosswalk Design and Driver Behaviors, and Volume VII – Human Factor Assessment of Traffic Control Device Effectiveness. These reports document a Federal Highway Administration (FHWA) project to investigate and evaluate several important aspects of roundabout design and operation for the purpose of providing practitioners with better information, leading to more widespread and routine implementation of higher quality roundabouts.

This research sought to develop a simple methodology for estimating pollutant emissions generated at roundabouts and comparing them to those generated at signalized intersections. The premise for this research is that the environmental performance is tied to the operational performance of the roundabout, with emission levels being sensitive to levels of traffic volume and congestion. The research resulted in empirically-based vehicle activity models and emissions models for roundabouts and signalized intersections. The activity models take into account driver behavior, traffic conditions and infrastructure design, and were produced under consideration of three trajectory types though the intersections as a function of the demand volume and, when appropriate, signal timing. The emissions models were based on Portable Emissions Measurement System (PEMS) data, and consider vehicle specific power (VSP) distributions for vehicles measured at roundabouts and signalized intersections. Combining the two models via the VSP approach resulted in emission estimates near the intersections at various temporal and spatial scales. All models are macroscopic in nature and were implemented in a spreadsheet-based emissions computational engine. The analysis approach is most suitable in a planning-level assessment of roundabouts in relation to traffic signals. Results indicate that emissions rates at roundabouts tended to be lower than those at intersections (1) for demand-to-capacity (d/c) ratios less than 0.7, (2) for higher d/c ratios if signal progression at the intersections was poor, and (3) in general for oversaturated periods.

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CHAPTER 1. INTRODUCTION

Intersections are a major source of congestion on arterial streets. Signal optimization, alternative intersection designs, or alternative routes for traffic are among the techniques employed to mitigate intersection congestion. Congestion is deemed to be a significant source of vehicle emissions, because stop-and-go traffic and associated acceleration/deceleration patterns have been linked to increased emissions. Roundabouts can have operational and safety benefits over signalized intersections under certain circumstances. For example, the average vehicle delay can be significantly lower during off-peak periods for roundabouts compared to signalized intersections, and under peak traffic conditions, roundabouts can often match or even outperform traffic signals operationally. Due to the geometric and design characteristics of roundabouts, they can function as a traffic calming device, and they have been shown to provide substantial safety benefits over signalized intersections.

Roundabouts have also been characterized as a more environmentally-friendly form of intersection based on analyses comparing them to conventional signalized intersections.[1] In these analyses, simulation models determined that roundabouts experienced lower emissions due to less stop-and-go traffic patterns. However, the hypothesis that roundabouts experience lower vehicle emissions than signalized intersections has been largely untested. It has neither been field tested nor substantiated by extensive empirical research using vehicle emission patterns collected at roundabouts in the field.

The premise for this research is that the environmental performance of roundabouts is tied to their operational performance, with emission levels sensitive to traffic volume and congestion. An increase in traffic volume leads to an increase in stop-and-go traffic patterns, which in turn leads to an increase in emissions. The evaluation of the environmental performance of roundabouts therefore requires quantification of factors impacting their operation. The research also sought to create comparable methods for calculating emissions at roundabouts and at signalized intersections, so the results could be compared.

This research explored emission patterns of vehicles traversing roundabouts through empirical analysis of vehicle trajectories, and proposes a methodology to compare emissions generated at roundabouts to those generated at signalized intersections. The research incorporated emission factors for different classes of passenger cars and passenger trucks, any combination of which can be tested. Heavier classes of trucks were not included in this research, because calculating their emissions requires a different methodology. This research categorized roundabouts and signalized intersections into two bins based on approach speed: high speed (greater or equal to 56 km/h (35 mph)); and low speed (less than 56 km/h (35 mph)). Two predictive models were developed for the two speed groups.

BACKGROUND

A great deal of research has been performed regarding emissions generated at roundabouts. That research includes a large and diverse set of methods, and a similarly large and varied set of findings and conclusions. The lack of consensus in the research community, with respect to both methods and findings, justified this research. Before the literature is reviewed, some fundamental emission terms and variables must be defined to put the review in context.

First, five major factors impact vehicle fuel consumption and vehicle emissions on any roadway segment or intersection,[2] namely:

1. Driver behavior, especially in relation to vehicle acceleration/deceleration and driver aggressiveness.
2. Vehicle attributes, including vehicle age, weight, engine size, transmission, emissions prevention and control systems, and fuel type and condition.
3. Traffic conditions, characterized by the level of congestion and conflicting traffic.
4. Infrastructure design and control, including design speed, signal timing and grades.
5. Ambient conditions including temperature, humidity, and barometric pressure.

Second, a relationship and distinction between vehicle activity and vehicle emissions exists. Items 1, 3 and 4 are the principal items affecting vehicle dynamics, motion, or activity, and items 2 and 5 principally impact the resulting emission and fuel consumption rates. Any analysis of roundabout environmental effectiveness must account or control for those factors when comparing them to the competing types of control.

Most research on vehicle emissions at roundabouts recognizes that at the root of all vehicle activity is the individual vehicle trajectory, or the speed profile of the vehicle, as it traverses the segment or intersection of interest. Trajectories provide information on speed, acceleration and deceleration rates and idling times as a function of driver behavior, traffic conditions (congested vs. uncongested), roadway design, and control (roundabout vs. signal). In essence the trajectory captures all the effects listed in items 1, 3 and 4 above. In past research, trajectories have been measured directly in the field using Global Positioning System (GPS), Portable Emissions Measurement System (PEMS), or generated synthetically from macroscopic or microscopic simulation models.

Researchers must then link activity and trajectory to emissions, which can be done in many ways. In a simulation environment, trajectory estimates can be made for individual vehicles in the form of speed versus time at a second-by-second or lower resolution. Such trajectories can be used with modal emission models to estimate average emission rates or total emissions for a trajectory. The same computations can be performed for fuel usage. Vehicle operating modes, such as idle, acceleration, deceleration, and cruise can be determined given trajectory data. Moreover, operating modes can be estimated in terms of continuous ranges of engine load taking into account second-by-second speed and accelerations.[3]

For example, SIDRA uses a four-mode model of acceleration, deceleration, idle, and cruise to predict fuel and emissions. CORSIM uses look-up tables of instantaneous speed and acceleration rates to estimate emissions on a second-by-second basis. Other microscopic models such as VISSIM, Paramics, and AIMSUN provide their own emission estimation procedures embedded in the models, and are based on look-up tables for speeds and accelerations. Finally, in the PEMS emissions estimation approach, both vehicle activity and fuel and emissions are measured simultaneously, thus providing the firmest linkage between the two. The current MOVES model by the US Environmental Protection Agency[4] uses a series of emission factor models based on vehicle operating mode; modes are defined as unique combinations of Vehicle Specific Power (VSP) and speed. VSP is a function of instantaneous vehicle speed (v), vehicle acceleration (a) and road grade (r). VSP has consistently been found to be highly correlated with vehicle emissions, and it is used in the MOVES model.[5,6] VSP is expressed using the equation in figure 1:

$$VSP = v[1.1a + 9.81(\sin(\tan^{-1}(grade))) + 0.132] + 3.02 \times 10^{-4} v^3$$

Figure 1. Equation. Vehicle specific power calculation.

The MOVES model can estimate emission rates and inventories at the project, county, and national scales. Emission factors can be estimated for selected vehicle source categories, model years, calendar years, ambient conditions, and driving schedules using a project-level analysis feature.

OBJECTIVE

The primary objective of this research was to develop a simplified methodology for estimating and comparing the pollutant emissions generated by vehicles passing through a roundabout and a signalized intersection, with the methodology based on actual, field-collected data. The methodology is macroscopic in nature, and uses inputs deemed readily available to analysts performing a planning-stage evaluation of roundabouts. A second objective of the research was to show how real-world data, including vehicle trajectories and other traffic characteristics such as demand, vehicle speed, approach capacity, signal timing, and the proportion of demand arrivals during the green phase (known as the “arrival type” in the HCM), affect the amount of pollutant emissions generated at signalized intersections and roundabouts. The research also attempted to identify variables and thresholds that may cause one type of intersection to have more pollutants than the other.

The methodology was developed and demonstrated using over 1,980 vehicle trajectories at roundabouts and signaled intersections at a one-second resolution. The VSP method was used as the key explanatory variable for emissions estimation.[5,7] Activity and emission models were developed using speed characteristics, demand, and signal timing. The basic outputs of the model are the average emission rates for four primary pollutants (including carbon monoxide (CO), hydrocarbon (HC), and mono-nitrogen oxides (NO_X)), expressed in milligrams/vehicle, grams/hr, and grams/vehicle-mile-traveled (grams/VMT).

CHAPTER 2. LITERATURE REVIEW

Various research projects and simulation tools have attempted to compare emissions generated at roundabouts and signalized intersection under different traffic conditions. Hallmark et al.[8] found roundabouts had marginally better traffic flow within signalized corridors than stop-controlled and signalized intersections. The same authors then conducted a real-world, in-field assessment of vehicle emissions at a roundabouts compared to those at a signalized intersections.[9] The authors demonstrated that, when traffic was not congested, vehicles traversing roundabouts did not have lower emissions than those traversing signalized intersections in the same corridor. Other research[10] assessed the average speeds, delays, and travel times of six roundabouts along a rural corridor in South Africa and compared them to fixed-cycle traffic signals. The authors concluded that roundabouts had operational advantages over traffic signals, but also that roundabouts were inefficient in high-demand scenarios.

In contrast, U.S. researchers[11] concluded that the environmental benefits posed by converting a signalized intersection to a two-lane roundabout in an urban corridor were only meaningful at the intersection level and for right-turn movements from the minor street to the main street. They also found that, at the corridor-level, turning movements from the main street produced higher total emissions at the roundabout than at the signalized intersection, while turning movements from the minor street produced lower total emissions at the roundabout than at the signalized intersection. Other U.S. research[12] estimated that variability associated with driving behavior results in differences in vehicular emissions at a roundabout. Other studies have integrated simulated vehicle dynamic data and microscopic modeling to estimate vehicle emissions at roundabouts.[13,14,15] In these studies, the findings were inconclusive regarding the benefits from roundabouts concerning emissions reductions.

The effect of speed and acceleration on arterials on fuel consumption is complex. High fuel consumption rates on arterials are typically associated with driving in congested traffic, characterized by higher speed fluctuations and frequent stops at intersections, leading to frequent accelerations.[16] The accelerations lead to high fuel use rates compared to idling or deceleration.[16] However, low traffic and continuous progression along streets dis not guarantee the lowest fuel consumption and emissions rates. The authors[16] further suggested that the best flow of traffic on arterial streets in terms of fuel consumption and emissions is the one with the fewest stops, shortest delays, and moderate speeds maintained throughout the commute.

Other research on arterials found that, to investigate emissions on existing arterial roads using micro-simulation models, and to study the effects of improvements to traffic flow, the simulated traffic on arterials must accurately represent that in the real world. SIDRA is a software tool enabling evaluation of vehicle emissions, especially at roundabouts and other forms of intersections.[17] SIDRA defines drive cycles for the simulated traffic based on initial and final speed for each element of a driving maneuver. The drive cycle is used to calculate delays, queues, number of stops, and acceleration and decelerations. The information is then used to calculate the fuel consumption and emission rates based on a set of set of equations.

Roundabouts and signalized intersections are hypothesized to have different localized effects on vehicle second-by-second (1 Hz) speed trajectories.[11] Research has documented that vehicle emissions depend on this second-by-second resolution engine load, and has further demonstrated that this second-by-second engine load can be closely estimated using VSP.[6] VSP is based on second-by-second road grade, and the speed and acceleration profiles of the vehicle. Vehicle fuel use and the emission rates of tailpipe exhaust pollutants, including CO, HC, and NO_X, are highly sensitive to the underlying VSP distribution.[5,7] VSP is the underlying conceptual basis for the U.S. Environmental Protection Agency's MOVES vehicle emission factor model.[5]

A recent study investigated the amount of error in emissions estimates using VSP distributions of vehicle activity data from VISSIM and the sensitivity of VSP distributions to modeling parameters.[18] It was observed that second-by-second empirical vehicle activity data and simulated vehicle activity data from a calibrated and validated VISSIM model did not yield the same VSP distributions and the results needed to be calibrated using GPS data.

Relevant research studies on emissions at roundabouts and other intersections are listed in table 1. They are summarized in terms of activity measurements, estimated emissions and principal findings. No one standard method or approach currently analyzes the environmental impact of intersection control type, although certain approaches are more widely used than others.

Table 1. Survey of emissions studies at roundabouts and other intersection controls.

Cited Research Study	Vehicle Activity Source	Fuel & Emissions Model Source	Roundabout Environmentally Effective?
Ahn et al. (2009)[13]	VISSIM	VT-Micro/CMEM	Negative when congested
Chamberlain et al. (2011)[14]	Own Micro-Model	CMEM/MOVES	Negative impact
Coelho et al. (2006)[1]	Synthetic Profiles	VSP	Congestion-dependent impact
Hallmark et al. (2011)[9]	PEMS	PEMS	Inconclusive-low traffic
Mandavilli et al. (2008)[15]	SIDRA	SIDRA	Positive impact

It is clear from the literature review that the findings are mixed, and to some extent dependent on the approach used to estimate activity and emissions. Analysis tools, whether macroscopic or microscopic, make assumptions regarding driver behavior and vehicle motion, none of which appears to have been thoroughly vetted against actual recorded vehicle data at roundabouts. This is a critical component of our approach to emissions modeling: we measured vehicle performance in the field. The same applies to the emission factor models. PEMS activity and emissions data at roundabouts have been collected on a limited basis involving very few drivers and limited traffic congestion levels. That data is not enough to enable the analyst to reach meaningful statistical conclusions regarding the effect of intersection type on emissions. In order to disentangle the confounding effects of driver behavior and congestion levels from the type of intersection control, more controlled methods are needed.

CHAPTER 3. METHODOLOGY

The literature review identified a limited number of studies that have inferred that vehicle emissions at roundabouts were less than that at signalized intersections. However, there is no simplified methodology allowing an analyst to readily compare the emissions at roundabouts and signalized intersections over a range of traffic conditions and in a deterministic analysis framework. Further, most prior research used models were not calibrated using real world, in-field trajectory data collected in the United States.

To evaluate the differences in emissions between roundabouts and signalized intersections, this project developed a method taking into account speed trajectories and their effect on emissions over a period of vehicle operation of approximately one minute. Although traffic simulation models can simulate second-by-second speed trajectories, they are typically calibrated using macroscopic parameters, and the accuracy of the trajectories themselves has been shown to not match real-world driving behavior, particularly on urban arterials.[11] Therefore, this research developed a method based on measured real-world trajectories. The data used to develop the method could also be used to evaluate simulated trajectories from traffic simulation models.

This research uses the concept of VSP as the basis for estimating emissions associated with a speed trajectory.[5,7] The methodology relies on a combination of PEMS and GPS field studies to characterize both vehicle activity and fuel and emissions at a second-by-second level. An illustration of the PEMS system used in this project is depicted in figure 2 and figure 3.

. To account for varying driver acceleration and deceleration profiles, the team used existing and new activity and emissions data from multiple drivers to capture the mean and variance of activities across drivers. To account for the impact of congestion, the team sorted the activity data into congestion-dependent bins as documented in research.[1]

Figure 2. Photo. Illustration of PEMS tailpipe emissions measurement (for additional details on PEMS see [2]).

Figure 3. Photo. Illustration of PEMS computer recording unit (for additional details on PEMS see [2]).

The methodology used in this research is based on two categories of models. The first category is *Activity Models*. There are a total of six models in this category, with three speed-profile models for roundabouts and three for signalized intersections. The three models within each intersection type differed in terms of the frequency of trajectory types A (those experiencing no stops), B (those experiencing a single stop at the stop or yield line) and C (multiple stops in the queue and at the stop or yield line). The trajectory types are a function of the approach or conflicting demand volume. The data for developing the three activity models for roundabouts were collected from observing overhead videos of roundabouts and classifying each vehicle arrival into one of the three trajectory categories. The data for signalized intersections included real-world trajectories of vehicles approaching signalized intersections; however, the models for estimating the proportion of Type A, B, and C trajectories at signals, however, were estimated from a series of VISSIM simulation models. The latter approach was needed, because a multitude of factors impact the probability of no stops, single stops, or multiple stops, including traffic demand levels, green and cycle time, quality of signal progression, and more. Simulation enabled controlled manipulation of these variables to generate the appropriate predictive models. Finally, separate models were developed for high (> 56 km/h (35 mph)) and low speed (≤ 56 km/h (35 mph)) approaches.

The second category of models is *Emission Models*. The emission models are described in a series of charts and reference tables shown in the results section. The six charts show representative VSP distributions for signalized intersections and roundabouts for each trajectory Type A, B, and C. The data to develop these VSP distributions were from second-by-second speed trajectories collected with PEMS or other GPS devices from vehicles approaching roundabouts and signalized intersections. The reference tables list emission factors developed from PEMS emission measurements from 95 vehicles, collected by North Carolina State University.[19]

Figure 4 is an overview of the methodology used here, and illustrates the six analysis steps once field data collection was completed. Details for each of the method's components are described concurrently with the results in the next section.

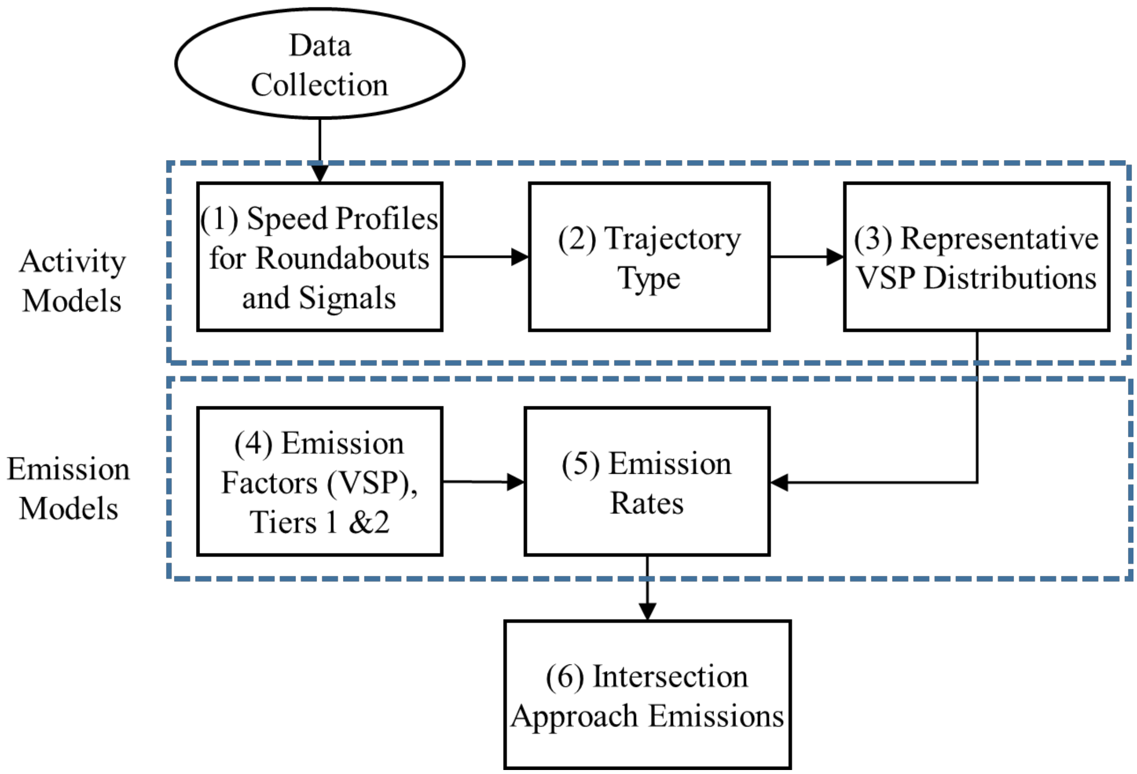


Figure 4. Diagram. Overview of the methodology.

CHAPTER 4. RESULTS

This section presents the results of the emissions estimation methodology. Results are presented in the sequence of the overall methodology, as shown in the flowchart in figure 4. The methodology starts with the activity models and moves on to the emissions models.

ACTIVITY MODELS

The activity model component of the analysis methodology consisted of (1) the speed profiles for roundabouts and signalized intersections, and (2) the estimation of the frequency for Trajectory Types A, B, and C. The two components are discussed in order below.

Speed Profiles

Based on field measurements from available research on emissions,[1,20] there are three general classifications for speed trajectories of a vehicle approaching an intersection. These classifications are distinguished based on changes in speed, duration, and number of stop-and-go cycles at the intersection, and changes in the acceleration and deceleration profiles. An individual vehicle trajectory through a roundabout or a signalized intersection can take on a variety of shapes in terms of speed versus time, as shown in figure 5. The three speed profiles were:

A. No stop through the intersection.
B. Single stop at the intersection entry approach, normally at the front of the queue.
C. Multiple stops as the vehicle joins the back of the queue at the intersection approach.

It is hypothesized that vehicles experiencing each of these speed profiles generate different levels of emissions. Type A was expected to generate the least amount of emissions because it has the least amount of acceleration and deceleration. On the other extreme, Type C was expected to generate the highest amount of emission because it has the most acceleration and deceleration cycles. The three speed profiles are illustrated in figure 5.

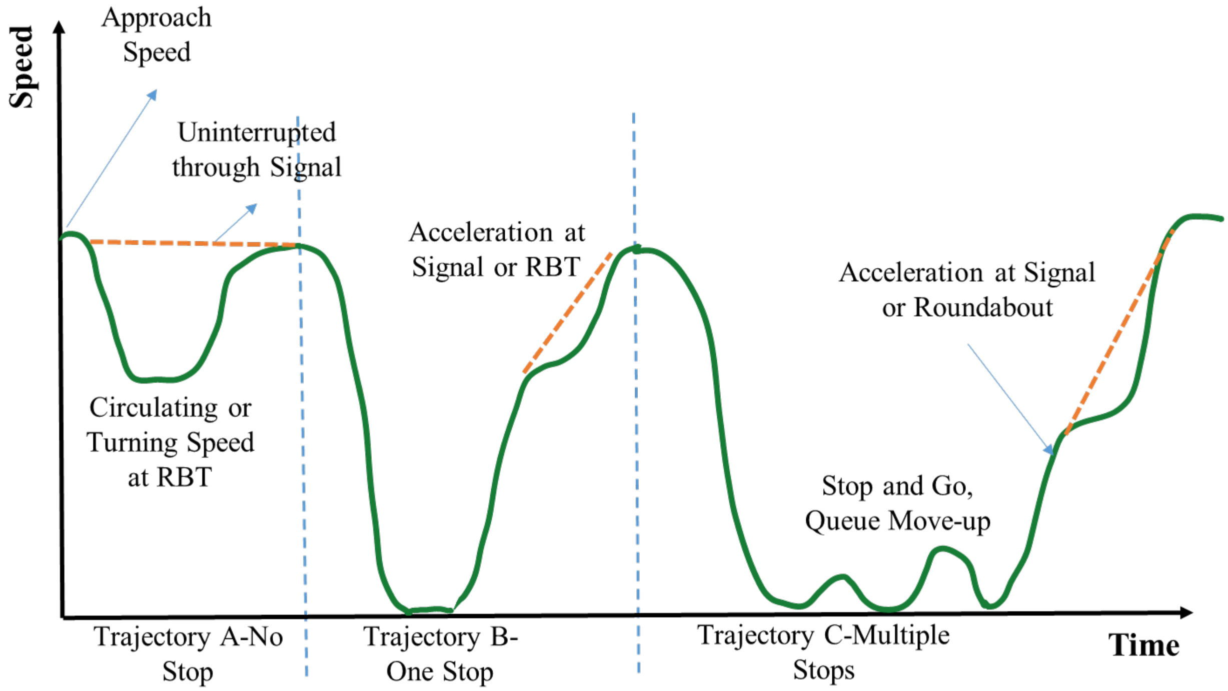


Figure 5. Graph. Illustration of the three types of trajectories (A: no-stop, B: one-stop, and C: multiple-stops) for a roundabout and signalized intersection approach.

In figure 5, the green (solid) line shows the three speed trajectory classes for a roundabout approach. Variations shown with the orange dashed lines denote speeds at signals that are hypothesized to be different than those at roundabouts. For a Type A trajectory, speeds through the roundabout are lower due to the curvature and geometry of the circulatory roadway compared to those through intersections, where vehicles going straight through might not have to slow down. For Type B and C trajectories, vehicles come to a complete stop, so vehicle acceleration/deceleration is expected to be more rapid at signals than at roundabouts, again because the roadway curvature at roundabouts constrains the vehicle trajectories.

The proportions of vehicles experiencing these three types of speed trajectories is expected to be sensitive to the level of traffic demand on the intersection approach, and at signalized intersections, the signal timing. The team constructed the emissions estimation models based on VSP as a function of these three speed trajectory types. The frequency models estimate the probability that an approaching vehicle will experience no-stops, one-stop, or multiple-stops. The corresponding VSP distribution models for each of the speed trajectory types was then invoked. Separate VSP distribution models were developed for low-speed intersection approaches (free-flow speed less than or equal to 56 km/h (35 mph)) and high-speed intersection approaches (free-flow speed more than 56 km/h (35 mph)) at both signalized intersections and roundabouts. The 56 km/h (35 mph) threshold was chosen based on the speed data available from study locations, representing a natural break between low speed and high-speed approaches under study. A detailed explanation of each of these models follows.

Trajectory Profile Frequency

Using approach demand and signal timing data for a given intersection, the team developed frequency distributions for the occurrence of trajectories Types A, B, and C (figure 5). Previous research has shown that the frequency of each trajectory type for a vehicle at the approach of a roundabout is a function of both the approach demand flow and circulating demand flow.[1,20] For signalized intersections, the frequency of each trajectory type is a function of the approach demand, the green-to-cycle length ratio, approach capacity, and signal progression.[1,20]

It was assumed in this work that vehicle type (passenger cars or passenger trucks) or Tier (Tier 1 and Tier 2) had no bearing on the activity model itself. The Tiers are emission standards for light duty vehicles in the United States defined in the Clean Air Act Amendments of 1990. Tier 1 standards were adopted in 1991 and were effective from 1994 to 2003. Tier 2 standards were phased in from 2004 to 2013. The Tiers do, however, have a bearing on the emissions model, and will be discussed further there.

Roundabout Profiles

The frequency distribution functions for each trajectory type at roundabouts were developed based on approximately 48 hours of overhead videos taken at:

- Carmel, IN: Old Meridian St.
- Gig-Harbor, WA: Borgen Blvd.
- Malta, NY: SR 67
- San Diego, CA: La Jolla Blvd.
- Avon CO: Avon Rd.
- Golden CO: Golden Rd.
- Carmel, IN: Spring Mill Rd.
- Whatcom County, WA: SR 539

Details regarding study locations can be found in Appendix B. All these roundabout are two-lane, but the models developed can also be used for single-lane roundabouts since the data was collected and analyzed on a per-lane basis. At each study location, 15-minute traffic counts including entry volume per lane and circulating traffic volumes were recorded. Every entering vehicle was classified as a trajectory category of Type A, B, or C. Regression models were subsequently developed to estimate the frequency of each trajectory type. To ensure that the sum of the proportions for each trajectory type added up to 100 percent, the proportion of vehicles with speed profile B was calculated as 100 percent minus the fraction of trajectories of Types A and C.

At roundabouts and signalized intersections, vehicles may yield to pedestrians at the crosswalk, and pedestrian volume therefore has an effect on the trajectory type. The dataset did not have enough pedestrian data for it to be included in the models.

Figure 6, figure 9, and figure 11 show the frequency distributions for Type A, B, and C trajectories at the studied roundabouts based on summing the entry and circulating flow rates, which is a proxy for the congestion level observed at each of the roundabouts. Each data point represents the proportion of the A, B, or C profiles in a 15-minute observation period. The x-axis shows the 15-minute flow rate in vehicles per hour during the observation periods. Approximately 190 15-minute observations were used to create the dataset. The user can adjust the A, B or C profile distributions as available from local data. The observed flow rates were between 200 to 1700 vph.

Figure 6 shows the proportion of vehicles entering the roundabout without stopping (Type A). The data collected at the roundabouts shows that this proportion can be estimated using a cumulative normal distribution with a mean value of 720 and a standard deviation of 340. This means that if the combined approach and conflicting flow rate at the roundabout is equal to 720 vph, 50 percent of the vehicles would not stop. The R-squared value for the model is 0.51.

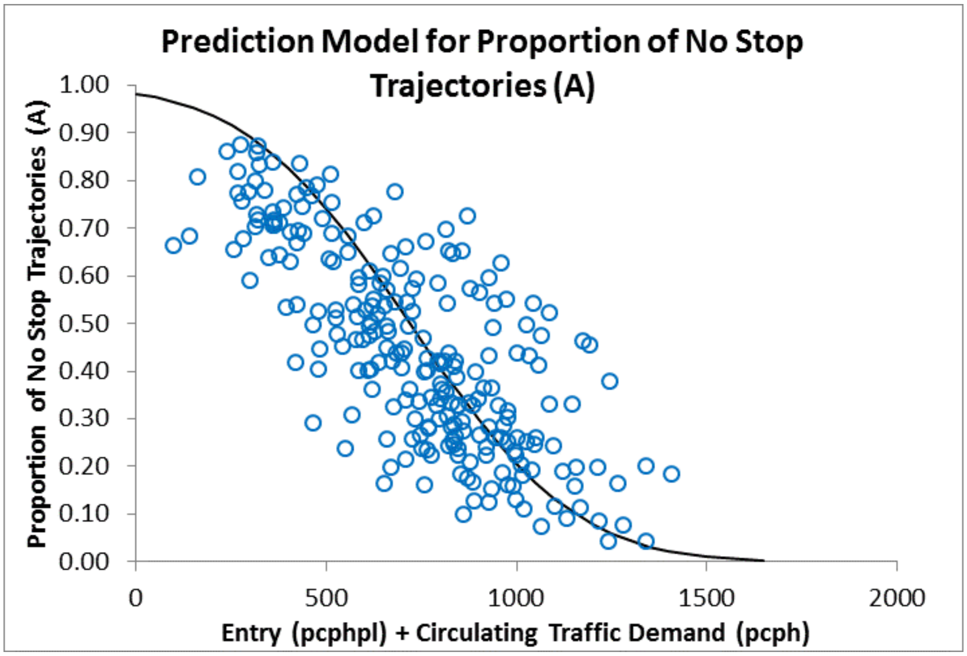


Figure 6. Graph. Prediction model for proportion of no-stop trajectory (Type A).

The proportion of the number of stops in trajectory Type A is calculated from a normally-distributed cumulative distribution function (CDF) with parameters shown in figure 7:

$$\text{Proportion of No Stops (A)} = 1\text{- Normal CDF}(\mu = 720, = \sigma\ 340),\ R^2 = 0.51$$

Figure 7. Equation. Proportion of Type A trajectories (no stops).

The proportion of Type B trajectories is shown in figure 9. As mentioned before, to ensure that the sum of the proportion of each trajectory type adds up to 100 percent, the proportion of vehicles with Type B trajectories was calculated as equal to 100 percent minus the percentage of Types A and C trajectories. Thus, it is calculated as shown in figure 8:

$$\text{Proportion of vehicles experiencing a single stop} = 1\text{- [Proportion of Vehicles with No Stops (Profile A)} + \text{Proportion of Vehicles with Multiple Stops (Profile C)]},\ R^2 = 0.37$$

Figure 8. Equation. Proportion of Type B trajectories.

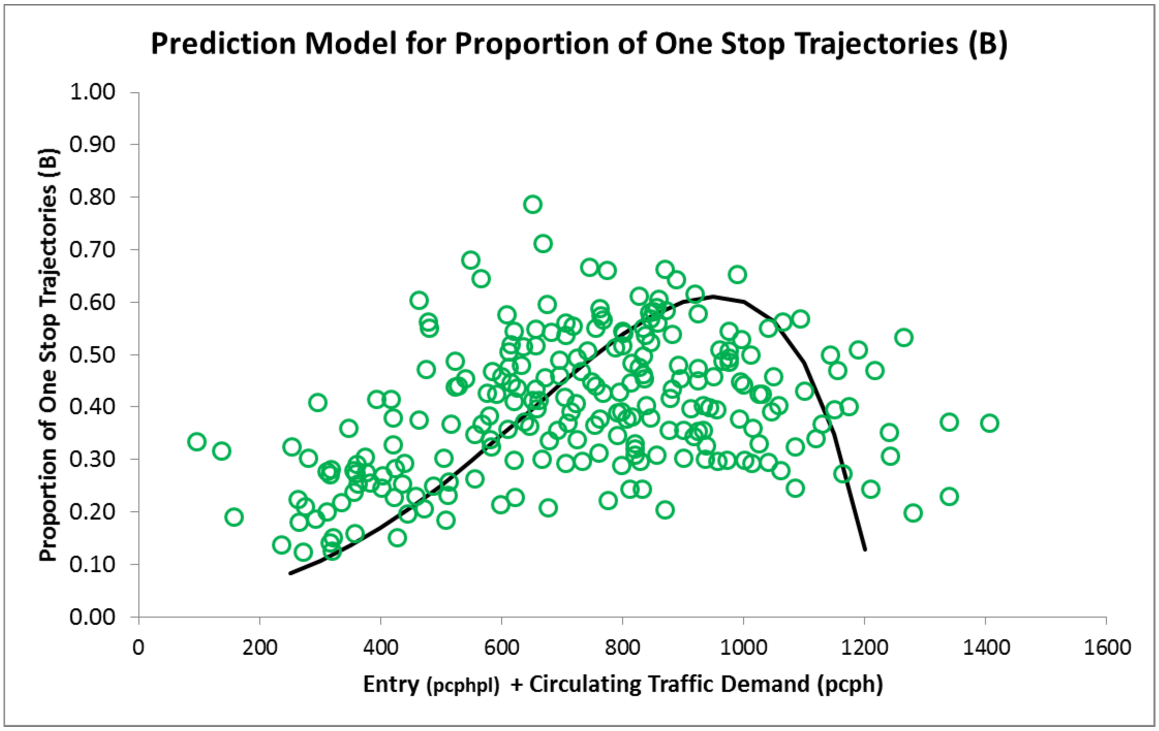


Figure 9. Graph. Prediction model for proportion of one-stop trajectory (Type B).

The proportion of Type C trajectories was determined using a two-regime function. When the sum of entry and circulating volumes is less than 400 vph, no Type C profiles were observed and therefore the value for percentage of Type C trajectories was set to zero. For flow rates greater than 400 vph the proportion of Type C trajectories was calculated using an exponential function. The R^2 for this model is 0.38. The model for Type C trajectories is described by the equation in figure 10 and shown in figure 11.

$$\text{For } Q_{ent} + Q_{conf} \leq 400 \text{ vph: Proportion } C = 0$$

$$\text{For } Q_{ent} + Q_{conf} > 400 \text{ vph: Prop. } C = \text{Exp. } [\, 0.000004 * (Q_{ent} + Q_{conf})^{1.68} - 1]$$

$$\text{For } Q_{ent} + Q_{conf} \geq 1{,}200 \text{ vph: Proportion } C = 1$$

$$R^2 = 0.38$$

Figure 10. Equation. Proportion of Type C trajectories.

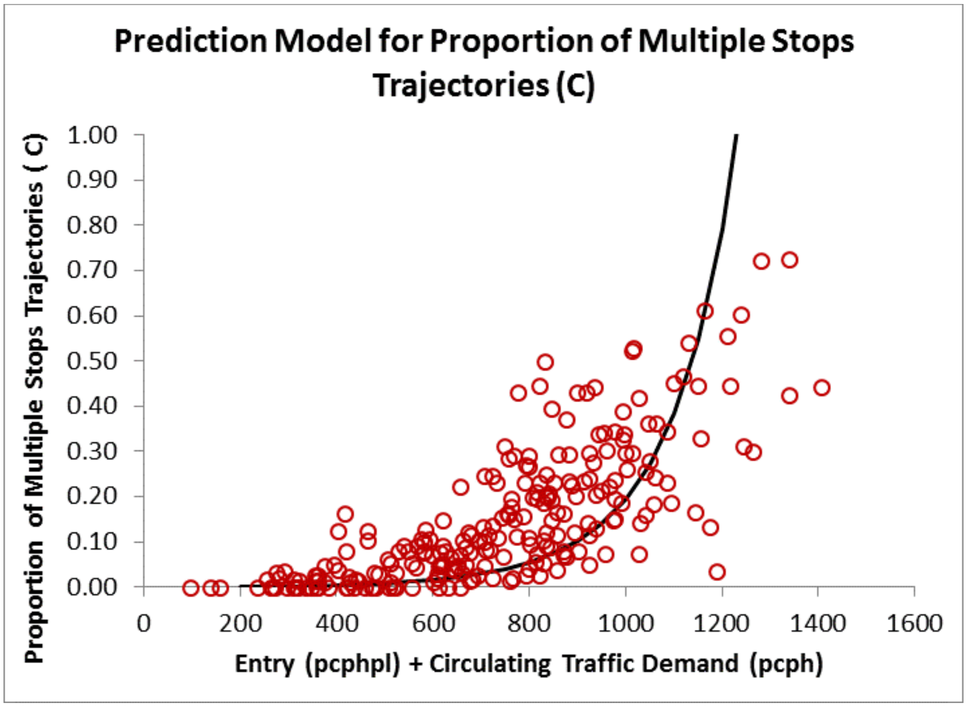


Figure 11. Graph. Prediction model for proportion of multiple-stop trajectory (Type C).

Signalized Intersections

At signalized intersections, the modeling approach differed from that of the strictly empirical roundabout models. It was hypothesized that the likelihood of experiencing one or multiple stops at a signalized intersection was correlated to the signal timing on the approach, the level of signal progression (or the proportion of vehicles that arrive during the green phase), and the demand-to-capacity ratio (d/c) for the approach. Given the more predictable and cyclical nature of traffic patterns at signals compared to roundabouts, the Highway Capacity Manual[21] approach for characterizing signal progression was used to help develop the functional forms for frequency models for Type A, B, and C trajectories at signalized intersections. Actual trajectory A, B, and C frequencies were obtained from a simple simulation experiment designed in the VISSIM microsimulation model[22]. The experiment varied the approach demand, g/C ratio (effective green to cycle length ratio), d/c ratio (demand to capacity ratio), and modeled all HCM arrival types by changing the signal offset at two signalized intersections.

The HCM defines six arrival types to describe signal progression quality, with one being very poor progression and six being exceptional progression, as listed in table 2. It is known that progression quality, or arrival type, affects the speed trajectory of the vehicles and the number of stops vehicles experience as they go through a signalized intersection.

Table 2. Progression quality and arrival type (Source [21]).

Arrival Type	Progression quality	Platoon Ratio (R_p)	Conditions Under Which Arrival Type Is Likely to Occur
1	Very poor	0.33	Coordinated operation on a two-way street where the subject direction does not receive good progression
2	Unfavorable	0.67	A less extreme version of Arrival Type 1
3	Random Arrivals	1.00	Isolated signals or widely spaced coordinated signals
4	Favorable	1.33	Coordinated operation on a two-way street where the subject direction receives good progression
5	Highly Favorable	1.67	Coordinated operation on a two-way street where the subject direction receives good progression
6	Exceptional	2.00	Coordinated operation on a one way street in dense networks and central business districts

For the VISSIM simulation two sets of eight models were developed. The design of the VISSIM network is a simple two-lane (two lanes per approach) link network with two pre-timed signals located at a specific distance of 457 m (1500 ft) from each other on this link. The first set of eight models simulated a high speed environment with an average free-flow speed of 72 km/h (45 mph), and the second set of eight models simulated an environment with an average free-flow speed of 56 km/h (35 mph). Since the speeds follow a normal distribution in VISSIM with standard deviation of 11 km/h (7 mph), a range of vehicle speeds were captured through the simulation. The signals in the models have a cycle length of 120 s.

Each of the eight models in each represents a specific g/C ratio, which is achieved by varying the effective green (g) values (30 s, 40 s, 50 s, 60 s, 70 s, 80 s, and 90 s) while keeping the cycle length constant at 120 s. The signal offset (quantity describing relative start time of coordinated phases for adjacent signals) was set to simulate three arrival patterns: (1) poor progression, (2) random arrival, and (3) good progression.

The traffic volume during the simulation period was varied for each of the models to cover a d/c ratio range from 0.1 to approximately 1.4. All scenarios had 48 simulation models, and each model was run 10 times, resulting in 480 simulation runs, each for a period of 1 h. After the simulation runs were complete, a macro was developed to process each modeled vehicle trajectory and to calculate the fraction of A, B, and C trajectory types for the simulation period. The data was used to develop the models in table 3. Additional details and sample output from the simulation are included in Appendix C.

The combination of simulation and HCM-based arrival type models showed that the proportion of vehicles with Type A speed trajectories depended on the green-to-cycle length ratio (g/C), demand-to-capacity ratio (d/c), and the platoon ratio (R_p). The platoon ratio depended on the level of signal progression, which in turn was estimated from HCM arrival types and the proportion of vehicles arriving during green. The model coefficients were also sensitive to the quality of signal progression along the corridor. The functional form of the estimated relative frequency of A profiles at signals is shown in the equation in figure 12.

$$Proportion\ of\ Trajectory\ Type\ A = b_0 - b_1(d/c)^{b_2}$$

Figure 12. Equation. Proportion of trajectory Type A, modified.

Where:

- b_0 = intercept value which is a function of arrival type (or HCM platoon ratio)
- b_1 = coefficient for d/c ratio
- d/c = demand to capacity ratio on the signalized approach; capacity per lane is = S g/C, where S is the lane saturation flow rate
- b_2 = power coefficient for the d/c ratio
- Rp = platoon ratio which varies from 0.33 to 2 depending on arrival type (arrival Type 1: very poor to 6: exceptionally favorable. Values can be found in table 3
- g/C = approach (through) effective green to cycle length ratio

Table 3 lists the associated coefficients for each HCM arrival type estimated from the simulation experiments, with higher arrival types referring to generally better progression quality on an arterial street.[21]

Table 3. Coefficients of variables used for predicting the likelihood of no-stop (Type A) speed profile at a signalized intersection approach.

Arrival Type	Platoon Ratio, R_p	b_0	b_1	b_2
1	0.33	Min[1,R_p(g/c)]	-0.0195+0.580*g/C	3
2	0.67	Min[1,R_p(g/c)]	-0.0195+0.580*g/C	3
3	1	Min[1,R_p(g/c)]	-0.0195+0.580*g/C	3
4	1.33	Min[1,R_p(g/c)]	-0.9809(g/C)2+1.2748(g/C)-0.0149	5(R_p g/C)
5	1.67	Min[1,R_p(g/c)]	-1.7314(g/C)2+1.9424(g/C)-0.0852	4(R_p g/C)
6	2	Min[1,R_p(g/c)]	-2.2578(g/C)2+2.1815(g/C)-0.0487	4(R_p g/C)

As an illustrative example, let the HCM arrival type be 2, g/C be 0.4, and d/c be 0.80. The relative Type A trajectory frequency then is calculated using the equation in figure 13.

$$Min(1,\ 0.67 \times 0.4) - (-0.0195+0.580 \times 0.4)\ (0.80)^3 = 0.16$$

Figure 13. Equation. Example of Type A trajectory calculation.

This result suggests that 16 percent of the approaching vehicles would not stop on this approach.

The proportion of vehicle experiencing Type C trajectories is formulated as a function of signal progression (HCM arrival types) and demand-to-capacity ratio. Similar to roundabouts, the proportion of Type B trajectories is calculated as the difference between 100 percent and the proportion of A plus C trajectories. The proposed models for estimating the relative frequency of speed trajectory Type C are shown in table 4.

For the numerical example above, if arrival Type is 2 and d/c is 0.80, then the fraction of Type C trajectories is calculated using the equation in figure 14, or 52 percent.

$$3.1458(0.80)^2-2.3934(0.80)+0.422=0.52$$

Figure 14. Equation. Example of Type B trajectory calculation.

Table 4. Functions for predicting the proportion of Type C trajectories at a signalized intersection approach.

Arrival Type	d/c	Fraction of Type C Trajectories	R^2
1,2	Less than or equal to 0.7	0	0.95
1,2	Between 0.1 and 1.2	Figure 15	0.95
1,2	Greater than or equal to 1.2	1	0.95
3-6	Less than or equal to 1	0	0.90
3-6	Between 1 and 1.213	Figure 16	0.90
3-6	Greater than or equal to 1.213	1	0.90

$$3.1458(d/c)^2-2.3934(d/c)+0.422$$

Figure 15. Equation. Example of Type C trajectory calculation, arrival types 1 and 2.

$$22.137\ (d/c-1)^2$$

Figure 16. Equation. Example of Type C trajectory calculation, arrival types 3 through 6.

As stated earlier in this section, the Type B trajectories were estimated by subtracting the percentage of Type A and C trajectories from 100 percent, which, in the example problem would yield 100 minus 16 minus 52, equaling 32 percent of the approaching vehicles stopping once.

Emissions Estimation

After predictions of the proportions of trajectories in Types A, B, and C, were completed, the analysis proceeded to emissions estimation, following the procedure in the flow chart in figure 4.

Vehicle Specific Power and Vehicle Emission Rates

For the emissions estimation, the analysis initially used VSP and estimated the vehicle emissions rates for each VSP mode (Steps 4 and 5 in figure 4)

Researchers[3,23] developed a “modal binning approach” for calculating the vehicle emissions based on vehicle specific power or VSP. VSP, an indicator of engine load, accounts for engine power demand associated with changes in vehicle kinetic energy, changes in vehicle potential energy (e.g., hill climbing), rolling resistance, and aerodynamic drag,[7] and is calculated using the equation in figure 17.

$$VSP = v[1.1a + 9.81(\sin(\tan^{-1}(grade))) + 0.132] + 3.02 \times 10^{-4} v^3$$

Figure 17. Equation. Vehicle specific power calculation (from figure 1).

Where:

VSP = Vehicle specific power at 1 Hz resolution (kW/ton)

v = Speed at 1 Hz resolution (m/s)

a = Acceleration at 1 Hz resolution (m/s^2)

grade = The terrain gradient for change in elevation versus distance (ratio)

VSP values estimated at second-by-second resolution (1 Hz) are categorized into 14 modes and are shown in figure 18.[3,23] VSP modes 1 and 2 are for negative VSP values associated with deceleration or travel on negative (down-sloping) road grades. VSP mode 3 is for idle. VSP modes 4 to 14 are for ranges of increasing positive VSP, which can represent acceleration, steady-speed cruising at various speeds, or climbing hills with positive road grade. Average VSP modal emission rates were estimated for each vehicle. These modal rates were weighted by the amount of time spent in each VSP mode for a given speed trajectory to estimate trajectory-average rates.

T1 PC (n=24); T2 PC (n=39)			Tier 1 Passenger Cars, Average Emission Rates				Tier 2 Passenger Cars, Average Emission Rates			
	VSP Mode	VSP Range*	NOx_mg/s	HC_mg/s	CO_mg/s	CO2_g/s	NOx_mg/s	HC_mg/s	CO_mg/s	CO2_g/s
Passenger Cars	1	VSP<-2	0.8	0.2	3.9	1.2	0.6	0.3	1.4	1.1
	2	-2≤VSP<0	1.0	0.3	4.8	1.4	0.6	0.2	1.6	1.3
	3	0≤VSP<1	0.4	0.2	3.3	1.0	0.2	0.2	1.3	0.9
	4	1≤VSP<4	1.9	0.5	8.5	2.4	1.2	0.4	2.7	2.2
	5	4≤VSP<7	2.8	0.6	11.3	3.3	1.8	0.5	3.7	3.0
	6	7≤VSP<10	3.8	0.8	13.8	4.1	2.3	0.6	5.0	3.8
	7	10≤VSP<13	4.9	0.9	17.0	4.9	2.5	0.7	6.8	4.5
	8	13≤VSP<16	5.9	1.0	19.6	5.5	2.6	0.8	7.8	5.1
	9	16≤VSP<19	7.1	1.1	24.7	6.1	2.7	0.9	10.3	5.7
	10	19≤VSP<23	7.8	1.2	28.6	6.5	2.8	1.0	12.4	6.2
	11	23≤VSP<28	9.1	1.3	36.5	6.9	3.4	1.1	16.7	6.7
	12	28≤VSP<33	10.7	1.4	46.0	7.5	4.0	1.1	27.3	7.4
	13	33≤VSP<39	12.7	1.6	70.9	8.0	4.7	1.3	34.9	8.2
	14	39≤VSP	11.7	1.9	187.7	8.7	6.5	1.4	69.5	9.2
T1 PT (n=10), and T2 PT (n=22)			Tier 1 Passenger Trucks, Average Emission Rates				Tier 2 Passenger Trucks, Average Emission Rates			
	VSP Mode	VSP Range*	NOx_mg/s	HC_mg/s	CO_mg/s	CO2_g/s	NOx_mg/s	HC_mg/s	CO_mg/s	CO2_g/s
Passenger Trucks	1	VSP<-2	0.8	0.5	7.4	1.8	0.2	0.4	3.8	1.9
	2	-2≤VSP<0	0.9	0.5	7.2	2.1	0.2	0.4	4.0	2.3
	3	0≤VSP<1	0.3	0.4	2.8	1.4	0.0	0.2	2.1	1.4
	4	1≤VSP<4	1.8	0.8	12.8	3.4	0.3	0.6	6.6	3.5
	5	4≤VSP<7	2.9	1.0	18.1	4.6	0.4	0.8	9.8	4.8
	6	7≤VSP<10	3.9	1.3	24.8	5.7	0.6	1.1	12.0	6.0
	7	10≤VSP<13	5.2	1.5	26.8	6.6	0.7	1.2	14.9	7.0
	8	13≤VSP<16	6.3	1.7	29.1	7.5	0.8	1.3	16.9	8.0
	9	16≤VSP<19	8.1	2.0	35.1	8.2	1.0	1.5	19.4	9.0
	10	19≤VSP<23	8.7	2.2	40.2	8.8	1.2	1.7	27.6	9.8
	11	23≤VSP<28	11.0	2.4	53.6	9.6	1.5	1.9	28.5	10.7
	12	28≤VSP<33	13.9	2.6	78.1	10.7	1.9	2.0	37.3	11.8
	13	33≤VSP<39	14.7	2.8	97.9	12.0	2.4	2.3	56.8	13.2
	14	39≤VSP	20.8	3.1	171.6	13.0	3.2	2.8	149.3	15.7

* The VSP Ranges are the ranges of VSP values in KW/ton for each VSP mode

Figure 18. Image. Table of average emission rates by vehicle specific power (VSP) mode for Tier 1 and Tier 2 passenger cars and passenger trucks (Source: [23]).

Figure 18 lists a summary of emission data collected from 95 vehicles.[23] Emission data for each of the 95 vehicles were collected using three key instruments: (1) the OEM-2100 “Axion System” PEMS manufactured by Clean Air Technologies International, Inc.; (2) a Garmin GPS receiver with barometric altimeter; and (3) a “scantool” data logger for the on-board diagnostic (OBD) link of the vehicle electronic control unit (ECU)[3]. The PEMS measures the tailpipe exhaust concentrations of carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbons (HC), nitric oxide (NO_X), and oxygen (O_2). The data went through a detailed and robust quality-control and quality-assurance process before being used for the analysis.

The OBD scantool was used to record vehicle and engine data including vehicle speed, mass fuel flow (MFF), engine revolutions per minute (RPM), and others. Road grade was quantified based on data from global position system (GPS) receivers with barometric altimeters.[2] Data analysis included: (1) converting OBD data to a second-by-second basis[7]; (2) synchronizing second-by-second data from multiple instruments into one database[2]; (3) quality assurance (QA); and (4) modal analysis of the data.[2]

From 2008 to the present, data have been collected for passenger cars (PCs) and passenger trucks (PTs) in the Research Triangle Park, NC area, including parts of Raleigh, Cary, Durham, Apex and Morrisville. Data for vehicle activity on multiple road functional classes (e.g., feeder/collector streets, minor arterials, major arterials, freeways, and ramps) and a wide range of speeds and accelerations[2,3] were collected. More details on the data collection routes and map of the routes can be found in Appendix B.

Passenger cars were defined as light duty vehicles intended for the carriage of passengers.[4] Passenger trucks were defined as minivans, pick-ups, sport utility vehicles (SUVs), and other two-axle, four-tire trucks used primarily for personal transportation and with gross vehicle weight less than 14,000 lbs.[4] Data were collected for 1997 to 2013 model years. For each vehicle, there were typically over 12,000 seconds of valid, quality-assured data. Heavier classes of trucks require a separate methodology for emissions calculation and were not included here.

The vehicle sample includes vehicles subject to different emission standards for light duty vehicles in the U.S., Tier 1 and Tier 2, defined according to the Clean Air Act Amendments of 1990. The measured vehicles of model years 1997 to 2003 were certified under Tier 1 (T1) exhaust emission standards, and those for model years 2004 to 2013 were certified under the more stringent Tier 2 (T2) standards.[24,25] Tier 2 standards were phased in from 2004 to 2013. PCs and PTs are subject to the same standards. Fleet average VSP modal rates were estimated for each of four vehicle groups: T1 PC (n=24); T2 PC (n=39); T1 PT (n=10), and T2 PT (n=22). The mean values for pollutants NO_X, HC, CO_2 and CO for VSP modes (emission factors) are shown in figure 18.

Typically, the modal emission rates are lowest for VSP Mode 3 and increase monotonically from Mode 3 to 14. The trends differ by pollutant; for example, the ratio of mean emission rate for Mode 14 versus Mode 13 is much higher for CO than for other pollutants. Therefore, differences in speed trajectories will affect emission rates among pollutants differently.

Generating Representative VSP Distributions

Building on the VSP modes and emissions rates described above, representative VSP distributions were developed for both roundabouts and signalized intersections (Step 3 in figure 4). Over 1,980 speed trajectories at a second-by-second resolution were collected from 42 signalized intersections in North Carolina and 24 roundabouts in six states across the country (Appendix B). The speeds were collected with a GPS unit from vehicles driving through the two intersection types at the speed typical for that roundabout or signalized intersection.

The magnitude and frequency of changes in speed are the primary factors affecting emissions. The research hypothesized that slowing down or coming to a full stop to enter an intersection or roundabout from higher approach speeds requires higher deceleration rates than doing so from lower approach speeds. It would also require higher acceleration rates after passing through the intersection or roundabout, and emission rates were also expected to be higher. The distinction is particularly important for roundabouts, since vehicles have to slow down to negotiate the curves as they enter the roundabout. Thus, for each intersection, vehicle speeds were extracted from mid-block upstream of the intersection to mid-block downstream of the intersection. Based on the speed data available from all the intersections, two types of models were generated for low-speed and high-speed intersection approaches. The 56 km/h (35 mph) threshold was chosen based on the speed data available from study locations, with the given threshold showing a natural break in the collected data.

For each speed trajectory analyzed, the VSP was estimated for every second of the trajectory, and the emission rate for the corresponding VSP was selected. The process was repeated for the 1,980 available speed profiles. The overall distribution of time spent in each VSP mode was estimated for each type of intersection (roundabout, signalized intersection), speed range (low, high), and trajectory (Type A, B, and C).

Figure 19, figure 20, and figure 21 show the VSP distribution, or the percent of time spent in each VSP mode, for low-speed roundabouts and signalized intersections for each trajectory type. Figure 22, figure 23, and figure 24 show the same results, but for high-speed roundabouts and signalized intersections. The VSP distributions shown in those six figures were used to calculate pollutant emissions as follows:

1- Obtain the amount of gram (or milligram) per second for each pollutant is known for each VSP mode rom the emission factors in figure 18.
2- Calculate the travel time through the intersection for a given input travel distance based on average speeds for each trajectory (Type A, B C).
3- Estimate how many seconds of travel time through the intersection is spent in each VSP mode, based on the VSP distribution (see figure 19 through) defined for a given trajectory (Type A, B and C) and for either a signalized intersection or a roundabout.
4- Calculate the total grams of pollutant emissions for the given distance (segment length).
5- Estimate what proportion of vehicles experience each of the three types of profiles, based on the frequency functions.
6- Prorate the total emission rates based on proportion of A, B and C speed profiles in the approach traffic flow.

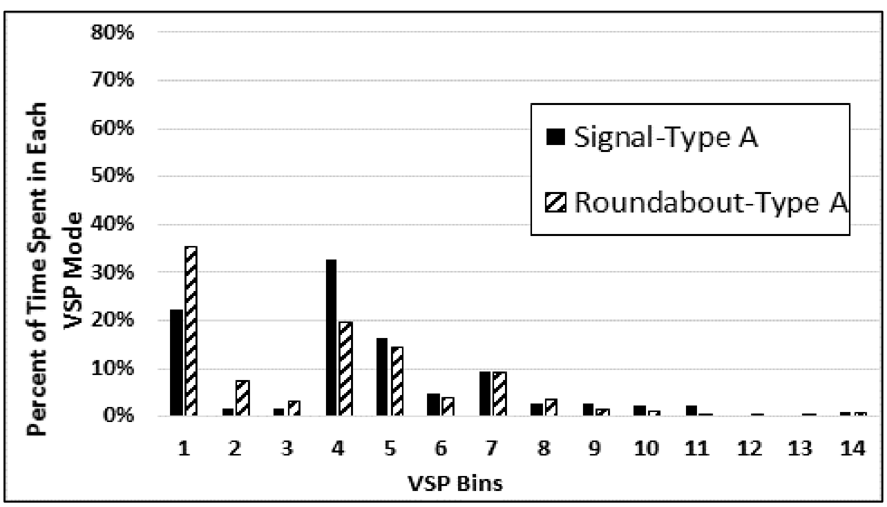


Figure 19. Chart. Percent time spent in VSP modes at low speed approaches for trajectory Type A.

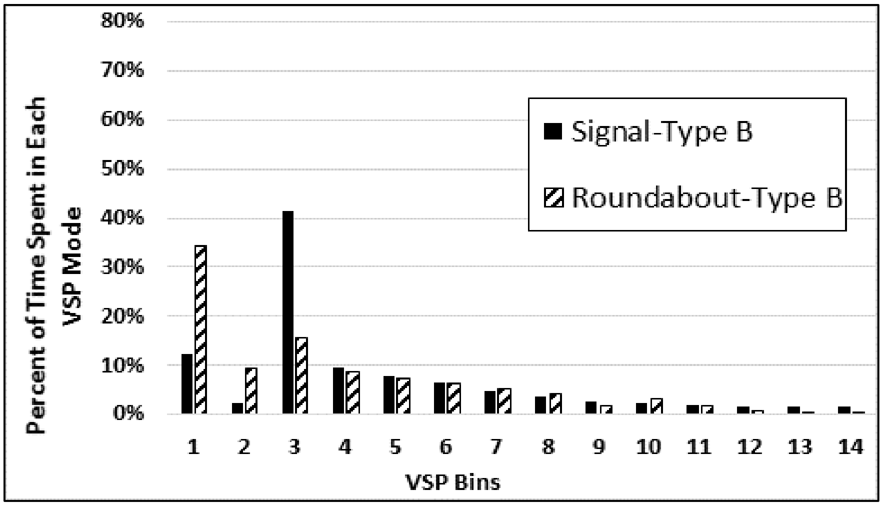


Figure 20. Chart. Percent time spent in VSP modes at low speed approaches for trajectory Type B.

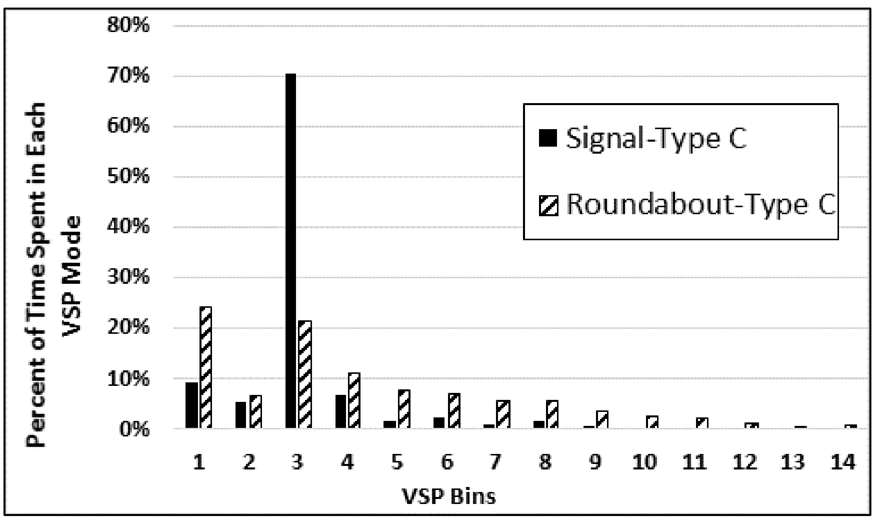


Figure 21. Chart. Percent time spent in VSP modes at low speed approaches for trajectory Type C.

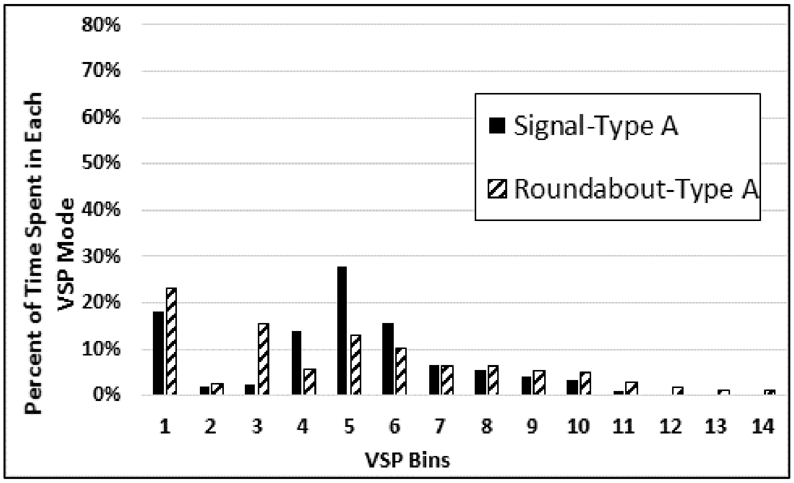


Figure 22. Chart. Percent time spent in VSP modes at high speed approaches for trajectory Type A.

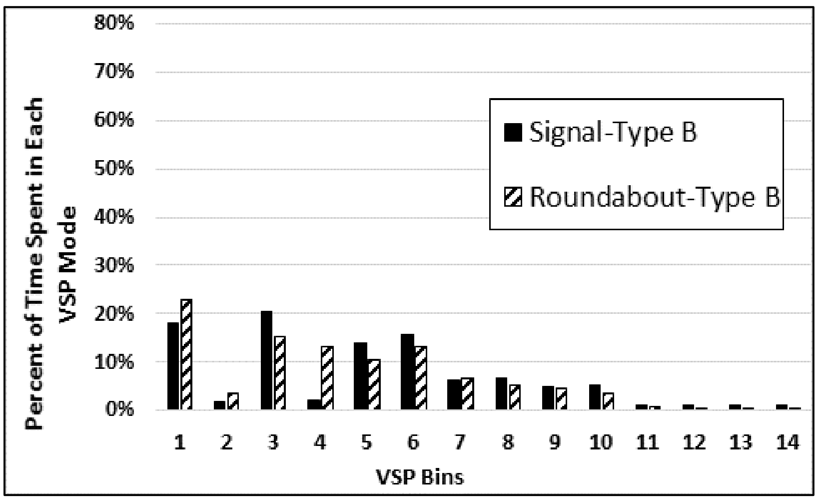


Figure 23. Chart. Percent time spent in VSP modes at high speed approaches for trajectory Type B.

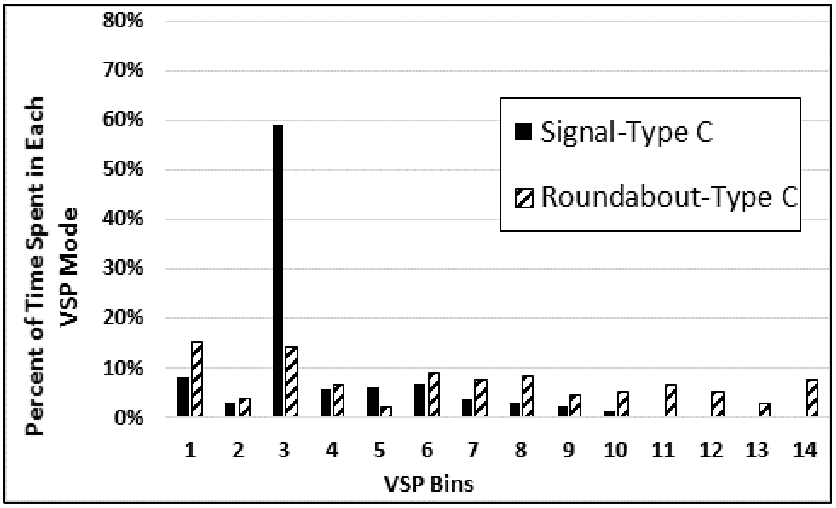


Figure 24. Chart. Percent time spent in VSP modes at high speed approaches for trajectory Type C.

Intersection Approach Emission Estimation Method Using VSP

In the final step, the emission estimates were aggregated by intersection approach. Since VSP is a function of instantaneous speed and acceleration rates, the three trajectory types had distinctive effects on the distribution of time spent in each VSP mode and subsequently on the trajectory average emission rate. Therefore, to calculate hourly (or on any other time scale) emissions generated by vehicles approaching the intersection, the distribution of the three types of trajectories was taken into account, as shown in the equation in figure 25.

$$E_{Intersection\ approach} = E_A . P_A . Q_{in} + E_B . P_B . Q_{in} + E_C . P_C . Q_{in}$$

Figure 25. Equation. Hourly emission by vehicles approaching an intersection.

Where:

P_I = Proportion of vehicles in the traffic stream in each speed profile i = A, B and C;

Q_{in} = Entry demand flow rate (vph);

E_i = Emission associated with each speed profile, per vehicle (gms or mgms)

The total hourly emission was estimated from the sum of emissions generated by each speed profile (E_i), multiplied by the proportion of approach vehicles in that speed profile (P_i), and the hourly entry flow of the approach (Q_{in}). The emissions can also be estimated for other timescales or longer time durations by adjusting for entry flow and number of hours. In order to estimate the emission for each speed profile (E_i), second-by-second emission rates for the vehicle with that speed profile were calculated from the VSP equation in figure 1/figure 17.

Therefore E_i is shown in figure 26.

$$E_i = \sum_{n=1}^{Ni} EF_n$$

Figure 26. Equation. Total emission for each speed profile.

Where:

EF_n = Emission factor (g/s) assigned to the n^{th} second of the speed profile based on the instantaneous VSP mode. The value of EF_n for each pollutant is based on the VSP calculated for instantaneous speed (see figure 18).

N_i = Number of seconds in profile *i*;

E_i = Total emissions associated with each of the three profiles (i.e., *i* = Type A, B or C).

In order to calculate E_i complete second-by-second speeds for each speed profile were needed.

CHAPTER 5. IMPLEMENTATION

The methodology and models described in this report were modeled in Microsoft Excel in the form of a simple emission computational engine. The term "computational engine" describes the tool used here for application and testing of the research methods; it is not a commercial product.

The computational engine required a minimum number of inputs from the user, which can be entered for up to four approaches of an intersection or roundabout for various time durations and for AM peak, PM peak, and off-peak periods. Inputs and outputs of the computational engine are listed in table 5. Screenshots of the computational engine's input and output format are shown in Appendix D.

The computational engine was used to evaluate a case study, and the results are described in the next section.

Table 5. Computational engine inputs and outputs.

Input/ Output	Description
Input	Demand flow rate on the approach (veh/hr) (AM, PM and Off-Peak are optional and can be entered separately)
Input	Number of hours each volume level is applicable (AM, PM, Off-Peak, optional)
Input	Fraction of vehicle classes (passenger car, passenger trucks—including SUV's) and their Tier standard
Input	Distance upstream and downstream of the intersection for emission calculations
Input	Signal timing variables (g and C) and arrival type for signalized intersections
Input	Circulating flow rate for roundabout intersections
Input	Whether the intersection is in a low or high speed environment
Output	Hourly emission rates for all 4 pollutants (NO_X, HC, CO, CO_2) as described in figure 18, by vehicle class (for each volume level, AM, PM and Off-peak if provided in the input)
Output	Emission rates gram/VMT for each pollutant per approach, during a single or multiple time periods (AM, PM and Off-Peak)
Output	Demand-to-capacity ratio for each approach of the intersections
Output	Overall emissions for the intersection

The methodology described above was applied to illustrative case studies to demonstrate how comparisons can be made between emissions at roundabouts and signalized intersections for different demand (congestion) levels. Since the capacities of a roundabout and signalized intersection can differ on a per-lane basis, the team compared the roundabouts and signalized intersections using demand-to-capacity (d/c) ratio. Doing so creates a fair comparison, as the two are evaluated at the same congestion level.

Based on HCM concepts, reinforced by the VISSIM simulation results, traffic signal progression was expected to affect the distribution of trajectory types at a given intersection along a corridor. If there is good progression along the corridor – meaning that the majority of vehicles arrive in platoons during the green phase – those vehicles will make it through the subject intersection without stopping, resulting in a high proportion of trajectories of Type A. However, when progression is poor, the proportion of Type B and C trajectories will be greater. Therefore, the case studies presented herein include the effects of poor progression (arrivals type 1, as included in table 2), random arrivals (arrivals type 3), and favorable progression (arrivals type 5).

CASE STUDY INPUT PARAMETERS

This section describes the parameters for the case study. The vehicle fleet composition was assumed to consist of 20 percent Tier 1 PC, 30 percent Tier 2 PC, 20 percent Tier 1 PT, and 30 percent Tier 2 PT. The assumptions take into account the fact that both types of vehicles are common in a typical vehicle fleet, and that as older vehicles retire from the fleet, the proportion of Tier 2 vehicles will be higher than that of Tier 1 vehicles. These assumptions are also somewhat arbitrary, and can be easily manipulated by the user. The focus of this case study was on low-speed intersections, and emissions were calculated over a 457 m (1,500 ft) segment for a two-lane approach to the roundabout or signalized intersection. The case study is intended to illustrate the application of the methodology.

For the signalized intersection case, the saturation flow rate was set at 1,800 pcphpln (passenger cars/hour/lane), the cycle length at 120 s, and the g/C ratio at 0.5. For the comparable roundabout, the circulating flow rate was assumed to be 700 vehicles per hour (vph). Other variations of case study inputs include values of demand levels (d/c ratios), which were allowed to vary from 0.3 to 1.1, and the platoon ratio at the signal, which was chosen to represent HCM arrival types 1, 3, and 5 respectively.

CASE STUDY RESULTS

Pollutant emissions for NO_X, HC, CO and CO2 were estimated for the case study. All emissions are reported based on grams per vehicle-mile travelled (grams/VMT, kilograms/VMT for CO_2). The results are presented in figure 27 through figure 30, and discussed below the figures.

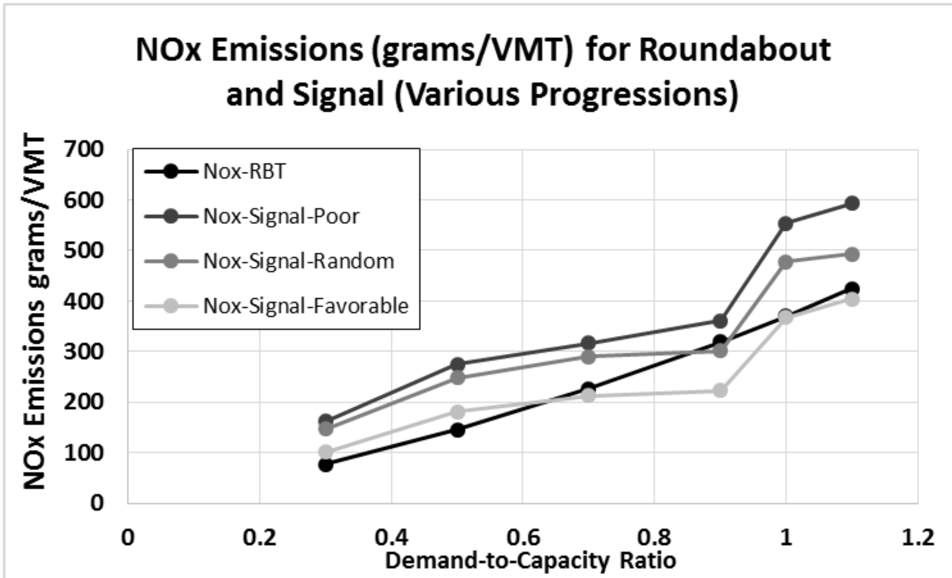


Figure 27. Graph. Comparison of estimated emission rates for NO_X for case study of roundabout (RBT) and signalized intersection (Signal) with varying signal progressions and d/c ratios.

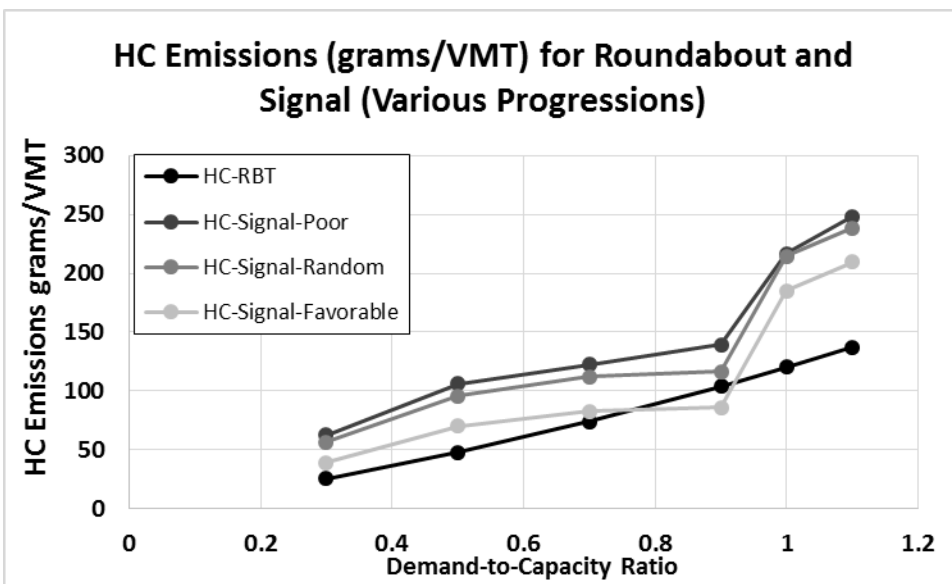


Figure 28. Graph. Comparison of estimated emission rates for HC for case study of roundabout (RBT) and signalized intersection (Signal) with varying signal progressions and d/c ratios.

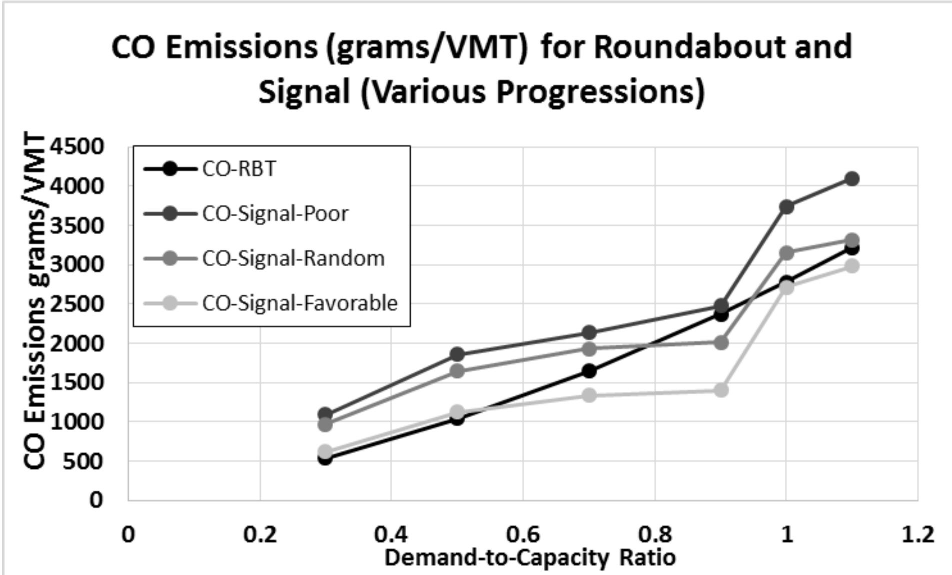


Figure 29. Graph. Comparison of estimated emission rates for CO for case study of roundabout (RBT) and signalized intersection (Signal) with varying signal progressions and d/c ratios.

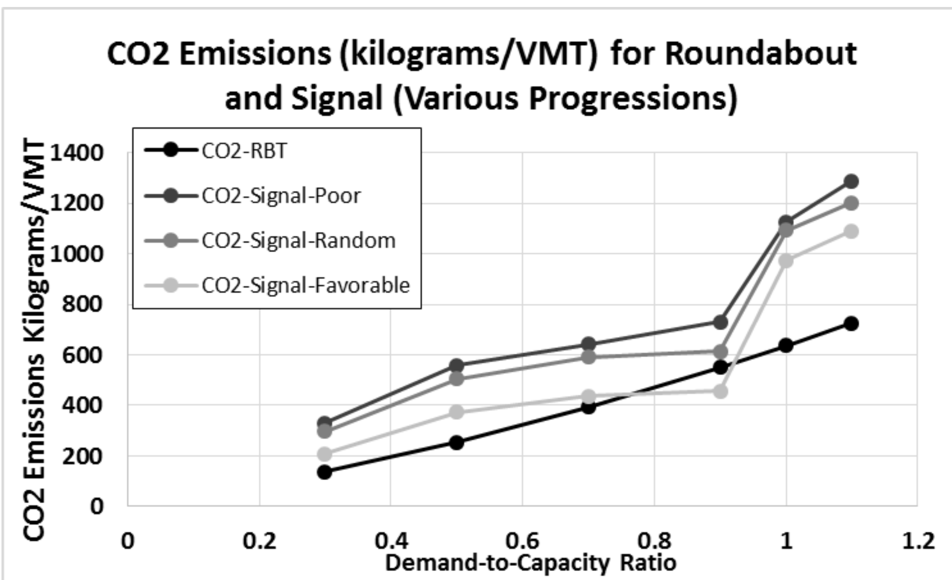


Figure 30. Graph. Comparison of estimated emission rates for CO_2 for case study of roundabout (RBT) and signalized intersection (Signal) with varying signal progressions and d/c ratios.

Emissions vs. Demand-to-Capacity Ratio

As the traffic load, or d/c ratio, increased, the pollutant average emission rates increased for both roundabouts and signalized intersections, assuming no change in the conflicting flow rate. However, for signalized intersections there was a steep spike in emission rates as soon as demand exceeded capacity (d/c>1) and the intersection shifted to an oversaturated state with frequent cycle failures. The spike was evident in for all signal progressions. The emission rates for a given d/c ratio were highest for the case with poor signal progression, where vehicles arrive mostly during red intervals.

Emissions vs. Signal Progression Type

For arrival type 1, poor progression, vehicles traversing roundabouts generated fewer grams/VMT pollutant emissions than those at signalized intersections. When progression was poor, the fraction of vehicles arriving in green for arrival type 1 was 0.33 times 0.5, or only 16 percent, resulting in a very high occurrence of Type B and C trajectories. In this case 84 percent of approaching vehicles stopped at least once. The stop-and-go cycles with poor progression resulted in higher emission rates than those at roundabouts and at signalized intersections with random and/or favorable progression.

In the case of arrival type 3, random arrivals, both CO_2 and HC emission rates were higher at signalized intersections than at roundabouts for all d/c ratios. The NO_X, HC and CO_2 emission rates were approximately the same, and the CO emission rates appear to be slightly lower at signals than at roundabouts. The reason for slightly higher CO emission rates at roundabouts could be because all vehicles traversing roundabouts must decelerate and accelerate, creating a higher proportion of high VSP than at signalized intersections, where a proportion of trajectories need not decelerate and accelerate to the same extent.

For favorable progression through the signal, arrival type 5, the majority of the vehicle platoons arrive during the green. Therefore vehicles progress through the signalized intersection with fewer stops, resulting in less emissions. For d/c ratios lower than 0.7 and greater than 1.0, vehicles traversing signalized intersections had higher emission rates than those traversing roundabouts for all progression types. However, for d/c ratios between 0.7 and 1 and with favorable progression, emissions at roundabouts were greater than those at signalized intersections. Therefore, vehicles traversing roundabouts are estimated to produce more emissions than those traversing signalized intersections in cases where the signals are optimally coordinated and at traffic levels close to capacity. This is mainly because, in those cases, signals can progress vehicles with higher efficiency than roundabouts.

Emissions vs. Vehicle Type

Figure 31 through figure 34 show how CO_2 emission rates varied between the four vehicle types and with d/c ratio depending on intersection type and, for signalized intersections, the arrival type. Given their typically lower fuel economy, passenger trucks typically have higher CO_2 emission rates than passenger cars. CO_2 emission rates are more sensitive to differences between vehicle types than to emission standards, since the standards do not address CO_2. Emission rates generally increase with d/c ratio, but the shape of the relationship differs. For example, for random arrivals at signalized intersections, the trend is sublinear, but for all other case, the trend is superlinear.

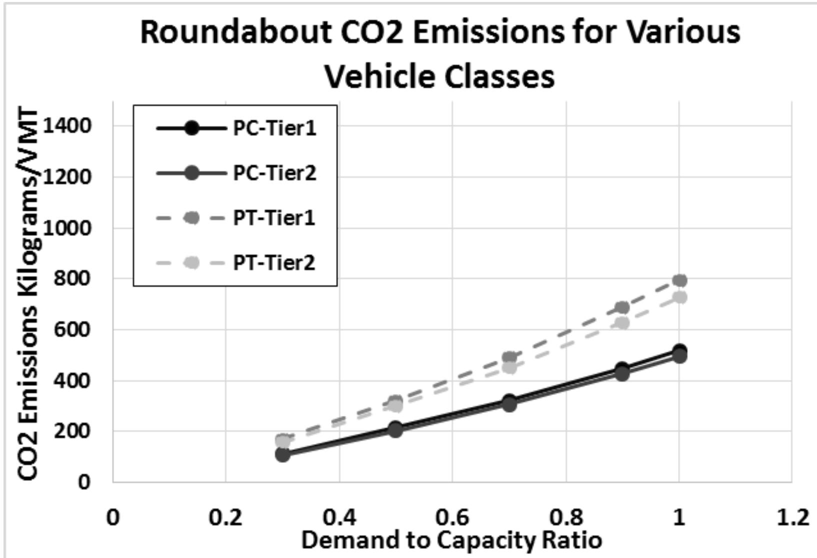


Figure 31. Graph. Comparison of estimated emission rates for CO_2 (kilograms/VMT) as a function of demand-to-capacity ratio for Tier 1 and Tier 2 passenger cars (PC) and passenger trucks (PT) for roundabouts.

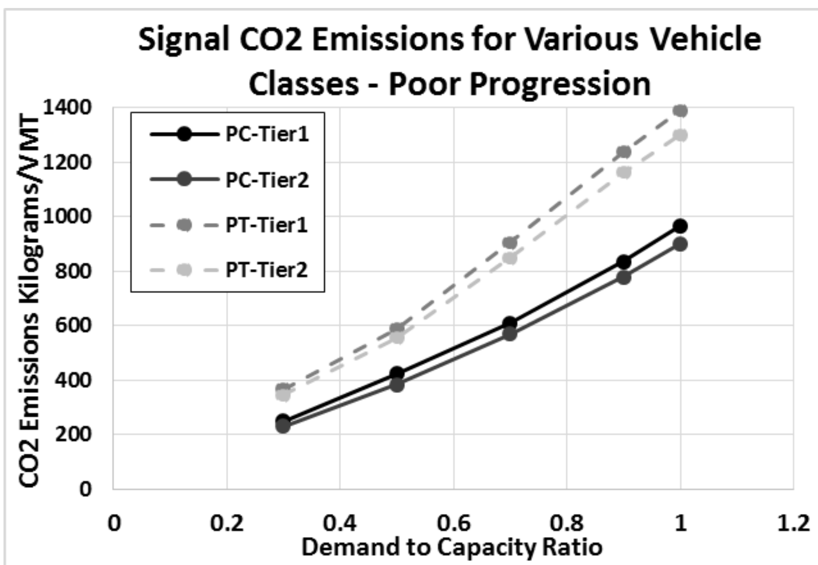


Figure 32. Graph. Comparison of estimated emission rates for CO_2 (kilograms/VMT) as a function of demand-to-capacity ratio for Tier 1 and Tier 2 passenger cars (PC) and passenger trucks (PT) for signalized intersections with poor progression.

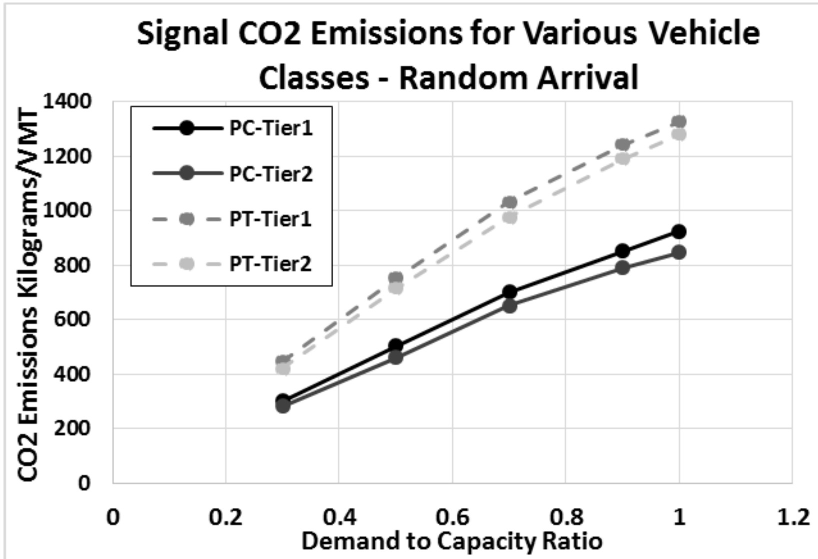


Figure 33. Graph. Comparison of estimated emission rates for CO_2 (kilograms/VMT) as a function of demand-to-capacity ratio for Tier 1 and Tier 2 passenger cars (PC) and passenger trucks (PT) for signalized intersections with random arrival progression.

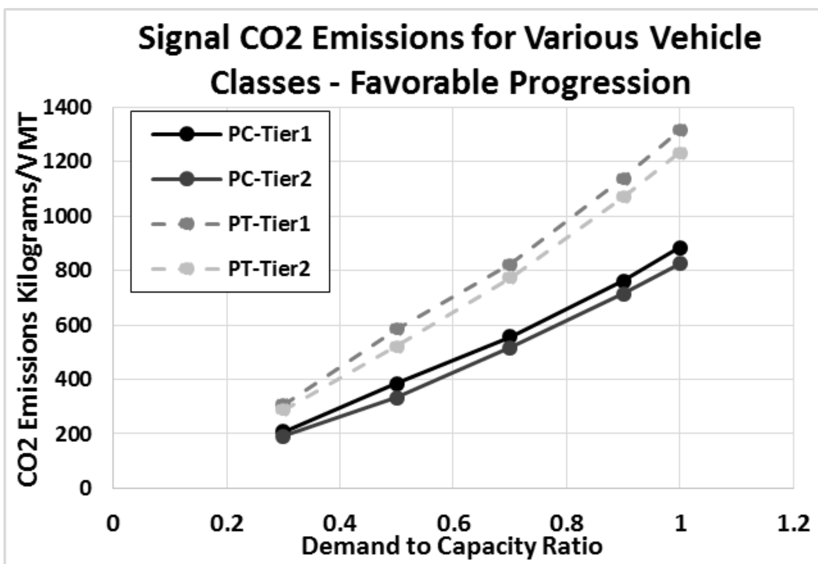


Figure 34. Graph. Comparison of estimated emission rates for CO_2 (kilograms/VMT) as a function of demand-to-capacity ratio for Tier 1 and Tier 2 passenger cars (PC) and passenger trucks (PT) for signalized intersections with favorable progression.

Emissions vs. g/C Ratio

An analysis with varying values of g/C, ranging from 0.3 to 0.6, led to a similar conclusion. Roundabouts have an advantage at low d/c ratios, or if the arrival type for signalized intersections is poor, or, for some pollutants, random. However, at high d/c ratios and a favorable arrival type, signalized intersections may have lower emission rates depending on the pollutant, with the highest advantage for signalized intersections occurring at d/c ratios of approximately 0.9.

CHAPTER 6. DISCUSSION AND CONCLUSION

The primary objective of this research was to develop a simplified methodology for estimating the pollutant emissions generated at a roundabout and comparing them to those at a signalized intersection, with the methodology based on actual, field-collected data. This methodology, which can be used at the planning stage, is sensitive to traffic operational input data such as demand, capacity, signal timing, signal progression, the estimated free flow speed, approach distance, and other variables. The research estimated emissions using the VSP method, which is based on micro-scale speed and accelerations, and is consistent with the EPA MOVES model approach.

There are five main factors impacting vehicle fuel use and emissions: (1) driver acceleration/deceleration behavior, (2) vehicle characteristics such as engine size and age, (3) traffic conditions, (4) infrastructure design, traffic control (e.g., speed limit, signal timing), and (5) ambient weather conditions. This research developed empirically-based vehicle activity models and emissions models for roundabouts and signalized intersections that took these five factors into account. The activity models took into account the driver behavior, traffic conditions and infrastructure design, which was reflected in the vehicle's speed profiles. The emission rate factors took into account vehicle technology. Combining the two via the VSP approach generated emission estimates near the intersection at various temporal and spatial scales.

The collected vehicle trajectories provided information on instantaneous speed, acceleration and deceleration rates, and idling times as a function of driver behavior, traffic conditions (congested vs. uncongested) and roadway design and control (roundabout vs. signal). Activity models were produced in terms of the frequency of trajectory Types A (no stop), B (single stop) and C (multiple stops) as a function of the demand volume and, when appropriate, signal timing. The emissions models were based on PEMS, which included VSP distributions for vehicles measured at signalized and roundabout intersections.

All models developed as part of this research were generated in an emissions computational engine in Microsoft Excel, which allowed for quick numerical calculations and comparisons. The inputs for the computational engine are listed in table 5, reproduced here as table 6 for reference.

Table 6. Computational engine inputs and outputs (from table 5).

Type	Description
Input	Demand flow rate on the approach (veh/hr) (AM, PM and Off-Peak are optional and can be entered separately)
Input	Number of hours each volume level is applicable (AM, PM, Off-Peak, optional)
Input	Fraction of vehicle classes (passenger car, passenger trucks—including SUV's) and their Tier standard
Input	Distance upstream and downstream of the intersection for emission calculations
Input	Signal timing variables (g and C) and arrival type for signalized intersections
Input	Circulating flow rate for roundabout intersections
Input	Whether the intersection is in a low or high speed environment
Output	Hourly emission rates for all 4 pollutants (NO_X, HC, CO, CO_2) as described in figure 18, by vehicle class (for each volume level, AM, PM and Off-peak if provided in the input)
Output	Emission rates gram/VMT for each pollutant per approach, during a single or multiple time periods (AM, PM and Off-Peak)
Output	Demand-to-capacity ratio for each approach of the intersections
Output	Overall emissions for the intersection

The methodology was applied to a case study comparing emissions produced at a roundabout and a signalized intersection under similar traffic load levels as quantified by demand-to-capacity (d/c) ratio. The results show that at d/c ratios of less than 0.7, or when progression quality is poor, vehicles traversing signalized intersections generally produced more emissions than those traversing roundabouts. At d/c ratios between 0.7 and 1, the opposite was true, with vehicles traversing roundabouts tending to produce more emissions. Once the d/c ratio exceeded 1, roundabouts once again saw less emissions than signalized intersections. Although the general trend was for roundabouts to outperform signalized intersections at d/c ratios less than 0.7 and greater than 1, for some pollutants, it seems roundabouts perform even better.

If the d/c ratio for peak period design hour volume (DHV) is around 0.85, a policy threshold in many cases, then over a period of 24 hours during which the greater number of hours have a d/c ratio of 0.7 or less, roundabouts are expected to perform better than signalized intersections. Of course, there are variations in these trends across the different pollutants estimated. It is noted that the comparison was performed on the basis of equal d/c ratios, but that the actual volume levels may be different between roundabouts and signals. The user is advised to utilize the computational engine to gain some insight into the mechanics of the emission estimation process.

The methodology is reasonably easy to use and implement. It requires inputs that are available or can be readily obtained during the planning stages of intersection design. It appropriately accounts for the key explanatory factors in emission estimation, which are types of speed profiles, traffic demand, segment length, and signal timing parameters.

CHAPTER 7. LIMITATIONS AND RECOMMENDATION FOR FUTURE WORK

The developed methodology does not take into account the geometric design features of the roundabouts and signalized intersections, such as deflection angle, inscribed diameter, lane width or intersection angle. Additional trajectory types that take pedestrian activity into account could be calibrated using the same methods as demonstrated here. The strength of the methodology is its simplicity and its use of real world speed and acceleration/deceleration profiles to generate the VSP distributions.

Further work is needed to address the limitations, such as research investigating the effects of roundabout geometry and pedestrian activity on vehicle emissions. Future work should also validate, using field observations, the simulation-based methodology for predicting the frequency of trajectory types at signalized intersections. Also, as additional vehicle trajectory data are collected, all the models described in this research should be updated and recalibrated.

APPENDIX A. LITERATURE REVIEW

INTEGRATION OF MICRO-SIMULATION MODELS WITH EMISSIONS MODELING

Many microscopic traffic simulation models such as NETSIM and INTEGRATION[26] and AIMSUN[27] have built-in fuel use and emissions estimation models. The working principle behind many of these models is vehicle-acceleration-indexed look up tables, which limit the ability of the models to handle road grades or vehicle operational history.[28] Several studies have demonstrated the integration of traffic microscopic simulation models with external emissions models and the subsequent application to evaluating traffic operations. In one study a communication interface between the VISSIM microscopic simulation model and the CMEM modal emissions model was developed to quantify and compare vehicle emissions for two traffic control and management strategies.[29] The VISSIM model was calibrated with road infrastructure data, traffic volumes, signal timing plans and public transport line information.

CMEM (Comprehensive Modal Emissions Model) is a microscopic modal emissions model that uses second-by-second vehicle activity data (speeds, accelerations, grades) and vehicle-specific parameters (engine displacement, maximum torque, etc.) to calculate the vehicle engine demand. It then calculates the instantaneous emissions of HC, CO, NO_X and CO_2 based on the vehicle's operating modes – deceleration, idling, acceleration, and cruising.[29,30] The authors constructed the communication interface between VISSIM and CMEM based on matching vehicle types between the models. The approach was used to show that setting exclusive bus lanes reduced tailpipe emissions of HC, CO and NO_X from buses but increased the emissions of HC and CO for cars and light duty gasoline vehicles. Signal timing optimization improved both traffic operations and emissions.

Other researchers[16] sought to integrate VISSIM, CMEM, and a stochastic signal optimization tool called VISGAOST to minimize fuel use and CO_2 emissions on signalized corridors.[16] In this approach, emissions estimated by CMEM for a particular signal timing plan in VISSIM are fed into VISGAOST, and a Genetic Algorithm procedure within VISGAOST is applied to create the optimized signal plan based on results from CMEM. Another study focused on the emissions from a single vehicle and the relationship between emissions and driver aggressiveness[31] by coupling VISSIM and CMEM. VISSIM and CMEM were also coupled to observe the changes in short-run emissions and long -run emissions due to induced demand in a network from two traffic-flow improvements.[32] The traffic flow improvements are a lane addition downstream of a merge between two urban priority arterials, and traffic signal coordination along a corridor. The authors found that the traffic flow improvement strategies reduced total emissions in the network, but relatively small increases in demand after the lane add or signal coordination resulted in emissions quickly returning to the original levels.

VISSIM has been combined with other microscopic air pollution models including MODEM and VT Micro. MODEM is a speed-based emissions inventory database.[33] The database was constructed based on results from chassis dynamometer driving cycle measurements and surveys of operating characteristics of vehicles in an urban environment in Europe. Fuel use and emissions are calculated in MODEM using instantaneous speed and acceleration for different vehicle types. A study conducted in the UK demonstrated the application of VISSIM and MODEM to estimate emissions under different traffic conditions.[34] The estimated emissions were found to be similar to the UK's standard macroscopic air pollution model specified in the Department of Transport's Design Manual for Roads and Bridges (DMRB), but in some cases significantly different from measured emissions from roadside pollutant monitors. Other researchers[13] studied the emissions impact of a hypothetical change in intersection control by coupling VISSIM with VT Micro and INTEGRATION with CMEM. The simulation models were calibrated with field data and validated with the length of side street queues. Compared to a base case of two-way stop control for a low-speed road intersecting a high-speed road, estimates were made for a replacement signalized intersection and for a roundabout. The results indicated that fuel consumption and emissions increased as a result of either of the replacements, and more so for the roundabout. INTEGRATION and VT-Micro were also used to compare an isolated intersection served by a traffic signal, all-way stop control, two-way stop control and a single-lane roundabout. The intersection was simulated as a simple four-way intersection with single-lane approaches and uniform demand. The roundabout was estimated to have lower emissions of NO_X, HC, CO and CO2, compared to the other alternatives, under conditions such as low left turns or when demand was 40 to 60 percent of total demand.[13]

A study combining the PARAMICS micro-simulation model with CMEM demonstrated that the Advanced Driver Alert Systems (ADAS) can reduce emissions at signalized intersections.[35] CMEM and PARAMICS were also coupled to investigate the impacts on vehicle emissions and air quality from Intelligent Speed Adaptation (ISA) technologies,[36] High Occupancy Vehicle (HOV) lanes,[36] High Occupancy Toll (HOT) lanes and uphill truck climbing lanes.[38] The emissions from varying freeway speed limits in Houston, TX were investigated by combining three different emissions models with micro-scale simulation data from TRANSIMS (TRansportation ANalysis SIMulation Systems) – the TRANSIMS emissions module, MOBILE5 and MOBILE5.[39] Others[30] consider MOBILE to be an "average-speed" model because the inputs for the model are mean travelling speeds and vehicle miles travelled. On the other hand, the TRANSIMS emissions module is based on the CMEM model. The authors found that under congested conditions, the MOBILE suit of models estimate lower emissions than the TRANSIMS emissions module because they are unable to capture the sharp accelerations and decelerations using the average speed approach.

ON-BOARD EMISSIONS USING PORTABLE EMISSIONS MEASUREMENT SYSTEM (PEMS)

Emission factors are the empirical relationships between vehicle activity and the resulting emissions.[40] Emission factors can be developed from experimental data collected under controlled laboratory conditions or in real-world environments. Several emissions models described earlier, which are integrated with micro-simulation models, use emission factors based on data from dynamometer testing in the laboratory. CMEM and MODEM are examples of emissions models which propose emission factors developed from chassis and engine dynamometer testing under controlled conditions. During dynamometer testing, driving cycles are simulated under laboratory conditions to collect instantaneous emissions data. Although this kind of testing is highly standardized and considered to be accurate, the emission factors from on-board measurement data are more representative of actual emissions in the field.

Portable Emissions Measurement Systems (PEMS) are able to capture second-by-second micro-scale emissions under real-world operating conditions.[41] This also allows researchers to utilize the data at different levels of aggregation and characterize the variability in emissions on a variety of road types. As part of previous and on-going research projects, NC State University has developed an extensive database of high-resolution vehicle operation and emissions measurements from PEMS equipped vehicles driving on pre-defined test routes between NC State University, North Raleigh and the Research Triangle Park. The research team uses the OEM-2100AX Axion System, which measures tailpipe exhaust concentrations of NO, HC, CO and CO_2 to collect emissions measurements.

The PEMS equipment include a sampling probe that continuously collects tailpipe emissions, a filter bowl to remove water vapor, non-gaseous materials and aerosol droplets and two five-gas analyzers to analyze the emissions. The gas analyzers measure NO (ppm) and O_2 (percent) by means of electrochemical sensors and HC (ppm), CO (percent) and CO_2 (percent) using a non-dispersive infrared (NDIR) optical chamber,[42] Once the sampled tailpipe gas passes through the analyzers, the exhaust and water vapor is removed via exhaust hoses. Along with the PEMS unit, an external engine scanner is used to collect vehicle activity and engine dynamics data from the vehicle's Electronic Controls Unit (ECU) via the vehicle's On-Board Diagnostics (OBD) port. The data includes second by second observations of speed, acceleration, engine RPM, manifold air pressure (MAP) and intake air temperature (IAT). During the PEMS tests, three GPS units are deployed to record the instantaneous positions of the vehicle.

The PEMS equipment, OBD engine scanner and GPS units are easily installed into vehicles. At the start of each testing period, the PEMS unit is calibrated using a calibration gas composed of 0.5 percent CO, 6 percent CO_2, 202 ppm HC and 298 ppm NO.[42] To prevent drifting, the PEMS unit is "zeroed" at 15 minute intervals using ambient air which contains negligible levels of NO, HC and CO. The two gas analyzers are never zeroed at the same time, ensuring that no gaps occur in emissions data collection. The computer that is integrated into the PEMS unit provides an interface for users to observe the output from the gas analyzers in real time as well as program the data to be saved to "bags" which can be used to denote a route or a time period.

PEMS field tests were conducted by NC State University on a set of test routes between the Research Triangle Park (RTP) and the NC State University Campus in Raleigh, NC. The tests consisted of collecting both instantaneous vehicle activity and tailpipe emissions data. The data were collected repeatedly on two routes between North Raleigh and the RTP and two routes between NCSU and North Raleigh, using light duty gasoline vehicles with a wide range of manufacturers, engine sizes and model years. The routes represent alternative commuting routes between the same origins and destinations, thus covering several facility types including freeways, ramps, local and arterial streets and a range of road grades. Figure 35 shows these routes.

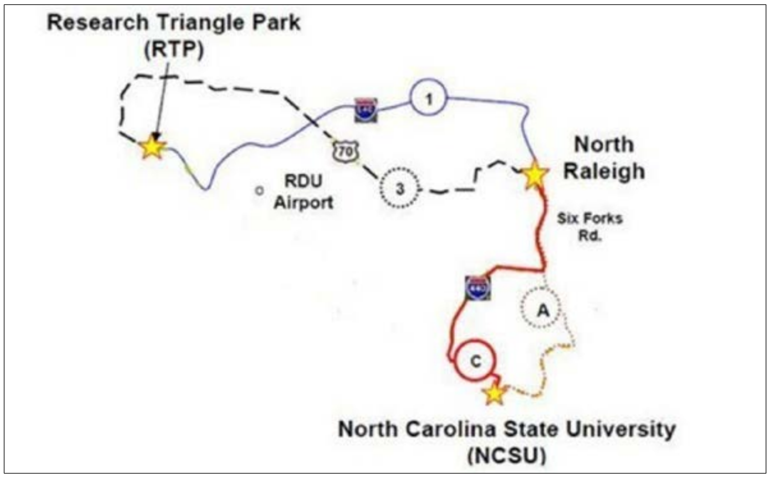


Figure 35. Map. Data collection routes between NC State University (NCSU), North Raleigh and Research Triangle Park (RTP).

During each testing period, a vehicle completed Routes A, C, 1 and 3 by travelling through a total of 36 miles of freeway and 76 miles of arterial streets. The test vehicles encountered different intersection controls along the routes which are summarized in table 7.

Table 7. Attributes of data collection routes.

Route No.	Route Name	Freeway Mileage (mi)	Arterial Mileage (mi)	No. with Signal Intersection Control	No. with Stop Sign Intersection Control	No. with Roundabout Intersection Control
1	A In	0	11	43	26	3
2	A Out	0	11	43	26	3
3	C In	5	6	29	16	2
4	C Out	5	6	29	16	2
5	1 In	13	3	4	3	0
6	1 Out	13	3	4	3	0
7	3 In	0	18	26	31	0
8	3 Out	0	18	26	31	0

During each testing period, second-by-second emissions of NO, HC, CO and CO_2 from the tailpipe exhaust are measured and recorded by the PEMS unit. Vehicle activity data are collected via GPS devices recording latitude, longitude and altitude of the test vehicle.[23] The On-board Diagnostics (OBD) port in each vehicle acquire the engine RPM, intake air temperature (IAT), mass air flow (MAF) and second-by-second speed and fuel flow. The internal clocks of each component are independent and need to be synchronized in order to match the data that was collected at the same time. The PEMS, GPS and OBD data were all converted to follow a frequency of 1Hz. Data from a pair of components were then synchronized by means of a "master" parameter and a "slave" parameter, based on the datasets exhibiting correlated trends in their time series.[43]

After synchronization, the combined datasets are checked for errors. There can be several types of errors in the data, including, but not limited to: unusual engine RPM, engine RPM “freezing” or remaining constant for more than 3 s, leakage in and overheating of the gas analyzers, negative emissions values due to random measurement errors, ambient air infiltration into exhaust gas sampling system and loss of power to any component of the PEMS equipment.[43] Errors in data are identified using quality assurance algorithms in LabView and corrected if possible or removed if the data is found to be invalid.

Once the data from all PEMS equipment are synchronized and quality assured, it is possible to characterize the second-by-second vehicle activity by using Vehicle Specific Power (VSP) and to develop modal emission factors from the instantaneous emissions data. The following section provides examples of integrating micro-simulation models and with VSP-based emissions estimation.

VEHICLE SPECIFIC POWER-BASED EMISSIONS MODELING

Researchers[7] introduced the concept of VSP to develop an instantaneous load-based emissions model. VSP accounts for a vehicle’s kinetic energy, rolling resistance, aerodynamic drag and the effects of gravity with road grade. It is a proxy variable quantifying the instantaneous tractive power per unit mass of the vehicle engine. Each value of VSP can be associated with an emission function based on laboratory dynamometer testing or field-based measurements.[44] Physical power-demand based emissions estimation techniques are able to take into account all factors affecting vehicle operations, including vehicle types, ages, models, fuel types, road grades etc. The authors[7] demonstrated stronger dependence of NO, HC and CO emissions on VSP rather than on parameters such as speed, acceleration, absolute power or fuel rate. The VSP-based approach to emissions modeling is simpler than CMEM.[45] VSP is directly calculated from field-measured parameters for which no assumptions are required, unlike for parameters such as engine speed or fuel rate.[7]

VSP is calculated using second-by-second speed, acceleration and road grade. The relationship in equation in figure 36 can be used to estimate VSP for light-duty gasoline vehicles.[45]

$$VSP = v\,(1.1a + 9.81\,(\sin(\tan^{-1}(r))) + 0.132) + 3.02 * 10^{-4} v^3$$

Figure 36. Equation. Vehicle specific power calculation (appendices).

Where:

VSM = Vehicle Specific Power (kW/ton)

v = velocity (m/s)

a = acceleration (m/s2)

r = road grade

Validation studies by North Carolina State University[45] showed that it is feasible to group instantaneous VSP into a discrete number of bins called “modes”. The number of bins was selected based on the objective of characterizing the variability in emissions from vehicle activity. Therefore, each of the 14 proposed bins are such that the average emission rate associated with the bin is statistically significantly different from any other bin and no one bin explains more than 10 percent of total emissions. Table 8 shows the VSP ranges within each of the 14 bins as proposed by North Carolina State University.[45]

Table 8. Definition of VSP bins.

VSP Mode	VSP Range (kW/ton)
1	Below -2
2	-2 – 0
3	0 – 1
4	1 – 4
5	4 – 7
6	7 – 10
7	10 – 13
8	13 – 16
9	16 – 19
10	19 – 23
11	23 – 28
12	28 – 33
13	33 – 39
14	Over 39

US EPA’s MOVES (Motor Vehicle Emissions Simulator) emissions model also uses VSP to determine the amount of time a vehicle spends in each of its 23 operating mode bins. Operating modes are categories that differentiate emissions and are based on combinations of speed and VSP.[46] In one study, the emissions on one-way and two-way streets in the peak and off-peak periods were compared using traffic data generated by VISSIM micro-simulation software in the US EPA’s MOVES model.[47] The detailed outputs of instantaneous speed and accelerations from VISSIM were used to calculate instantaneous values of VSP. Vehicle emissions were estimated from the distribution of VSP in 23 operating modes. The results indicated that two-way streets produce higher total emissions than one-way streets, especially under peak hour traffic conditions. PARAMICS micro-simulation model was integrated with both CMEM and MOVES emissions models to investigate alternative intersection designs – a three-legged intersection with pre-timed signal control and a single lane roundabout under light and heavy traffic.[14] The study showed that both models estimated higher emissions with the roundabout installed under light and heavy traffic. CMEM and MOVES were found to produce similar estimates for NO_X emissions but widely different estimates for CO, because MOVES used a detailed modeling approach with second-by-second speed profiles of vehicles while an average speed based approach was used in CMEM.

One study demonstrated the integration of VSP-based emissions modeling approach with micro-scale vehicle activity from VISSIM to evaluate the environmental performance of coordinated and non-coordinated signalized corridors in Beijing, China.[48] It was found that that optimizing signal timing on a coordinated corridor and controlling traffic demand significantly reduces vehicle emissions. The VSP modal emissions analysis was also applied to quantify emissions at single-lane roundabouts in Raleigh, NC and Lisbon, Portugal by means of a hybrid approach based on field data for vehicle activity and an existing emissions model.[1] Empirical data showed that vehicles at a roundabout follow one of three possible trajectories: (1) a vehicle travels through the roundabout by slowing down in response to the geometrics without stopping fully; (2) the vehicle comes to a full stop at the entry line of an approach to negotiate a gap in the circulating traffic, accelerate to the circulation speed before eventually accelerating back to original speed; and (3) the vehicle enters a queue and experiences stop-and-go motion until passing the yield line. Complete speed profiles for each possible trajectory through the roundabout were developed using the modeling approach of North Carolina State University[45] to obtain VSP values. VSP modal emission factors in g/s were then used to estimate emissions per vehicle, which, coupled with the proportion of vehicles following each of the three speed profiles and the approach entry flow rate, was used to determine total hourly emissions at the roundabout.

Use of VSP in estimating emissions was also demonstrated in a study of a regional road network in North Carolina created using the AIMSUN micro-simulation system.[50] This study used the modal emission factors estimated from data collected on the same road network using Portable Emissions Measurement System (PEMS) with the VSP distributions from AIMSUN-simulated data. The study found that for freeway segments of the routes, the total empirical emissions and emissions calculated from the modal model were within ± 10 percent of each other. The arterial sections did not share the same trend because of greater differences in VSP distributions between simulation and real world data. The authors recommended that for evaluating emissions on arterial segments using the VSP modal approach, the internal behavioral model parameters in AIMSUN should be calibrated appropriately to generate vehicle activity that is more representative of the real world.

Traffic on arterial roads experience larger and more frequent speed fluctuations in comparison to freeway traffic. The highest fuel consumption on arterials is associated with driving in congested traffic, characterized by higher speed fluctuations and frequent stops at intersections.[16] However, low traffic and continuous progression along streets do not guarantee the lowest fuel consumption and emissions. The authors suggested that the best flow of traffic on arterial streets in terms of fuel consumption and emissions is the one with the fewest stops, shortest delays, and moderate speeds maintained throughout the commute. To investigate the emissions on existing arterial roads and study the effects of improvements to traffic flow using micro-simulation models, it is necessary to ensure that the simulated traffic on arterials accurately represents what is or can be expected to in the real world. In a study that linked the output from macroscopic transportation models to the microscopic VSP-based emissions modeling approach, it was shown that arterial speed profiles can be grouped together with respect to the average link speed. Average emission rates increased with average speed for arterials.[48]

A recent study investigated the amount of error in emissions estimates using VSP distributions of vehicle activity data from VISSIM and the sensitivity of VSP distributions to modeling parameters[18]. It was observed that second-by-second empirical vehicle activity data and simulated vehicle activity data from a calibrated and validated VISSIM model did not yield the same VSP distributions. The parameters had been calibrated using GPS data and Remote Traffic Microwave Sensors (RTMS) data from freeways or expressways with flat terrain in Beijing and included: (1) Desired Speed distribution, (2) Desired Acceleration Distribution, (3) Maximum Acceleration, (4) Desired Deceleration Distribution, (5) Maximum Deceleration, (6) Maximum Deceleration for Co-operative Braking (7) Safety Distance Reduction Factor and (8) Maximum Look Ahead Distance. The differences between the simulated time-varying speeds and the RTMS-collected field speeds were less 15 percent, while the differences between traffic flow measures were less than 10 percent. The validation was done using the link average speed and flow. Emission rates per unit distance were calculated using MOVES emission factors and the VSP distributions for the simulated activity. The simulated vehicle activity produced high errors, especially for NO_X emissions. Simulation model overestimated emissions for low speed conditions by up to 248 percent and underestimated emissions for high speed conditions by up to 16 percent. It was found that these errors were systematic errors in the traffic simulation models, because they remained statistically the same when a sensitivity analysis was performed on eight parameters by increasing and decreasing their values by 10 percent.

It has been demonstrated that calibrating the distributions of acceleration, deceleration and speed of buses in AIMSUN micro-simulation model affect the emissions estimates from the vehicle activity.[48] Second-by-second bus performance data was collected automatically by the iBus system in London and used to modify input distributions of the relevant parameters pertaining to the motion of simulated buses. Emissions were estimated using the emissions model developed,[52] which is already embedded in AIMSUN. Emission functions which differ by vehicle, fuel, and pollutant types were used to modify the emissions calculated at each simulation step using the same formula for all pollutants.[52] The study showed that under the calibrated parameters, the buses produced significantly more emissions under heavy traffic flow conditions due to more stop-and-go cycles than under the default parameters. The emissions were less sensitive however, under low flow conditions.

The VSP modal approach was also used to compare numerically simulated data from five car following models - optimal velocity model (OVM), generalized force model (GFM), full velocity difference model (FVDM), Weidemann model, and Fritzsche model.[51] It was observed that the Fritzsche produced more realistic VSP distributions than the other models. VSP distributions from the Weidemann model showed larger differences with the field observed VSP distributions at higher speed and overestimated emission. The FVDM model gave the lowest RMSE when the acceleration distributions were compared between simulated and field data. However, RMSE increased as speeds increased to more than 40 km/h. The Fritzsche model had slightly higher RMSE than the FVDM model. The study found that speed-specific VSP distributions were highly correlated to the acceleration distribution and therefore, improving the acceleration distribution for certain speed bins is a promising method of improving calibration of car following models for estimating emissions using the VSP modal approach. Popular micro-simulation models, PARAMICS and VISSIM are based on the Fritzsche and Wiedemann models respectively. However, the exact differences between the models that are published in literature and the simulation models are not in the public domain.[53]

APPENDIX B. DATA COLLECTION DETAILS

This appendix includes the details for speed trajectories used in the computation engine to develop the emission factors reference tables and VSP distribution models for signalized intersections and for roundabouts. From 2008 to the present, data have been collected for Passenger Cars (PCs) and Passenger Trucks (PTs) in the Research Triangle Park, NC area representing vehicle activity for multiple road functional classes (i.e. feeder/collector streets, minor arterials, major arterials, freeway, ramp) and a wide range of speed and acceleration[2,3] The second-by-second speed trajectories and emissions generated from vehicle exhaust were collected from a fleet size of 95 vehicles. Each of these vehicles were equipped with a PEMS device and three GPS devices to report the second-by-second emissions and engine activity such as sped, deceleration rate, etc. The vehicles were set to drive through a certain route in the Research Triangle Park, NC, shown in figure 37. The data from PEMS were then analyzed to calculate the emission factors. Fleet average VSP modal rates were estimated for each of four vehicle groups: T1 PC (n=24); T2 PC (n=39); T1 PT (n=10), and T2 PT (n=22), with T1 indicating Tier 1 emission standards, and T2 indicating Tier 2 emission standards. The mean values for pollutants NO_X, HC, CO_2 and CO for VSP modes (emission factors) are shown in figure 18 and table 7 in the report.

The second-by-second data from GPS devices were also used to calculate the VSP distribution for signalized intersections. For every second of the speed trajectory, the VSP value of that speed and deceleration rate was calculated and then the associated VSP bin was identified. Last, for each compete speed profile through a certain intersection, the percent of time spent in each VSP mode was calculated from those data, and the VSP distribution models developed. Table 9 shows the list of the intersections that the data was collected from.

Table 9. List of the signalized intersections used for data collection.

Intersections	Approaches	No. of Lanes[1]	A Profiles	B Profiles	C Profiles
W. Morgan and Mayo (1)	4	EB: 1TR, 1T; WB 1LT	11	0	0
W. Morgan and St. Mary's (2)	4	EB: 1LT, 1TR; WB: 1LTR	9	2	0
W. Morgan and Glenwood (3)	3	EB: 1LT, 1T; WB: 1TR	11	1	0
W. Morgan and S. West (4)	4	EB: 1LT, 1TR; WB: 1LTR	10	2	0
W. Morgan and S. Dawson (5)	2	EB: 1T, 1TR; WB: 1T	11	1	0
Wake Forest and McNeill (8)	3	NB: 1L, 3T; SB: 1L, 1T, 1TR	18	4	0
Wake Forest and Hodges (9)	4	NB: 1L, 2T, 1TR; SB: 1L, 1T, 1TR	21	1	0

Intersections	Approaches	No. of Lanes[1]	A Profiles	B Profiles	C Profiles
Wake Forest and Creekside (10)	4	NB: 1L, 2T, 1TR; SB: 1L, 1T, 1TR	22	0	0
Six Forks and Ramblewood (13)	3	NB: 1L, 1T, 1TR; SB: 1L, 2T, 1TR	20	4	0
Six Forks and Dartmouth (15)	4	NB: 2L, 3T, 1R; SB: 2L, 2L, 1TR	15	9	0
Six Forks and Lassiter Mill (16)	4	NB: 2L, 2T, 1TR; SB: 1L, 2T, 1TR	12	10	2
Six Forks and Rowan (17)	4	NB: 1L, 2T, 1R; SB: 1L, 2T, 1TR	18	5	1
Six Forks and Northbrook (18)	4	NB: 1L, 1T, 1TR; SB: 1L, 2T, 1TR	16	8	0
Six Forks and Shelley (19)	4	NB: 1L, 1T, 1TR; SB: 1L, 1T, 1TR	42	3	0
Six Forks and East Millbrook (20)	4	NB: 1L, 2T, 1TR; SB: 1L, 1T, 1TR	13	27	5
Six Forks and Northclift/Sandy Forks (21)	4	NB: 1L, 2T, 1R; SB: 1L, 1T, 1TR	30	13	2
Six Forks and Lynn (22)	4	NB: 1L, 1T, 1TR; SB: 1L, 2T, 1R	30	15	0
Hillsborough and Meredith College Entrance (46)	4	EB: 1L, 1T, 1TR; WB: 1L, 1T, 1TR	13	11	0
Hillsborough and Gorman (47)	4	EB: 1L, 1T, 1R; WB: 1L, 1T, 1TR	8	15	1
Glenwood and Pinecrest/Westborough (37)	4	NB: 1L, 2T, 1R; SB: 1L, 2T, 1R	2	0	0
Glenwood and Ebenezer Church (38)	4	NB: 1L, 2T, 1R; SB: 1L, 2T, 1R	0	0	2

Intersections	Approaches	No. of Lanes[1]	A Profiles	B Profiles	C Profiles
Glenwood and Triangle (39)	4	NB: 1L, 2T, 1R; SB: 1L, 2T	2	0	0
Glenwood and Brier Creek (40)	4	NB: 2L, 3T, 1R; SB: 2L, 3T, 1R	0	0	2
TW Alexander and S. Miami (42)	4	NB: 1L, 3T, 1R; SB: 1L, 2T, 1R	1	6	0
TW Alexander and N. Entrance (43)	4	EB: 1L, 2T, 1R; WB: 1L, 2T, 1R	4	2	1
TW Alexander and Moore (44)	4	EB: 1L, 1T, 1TR; WB: 1L, 2T, 1R	2	1	4
TW Alexander and E. Cornwallis (45)	4	NB: 1L, 2T, 1R; SB: 1L, 2T, 1R	2	2	3
Hillsborough and Friendly/Dixie (48)	4	EB: 1LT, 1RT; WB: 1L, 1T, 1TR	6	0	0
Hillsborough and Brooks (49)	4	EB: 1L, 1T, 1R; WB: 1L, 1T, 1TR	4	2	0
Hillsborough and Gardner (50)	4	EB: 1L, 1T; WB: 1TR	4	1	1
Hillsborough and Horne (51)	4	EB: 1TR; WB: 1T	2	1	3

[1] EB = eastbound; WB = westbound; NB = northbound; SB = southbound; L = Left; R = Right; T = Through.

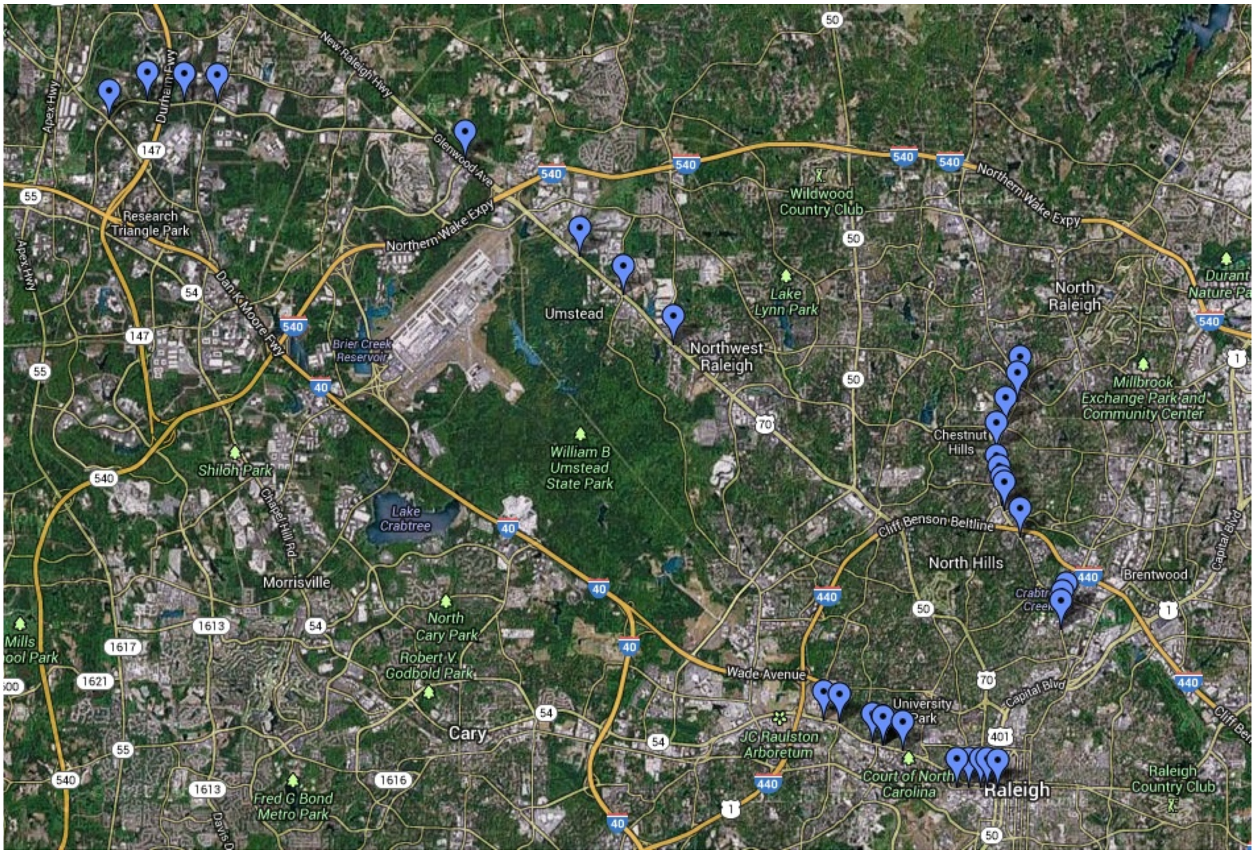


Figure 37. Map. Research Triangle Park, location of the signalized intersections.

As for the roundabouts, same as signalized intersections, second-by-second data were collected from GPS devices as vehicles were driving through the roundabouts to develop the VSP distribution models. The speed data were available from a previous project on roundabout corridors, NCHRP Project 03-100 (NCHRP Report 772).

These locations include the following roundabout corridors:

- Carmel, IN: Old Meridian St.
- Gig-Harbor, WA: Borgen Blvd.
- Malta, NY: SR 67
- San Diego, CA: La Jolla Blvd.
- Avon, CO: Avon Rd.
- Golden, CO: Golden Rd.
- Carmel, IN: Spring Mill Rd.
- Whatcom County, WA: SR 539

For more information on the location of the roundabouts can be found in the NCHRP Report 772, *Evaluating the Performance of Corridors with Roundabouts*.

APPENDIX C. SIMULATION EXPERIMENT DETAILS

This appendix exhibits the results of the VISSIM simulation used develop the regression models presented in the report. Table 10 lists the coefficients of variables used for predicting the likelihood for Type A trajectories. Table 11 lists the probability functions for predicting the proportion of Type C trajectories.

Table 10. Coefficients of variables used for predicting the likelihood of a no-stop (Type A) speed profile at a signalized intersection approach (table 3).

Arrival Type	Platoon Ratio, R_p	b_0	b_1	b_2
1	0.33	Min[1,R_p(g/c)]	-0.0195+0.580*g/C	3
2	0.67	Min[1,R_p(g/c)]	-0.0195+0.580*g/C	3
3	1	Min[1,R_p(g/c)]	-0.0195+0.580*g/C	3
4	1.33	Min[1,R_p(g/c)]	-0.9809(g/C)2+1.2748(g/C)-0.0149	5(R_p g/C)
5	1.67	Min[1,R_p(g/c)]	-1.7314(g/C)2+1.9424(g/C)-0.0852	4(R_p g/C)
6	2	Min[1,R_p(g/c)]	-2.2578(g/C)2+2.1815(g/C)-0.0487	4(R_p g/C)

Table 11. Functions for predicting the proportion of a Type C profile at a signalized intersection approach (table 4).

Arrival Type	d/c	Fraction of Type C Trajectories	R^2
1,2	Less than or equal to 0.7	0	0.95
1,2	Between 0.1 and 1.2	Figure 15	0.95
1,2	Greater than or equal to 1.2	1	0.95
3-6	Less than or equal to 1	0	0.90
3-6	Between 1 and 1.213	Figure 16	0.90
3-6	Greater than or equal to 1.213	1	0.90

For the VISSIM simulation two sets of eight different model were developed. The design of the VISSIM network is a simple two-lane link with two pre-timed signals located at a specific distance from each other on this link. Eight of these models (the first set) simulated a high speed environment with a Free Flow Speed (FFS) value of 72 km/h (45 mph) and the second set of eight models simulated an environment with a low FFS of 56 km/h (35 mph). The signals in the models have a 120 s cycle length. Each of the eight models in each set are set for a certain g/C ratio and effective green (g) values are 30 s, 40 s, 50 s, 60 s, 70 s, 80 s, and 90 s. The offset for the signals was set to simulated three arrival patterns, poor progression, random arrival and good progression. The volume during the simulation period changed to include d/c ratio range from 0.1 to approximately 1.4. All the scenarios resulted in 48 simulation models and each model was run 10 times resulting in 480 simulation runs, each for a period of 1 h. Then a macro was developed to process each vehicle trajectory type in the simulation run and calculate the percentage of Type A, B and C trajectories during the simulation period.

APPENDIX D. COMPUTATIONAL ENGINE DETAILS

This appendix contains screenshots of the computational engine developed for this project. Figure 38, figure 39, figure 40, figure 41, figure 42, figure 43, and figure 44 are all screenshots from the engine.

Instructions	
1	Use the "Signal Input" sheet and "Roundabout Input" sheet to enter the intersection information
2	You can choose to do the emissions analysis for only one time period (AM or PM or Off Peak) or a combination of time periods
3	Please note that some data are required for each time period individually, such as appraoch demand
4	Approach speed bin is 1 for speeds less than 35 MPH and 2 for speeds more than 35 MPH
5	The sume of Tier1 PC, Tier 2 PC, Tier 1 PT and Tier 2 PT should equal 100%
6	Use table below to enter the HCM arrival time
7	The results are shown in "Summary Output" sheet

HCM Arrival Type Describing Progression Quality at Traffic Signals

Rp	Arrival Type	Progression Quality from upstream signal
0.33	1	Very poor
0.67	2	Unfavorable
1	3	Random Arrivals
1.33	4	Favorable
1.67	5	Highly Favorable
2	6	Exceptionally Favorable

Approach Speed Bin	
1	Speeds less than 35 MPH
2	Speeds more than 35 MPH

Figure 38. Screenshot. Sheet 1 – instructions.

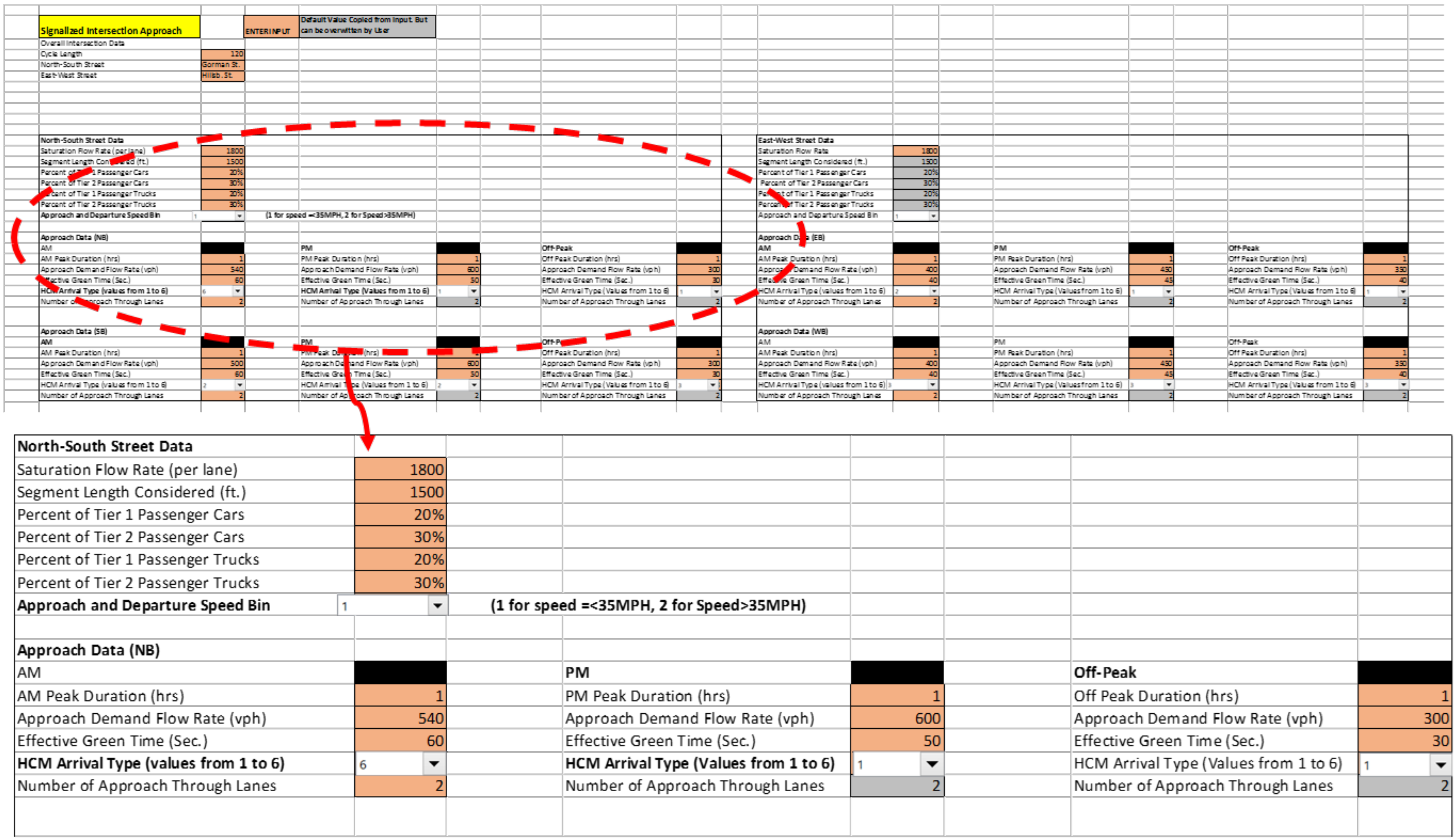
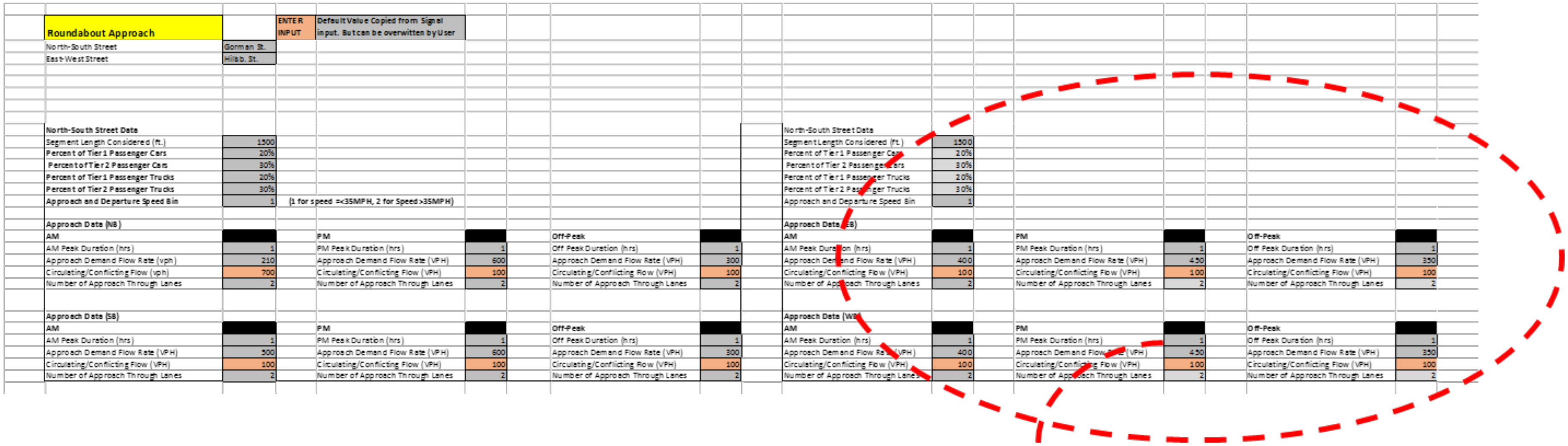


Figure 39. Screenshot. Signal input sheet.



Roundabout Approach		ENTER INPUT	Default Value Copied from Signal input. But can be overwritten by User
North-South Street	Gorman St.		
East-West Street	Hillsb. St.		

North-South Street Data		
Segment Length Considered (ft.)	1500	
Percent of Tier 1 Passenger Cars	20%	
Percent of Tier 2 Passenger Cars	30%	
Percent of Tier 1 Passenger Trucks	20%	
Percent of Tier 2 Passenger Trucks	30%	
Approach and Departure Speed Bin	1	(1 for speed =<35MPH, 2 for Speed>35MPH)

Approach Data (NB)					
AM		PM		Off-Peak	
AM Peak Duration (hrs)	1	PM Peak Duration (hrs)	1	Off Peak Duration (hrs)	1
Approach Demand Flow Rate (vph)	210	Approach Demand Flow Rate (VPH)	600	Approach Demand Flow Rate (VPH)	300
Circulating/Conflicting Flow (vph)	700	Circulating/Conflicting Flow (VPH)	100	Circulating/Conflicting Flow (VPH)	100
Number of Approach Through Lanes	2	Number of Approach Through Lanes	2	Number of Approach Through Lanes	2
Approach Data (SB)					
AM		PM		Off-Peak	
AM Peak Duration (hrs)	1	PM Peak Duration (hrs)	1	Off Peak Duration (hrs)	1
Approach Demand Flow Rate (VPH)	500	Approach Demand Flow Rate (VPH)	600	Approach Demand Flow Rate (VPH)	300
Circulating/Conflicting Flow (VPH)	100	Circulating/Conflicting Flow (VPH)	100	Circulating/Conflicting Flow (VPH)	100
Number of Approach Through Lanes	2	Number of Approach Through Lanes	2	Number of Approach Through Lanes	2

North-South Street Data					
Segment Length Considered (ft.)	1500				
Percent of Tier 1 Passenger Cars	20%				
Percent of Tier 2 Passenger Cars	30%				
Percent of Tier 1 Passenger Trucks	20%				
Percent of Tier 2 Passenger Trucks	30%				
Approach and Departure Speed Bin	1				
Approach Data (EB)					
AM		**PM**		**Off-Peak**	
AM Peak Duration (hrs)	1	PM Peak Duration (hrs)	1	Off Peak Duration (hrs)	1
Approach Demand Flow Rate (VPH)	400	Approach Demand Flow Rate (VPH)	450	Approach Demand Flow Rate (VPH)	350
Circulating/Conflicting Flow (VPH)	100	Circulating/Conflicting Flow (VPH)	100	Circulating/Conflicting Flow (VPH)	100
Number of Approach Through Lanes	2	Number of Approach Through Lanes	2	Number of Approach Through Lanes	2
Approach Data (WB)					
AM		**PM**		**Off-Peak**	
AM Peak Duration (hrs)	1	PM Peak Duration (hrs)	1	Off Peak Duration (hrs)	1
Approach Demand Flow Rate (VPH)	400	Approach Demand Flow Rate (VPH)	450	Approach Demand Flow Rate (VPH)	350
Circulating/Conflicting Flow (VPH)	100	Circulating/Conflicting Flow (VPH)	100	Circulating/Conflicting Flow (VPH)	100
Number of Approach Through Lanes	2	Number of Approach Through Lanes	2	Number of Approach Through Lanes	2

Figure 40. Screenshot. Roundabout input sheet.

North Bound

Signal- NB AM Peak

INPUT Values Copied from Signal Input Sheet

1- Approach Demand flow Rate (vph)	350
2-Saturation Flow Rate	1800
3- Cycle Length (sec)	120
4- Effective Green Time (sec)	40
5-HCM Arrival Type	3
6-Number of approach through lanes	2
7- Approach and Departure Speed Bin	1
8- Segment Length Considered (ft)	1500
9-Percent of Tier 1 Passenger Cars	20%
10- Percent of Tier 2 Passenger Cars	30%
11- Percent of Tier 1 Passenger Trucks	20%
12- Percent of Tier 2 Passenger Trucks	30%

1 Average Travel Speed

Bin1	Bin2
35.122	43.245
15.782	28.515
10.318	16.271

Travel Time Over the Segment for Selected Speed Bin

A	29.11 seconds
B	64.79 seconds
C	99.09 seconds

Arrival Type	Rp	b0	b1	b2	R-squared
1	0.33	Min[1,Rp(g/c)]	-0.0195+0.580*g/C	3	0.711
2	0.67	Min[1,Rp(g/c)]	-0.0195+0.580*g/C	3	
3	1	Min[1,Rp(g/c)]	-0.0195+0.580*g/C	3	0.4921
4	1.33	Min[1,Rp(g/c)]	-0.9809(g/C)2+1.2748(	5(Rp g/C)	
5	1.67	Min[1,Rp(g/c)]	-1.7314(g/C)2+1.9424(	4(Rp g/C)	0.5017
6	2	Min[1,Rp(g/c)]	-2.2578(g/C)2+2.1815(	4(Rp g/C)	

g/C=	0.333	d/c=	0.292				
bo	b1	b2	%A Calc.	%C Calc.	%A	%B	%C
0.11	0.173833333	3	0.105687	0	0.105687	0.894313	0
0.223333333	0.173833333	3	0.21902	0	0.21902	0.78098	0
0.333333333	0.173833333	3	0.32902	0	0.32902	0.67098	0
0.443333333	0.301044444	0.55	0.290465	0	0.290465	0.709535	0
0.556666667	0.369888889	0.893333	0.433629	0	0.433629	0.566371	0
0.666666667	0.4276	1.333333	0.583958	0	0.583958	0.416042	0

AM

Approach Signal Variables

Approach Signal (	**1200**
g/C Ratio	**0.333**
demand/capacity	**0.292**

% A profiles	33%
%B profiles	67%
%C-profiles	0%
Overall Average Travel Time (sec)	53.05

VSP Mode Distribution for Each Speed Bin

constant from another sheet>>>>

VSP Mod	Bin 1, Speed<35 MPH A	B	C	VSP Mod	Bin 2, Speed >35 MPH A	B	C
1	22.34%	12.20%	9.19%	1	18.03%	18.03%	8.10%
2	1.63%	2.24%	5.37%	2	1.86%	1.86%	2.93%
3	1.57%	41.23%	70.41%	3	2.15%	20.63%	59.01%
4	32.70%	9.53%	6.80%	4	13.76%	2.15%	5.87%
5	16.32%	7.91%	1.55%	5	27.68%	13.76%	6.01%
6	4.70%	6.30%	2.39%	6	15.60%	15.60%	6.70%
7	9.45%	4.84%	0.95%	7	6.43%	6.43%	3.63%
8	2.76%	3.78%	1.79%	8	5.52%	6.52%	2.93%
9	2.75%	2.53%	0.60%	9	4.02%	5.02%	2.51%
10	2.36%	2.36%	0.48%	10	3.27%	5.27%	1.47%
11	2.36%	2.12%	0.12%	11	0.95%	1.09%	0.49%
12	0.18%	1.64%	0.00%	12	0.29%	1.23%	0.28%
13	0.12%	1.78%	0.00%	13	0.17%	1.17%	0.07%
14	0.78%	1.55%	0.36%	14	0.25%	1.24%	0.00%

time Spent in Each VSP Mode for Each Profile

VSP Mode	A	B	C
1	6.503	7.904	9.105
2	0.473	1.450	5.321
3	0.456	26.712	69.768
4	9.520	6.174	6.740
5	4.750	5.125	1.537
6	1.367	4.082	2.365
7	2.752	3.134	0.946
8	0.804	2.449	1.774
9	0.801	1.639	0.591
10	0.687	1.529	0.473
11	0.687	1.373	0.118
12	0.053	1.063	0.000
13	0.035	1.153	0.000
14	0.228	1.004	0.355
SUM	29.114	64.790	99.094

Multiplied by % of time inEach profile gives travel time @VSP

	A	B	C	Sum
1	2.139	5.303	0.000	7.443
2	0.156	0.973	0.000	1.129
3	0.150	17.923	0.000	18.073
4	3.132	4.143	0.000	7.275
5	1.563	3.439	0.000	5.001
6	0.450	2.739	0.000	3.188
7	0.905	2.103	0.000	3.008
8	0.264	1.643	0.000	1.908
9	0.263	1.100	0.000	1.363
10	0.226	1.026	0.000	1.252
11	0.226	0.922	0.000	1.148
12	0.017	0.713	0.000	0.730
13	0.012	0.774	0.000	0.785
14	0.075	0.674	0.000	0.749
SUM	9.579	43.473	0.000	53.052

VSP Mode	Combined NOx EF from Emmissio	NOx emission s due to all	Overall NOx emission s per	Overall NOx emission s per
1	0.456	3.393	1187.607	4.180
2	0.751	0.848	296.657	1.044
3	0.954	17.237	6032.788	21.235
4	1.491	10.844	3795.333	13.360
5	1.948	9.743	3410.172	12.004
6	2.380	7.589	2656.293	9.350
7	2.735	8.225	2878.893	10.134
8	3.089	5.892	2062.362	7.260
9	3.448	4.701	1645.273	5.791
10	3.793	4.748	1661.917	5.850
11	4.269	4.899	1714.636	6.036
12	4.770	3.483	1219.201	4.292
13	5.319	4.177	1461.927	5.146
14	6.154	4.608	1612.655	5.677
	SUM	90.388	31635.71	111.358

Combined HC EF from Emmission Factors Tab	HC emissions due to all profiles (	Overall HC emissions per hour (mgrams/hr)	Overall HC emissions per mile (grams/
0.361	2.688	940.960	3.312
0.402	0.454	158.757	0.559
0.163	2.955	1034.111	3.640
0.739	5.376	1881.499	6.623
1.135	5.675	1986.375	6.992
1.516	4.833	1691.561	5.954
1.922	5.781	2023.374	7.122
2.309	4.405	1541.815	5.427
2.903	3.957	1385.107	4.876
3.163	3.960	1386.101	4.879
3.898	4.474	1565.903	5.512
4.803	3.507	1227.573	4.321
5.132	4.030	1410.481	4.965
7.088	5.307	1857.558	6.539
SUM	57.403	20091.174	70.721

Combined CO EF from Emmission Factors Tab	CO emissions due to all profiles (mgrams	Overall CO emissions per hour (mgrams/hr)	Overall CO emissions per mile (grams/VMT)
1.177	8.758	3065.467	10.790
1.262	1.425	498.590	1.755
0.788	14.248	4986.747	17.553
2.087	15.182	5313.649	18.704
3.017	15.089	5281.194	18.590
3.784	12.066	4223.083	14.865
4.810	14.469	5064.227	17.826
5.445	10.386	3635.053	12.795
6.536	8.910	3118.434	10.977
8.639	10.815	3785.387	13.325
9.757	11.197	3918.992	13.795
13.698	10.002	3500.873	12.323
19.202	15.080	5278.008	18.579
44.693	33.465	11712.676	41.229
SUM	181.093	63382.381	223.106

Combined CO2 EF from Emmission Factors Tab	CO2 emissions due to all profiles (	Overall CO2 emission s per	Overall CO2 emissions per mile
2.805	20.880	7307.908	25.724
2.882	3.252	1138.349	4.007
1.312	23.720	8301.867	29.223
4.971	36.162	12656.771	44.552
6.972	34.869	12204.133	42.959
9.392	29.947	10481.441	36.895
10.330	31.071	10874.728	38.279
11.365	21.680	7588.127	26.710
13.456	18.343	6420.046	22.599
15.247	19.089	6681.203	23.518
19.566	22.455	7859.145	27.664
27.264	19.909	6968.093	24.528
33.660	26.434	9251.730	32.566
56.470	42.283	14798.918	52.092
SUM	350.093	#########	431.314

Figure 41. Screenshot. Sample signal calculations sheet.

North Bound

Roundabout- SB AM Peak

INPUT Values Copied from Roundabout Input Sheet

1- Approach Demand flow Rate (vph)	350	175
2-Cirulating/ Conflicting flow rate (vph)	100	100
6-Number of approach through lanes	2	
7- Approach and Departure Speed Bin	1	
8- Segment Length Considered (ft)	1500	
9-Percent of Tier 1 Passenger Cars	20%	
10- Percent of Tier 2 Passenger Cars	30%	
11- Percent of Tier 1 Passenger Trucks	20%	
12- Percent of Tier 2 Passenger Trucks	30%	

1 Average Travel Speed

Bin1	Bin2
33.804	42.942
26.562	36.414
20.707	29.773

Travel Time Over the Segment for Selected Speed Bin

A	30.25 seconds
B	38.50 seconds
C	49.38 seconds

3

% A profiles	90%
%B profiles	8%
%C-profiles	2%
Overall Average Travel Time (sec)	31.22

VSP Mode Distribution for Each Speed Bin

constant from another sheet>>>>

	Bin 1, Speed<35 MPH				Bin 2, Speed >35 MPH		
VSP Mod	A	B	C	VSP Mod	A	B	C
1	35.39%	34.26%	24.28%	1	22.98%	22.98%	15.15%
2	7.23%	9.24%	6.83%	2	2.66%	3.66%	3.79%
3	3.27%	15.77%	21.47%	3	15.42%	15.42%	14.39%
4	19.46%	8.89%	11.06%	4	5.58%	13.10%	6.82%
5	14.25%	7.34%	7.76%	5	13.01%	10.30%	2.27%
6	3.90%	6.46%	6.93%	6	10.24%	13.25%	9.09%
7	9.09%	5.26%	5.65%	7	6.47%	6.47%	7.58%
8	3.48%	4.32%	5.55%	8	6.40%	5.41%	8.33%
9	1.43%	1.97%	3.64%	9	5.46%	4.46%	4.55%
10	1.08%	3.10%	2.41%	10	5.01%	3.58%	5.30%
11	0.39%	1.94%	2.06%	11	2.93%	0.93%	6.82%
12	0.20%	0.72%	1.03%	12	1.75%	0.19%	5.30%
13	0.10%	0.43%	0.54%	13	1.06%	0.13%	3.03%
14	0.74%	0.30%	0.79%	14	1.03%	0.12%	7.58%

time Spent in Each VSP Mode for Each Profile

VSP Mode	A	B	C
1	10.705	13.188	11.987
2	2.187	3.557	3.373
3	0.988	6.071	10.604
4	5.886	3.422	5.460
5	4.310	2.826	3.834
6	1.180	2.487	3.421
7	2.749	2.025	2.790
8	1.053	1.663	2.742
9	0.433	0.758	1.796
10	0.327	1.193	1.189
11	0.118	0.747	1.019
12	0.060	0.277	0.510
13	0.030	0.166	0.267
14	0.222	0.115	0.388
SUM	30.249	38.495	49.379

Multiplied by % of time inEach profile gives travel time @VSP

	A	B	C	Sum
1	9.685	1.033	0.203	10.921
2	1.979	0.279	0.057	2.314
3	0.894	0.476	0.180	1.550
4	5.325	0.268	0.093	5.686
5	3.900	0.221	0.065	4.186
6	1.067	0.195	0.058	1.320
7	2.487	0.159	0.047	2.693
8	0.952	0.130	0.047	1.129
9	0.391	0.059	0.030	0.481
10	0.296	0.093	0.020	0.409
11	0.107	0.059	0.017	0.183
12	0.055	0.022	0.009	0.085
13	0.027	0.013	0.005	0.045
14	0.201	0.009	0.007	0.217
SUM	27.366	3.015	0.838	31.219

VSP Mode	Combined NOx EF from Emmissio	NOx emissions due to all profiles (	Overall NOx emissions per hour	Overall NOx emissions per mile	Combined HC EF from Emmission Factors Tab	HC emissions due to all profiles (	Overall HC emissions per hour (mgrams/hr)	Overall HC emissions per mile (grams/
1	0.456	4.979	1742.577	6.134	0.361	3.945	1380.671	4.860
2	0.751	1.738	608.378	2.141	0.402	0.930	325.575	1.146
3	0.954	1.478	517.291	1.821	0.163	0.253	88.671	0.312
4	1.491	8.475	2966.350	10.442	0.739	4.202	1470.539	5.176
5	1.948	8.155	2854.175	10.047	1.135	4.750	1662.514	5.852
6	2.380	3.142	1099.748	3.871	1.516	2.001	700.334	2.465
7	2.735	7.365	2577.658	9.073	1.922	5.176	1811.657	6.377
8	3.089	3.488	1220.711	4.297	2.309	2.607	912.600	3.212
9	3.448	1.659	580.742	2.044	2.903	1.397	488.910	1.721
10	3.793	1.552	543.180	1.912	3.163	1.294	453.033	1.595
11	4.269	0.779	272.683	0.960	3.898	0.712	249.029	0.877
12	4.770	0.406	142.061	0.500	4.803	0.409	143.036	0.503
13	5.319	0.239	83.509	0.294	5.132	0.230	80.570	0.284
14	6.154	1.334	467.034	1.644	7.088	1.537	537.959	1.894
	SUM	44.789	15676.10	55.180	SUM	29.443	10305.099	36.274

Combined CO EF from Emmission Factors Tab	CO emissions due to all profiles (mgrams	Overall CO emissions per hour (mgrams/hr)	Overall CO emissions per mile (grams/VMT)	Combined CO2 EF from Emmission Factors Tab	CO2 emissions due to all profiles (	Overall CO2 emissions per	Overall CO2 emissions per mile
1.177	12.851	4497.960	15.833	2.805	30.637	10722.895	37.745
1.262	2.921	1022.498	3.599	2.882	6.670	2334.503	8.217
0.788	1.222	427.596	1.505	1.312	2.034	711.856	2.506
2.087	11.866	4153.034	14.619	4.971	28.264	9892.260	34.821
3.017	12.629	4420.143	15.559	6.972	29.184	10214.360	35.955
3.784	4.995	1748.424	6.154	9.392	12.399	4339.485	15.275
4.810	12.955	4534.329	15.961	10.330	27.820	9736.845	34.274
5.445	6.147	2151.587	7.574	11.365	12.833	4491.410	15.810
6.536	3.145	1100.733	3.875	13.456	6.475	2266.123	7.977
8.639	3.535	1237.215	4.355	15.247	6.239	2183.682	7.687
9.757	1.781	623.247	2.194	19.566	3.571	1249.859	4.400
13.698	1.165	407.921	1.436	27.264	2.320	811.920	2.858
19.202	0.861	301.494	1.061	33.660	1.510	528.484	1.860
44.693	9.692	3392.055	11.940	56.470	12.245	4285.848	15.086
SUM	85.766	30018.235	105.664	SUM	182.199	63769.530	224.469

Figure 42. Screenshot. Sample roundabout calculations sheet.

Summary Output

Table 1

Travel Time (Sec.)

	Roundabout			Signal		
	AM	PM	Off Peak	AM	PM	Off Peak
NB	35.95	26.88	25.02	30.65	60.39	62.01
SB	26.16	26.88	25.02	53.04	55.34	56.03
EB	31.37	31.54	31.22	56.26	60.63	61.02
WB	31.37	31.54	31.22	53.13	51.67	53.05

Table 2

% Vehicles with No Stop (A)

	Roundabout			Signal		
	AM	PM	Off Peak	AM	PM	Off Peak
NB	40%	83%	92%	96%	12%	8%
SB	86%	83%	92%	33%	26%	25%
EB	89%	88%	90%	24%	12%	11%
WB	89%	88%	90%	33%	37%	33%

Table 3

% Vehicles that Stop Only once (B)

	Roundabout			Signal		
	AM	PM	Off Peak	AM	PM	Off Peak
NB	41%	13%	7%	4%	88%	92%
SB	11%	13%	7%	67%	74%	75%
EB	9%	10%	8%	76%	88%	89%
WB	9%	10%	8%	67%	63%	67%

Table 4

% Vehicles that Stop More than Once (C)

	Roundabout			Signal		
	AM	PM	Off Peak	AM	PM	Off Peak
NB	18%	4%	1%	0%	0%	0%
SB	3%	4%	1%	0%	0%	0%
EB	2%	3%	2%	0%	0%	0%
WB	2%	3%	2%	0%	0%	0%

Table 5

d/c (Demand to Capacity Ratio)

	Roundabout			Signal		
	AM	PM	Off Peak	AM	PM	Off Peak
NB	0.30	0.57	0.28	0.30	0.40	0.33
SB	0.47	0.57	0.28	0.28	0.40	0.33
EB	0.38	0.43	0.33	0.33	0.33	0.29
WB	0.38	0.43	0.33	0.33	0.33	0.29

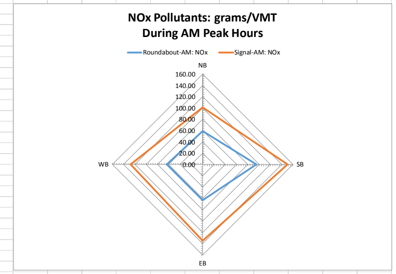


Table 6

NOx: mgrams/vehicle

	Roundabout			Signal		
	AM	PM	Off Peak	AM	PM	Off Peak
NB	79.97	55.91	51.12	53.22	95.78	98.10
SB	54.06	55.91	51.12	85.27	88.55	89.55
EB	45.04	45.32	44.79	95.73	103.00	103.63
WB	45.04	45.32	44.79	90.51	88.10	90.39

Table 7

NOx: mgrams/hr

	Roundabout			Signal		
	AM	PM	Off Peak	AM	PM	Off Peak
NB	16794.51	33548.67	15335.86	28738.28	57470.70	29431.16
SB	27028.78	33548.67	15335.86	42635.71	53131.11	26865.69
EB	18016.69	20393.18	15676.10	38290.87	46348.00	36271.15
WB	18016.69	20393.18	15676.10	36205.51	39643.17	31635.71

Table 8

NOx: grams/VMT

	Roundabout			Signal		
	AM	PM	Off Peak	AM	PM	Off Peak
NB	59.12	118.09	53.98	101.16	78.27	103.60
SB	95.14	118.09	53.98	150.08	187.02	94.57
EB	63.42	71.78	55.18	134.78	163.14	127.67
WB	63.42	71.78	55.18	127.44	139.54	111.36

Table 9

NOx: grams/ Time Duration Provided by User

AM + PM + Off Peak Duration

	Roundabout	Signal
NB	231.19	283.03
SB	267.21	431.67
EB	190.38	425.60
WB	190.38	378.35

Table 10

HC: mgrams/vehicle

	Roundabout			Signal		
	AM	PM	Off Peak	AM	PM	Off Peak
NB	28.36	20.38	317.25	20.68	37.06	37.95
SB	19.76	20.38	317.25	33.02	34.28	34.66
EB	29.61	29.80	85.77	60.61	64.98	65.37
WB	29.61	29.80	85.77	57.48	56.03	57.40

Table 11

HC: mgrams/hr

	Roundabout			Signal		
	AM	PM	Off Peak	AM	PM	Off Peak
NB	5956.51	12229.25	95173.90	11168.82	22237.15	11386.31
SB	9879.92	12229.25	95173.90	16508.27	20567.30	10399.14
EB	11844.77	13408.41	30018.24	24245.56	29242.94	22878.42
WB	11844.77	13408.41	30018.24	22991.65	25211.39	20091.17

Table 12

HC: grams/VMT

	Roundabout			Signal		
	AM	PM	Off Peak	AM	PM	Off Peak
NB	20.97	43.05	19.83	39.31	78.27	40.08
SB	34.78	43.05	19.83	58.11	72.40	36.60
EB	41.69	47.20	36.27	85.34	102.94	80.53
WB	41.69	47.20	36.27	80.93	88.74	70.72

Table 13

HC: grams/ Time Duration Provided by User

AM + PM + Off Peak Duration

	Roundabout	Signal
NB	83.84	157.67
SB	97.65	167.11
EB	125.17	268.81
WB	125.17	240.40

Table 14

CO: mgrams/vehicle

	Roundabout			Signal		
	AM	PM	Off Peak	AM	PM	Off Peak
NB	545.03	354.85	317.25	324.42	656.19	674.27
SB	340.30	354.85	317.25	574.25	599.81	607.61
EB	86.24	86.75	85.77	192.64	208.36	209.74
WB	86.24	86.75	85.77	181.37	176.14	181.09

Table 15

CO: mgrams/hr

	Roundabout			Signal		
	AM	PM	Off Peak	AM	PM	Off Peak
NB	114457.21	212909.96	95173.90	175186.33	393712.50	202279.58
SB	170151.27	212909.96	95173.90	287122.65	359888.41	182283.58
EB	34494.09	39036.49	30018.24	77056.01	93761.66	73407.38
WB	34494.09	39036.49	30018.24	72546.03	79261.22	63382.38

Table 16

CO: grams/VMT

	Roundabout			Signal		
	AM	PM	Off Peak	AM	PM	Off Peak
NB	402.89	749.44	335.01	616.66	1385.87	712.02
SB	598.93	749.44	335.01	1010.67	1266.81	641.64
EB	121.42	137.41	105.66	271.24	330.04	258.39
WB	121.42	137.41	105.66	255.36	279.00	223.11

Table 17

CO: grams/ Time Duration Provided by User

AM + PM + Off Peak Duration

	Roundabout	Signal
NB	1487.34	2714.55
SB	1683.39	2919.12
EB	364.49	859.67
WB	364.49	757.47

Table 18

CO2: mgrams/vehicle

	Roundabout			Signal		
	AM	PM	Off Peak	AM	PM	Off Peak
NB	149.53	107.38	98.91	109.61	194.40	199.02
SB	104.09	107.38	98.91	173.46	179.99	181.99
EB	183.12	184.12	182.20	370.07	397.27	399.65
WB	183.12	184.12	182.20	350.56	341.52	350.09

Table 19

CO2: grams/hr

	Roundabout			Signal		
	AM	PM	Off Peak	AM	PM	Off Peak
NB	31400.49	64427.06	29671.94	59188.65	116640.78	59706.47
SB	52046.97	64427.06	29671.94	86729.34	107996.09	54595.94
EB	73247.04	82855.00	63769.53	148028.58	178770.48	139877.00
WB	73247.04	82855.00	63769.53	140225.72	153682.83	122532.46

Table 20

CO2: kilograms/VMT

	Roundabout			Signal		
	AM	PM	Off Peak	AM	PM	Off Peak
NB	110.53	226.78	104.45	208.34	410.58	210.17
SB	183.21	226.78	104.45	305.29	380.15	192.18
EB	257.83	291.65	224.47	521.06	629.27	492.37
WB	257.83	291.65	224.47	493.59	540.96	431.31

Table 21

CO2: grams/ Time Duration Provided by User

AM + PM + Off Peak Duration

	Roundabout	Signal
NB	441.76	829.09
SB	514.43	877.61
EB	773.95	1642.70
WB	773.95	1465.87

Figure 43. Screenshot. Summary output sheet.

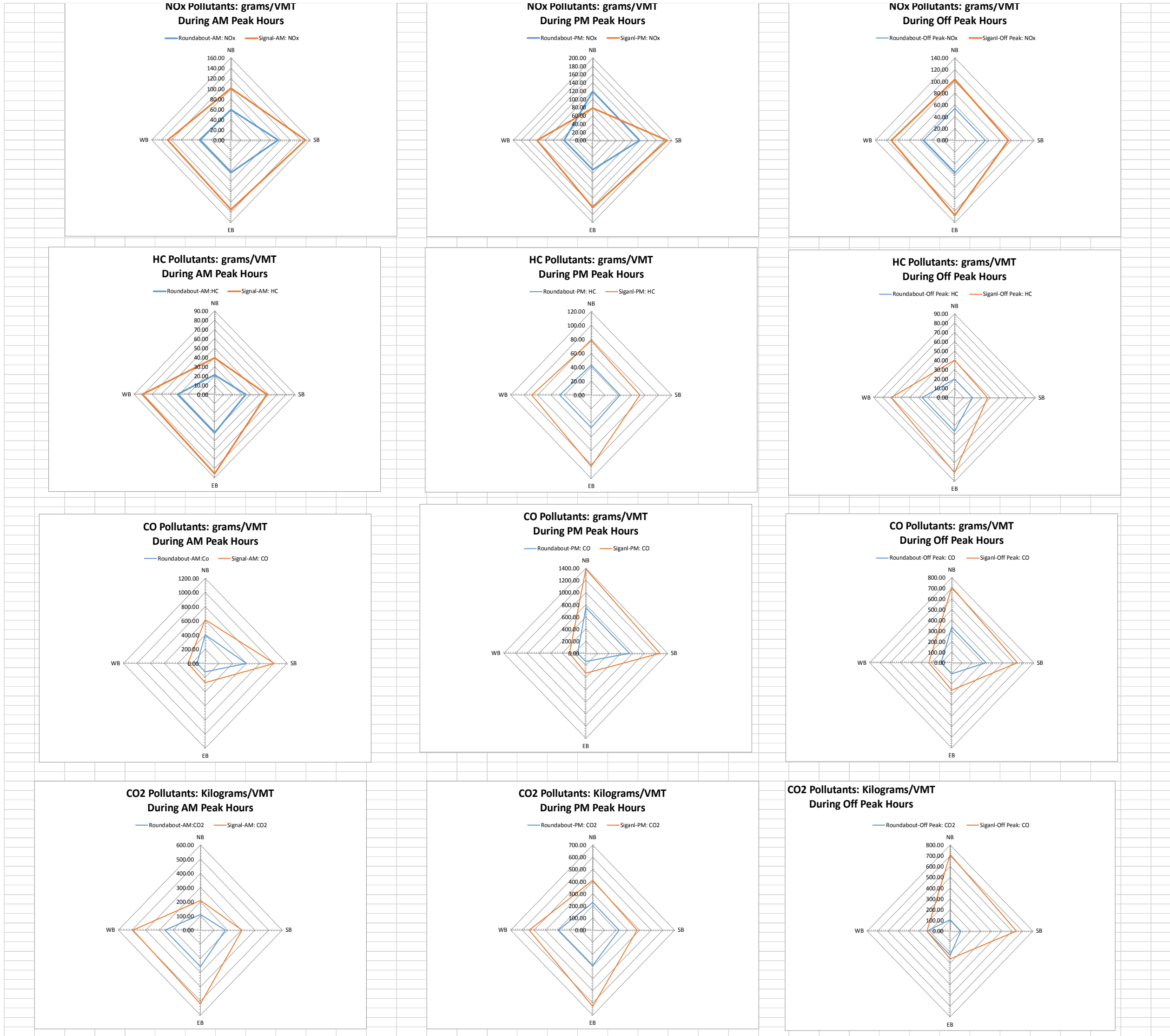


Figure 44. Screenshot. Summary output sheet – charts depicting emissions results.

APPENDIX E. VSP DISTRIBUTION VALIDATION DETAILS

The VSP distribution models and the emission values from the computation engine were validated by comparing the values of 30 actual vehicle trajectories that were not used in the model development process. These trajectories were:

Low speed roundabouts: 5A, 5B and 5C trajectories

Low speed signalized intersections: 5A, 5B and 5C trajectories

For each second of each speed trajectory, the value of the VSP was calculated using the VSP formula. Then the VSP bin (one out of 14 bins) was identified based on the VSP value. For each trajectory all VPS bins were identified for each second. The data was aggregated and the percent time spent in each VSP mode was determined. Below in figure 45 and figure 46 is a sample VSP calculations for a signalized intersection at low speed and Type A trajectory.

2006 Chevy Silverado W. Morgan and St. Mary’s (Intersection 24 S) (A)										
Speed [MPH]	Speed [m/s]	Time [s]	Distance [m]	Acceleration [m/s2]	VSP	Mode	Emissions			
							CO2	CO	NOX	HC
35	15.65	0	0.00	0	3.2	**4**	2.350747627	0.002346445	0.000189209	0.000492848
36	16.09	1	15.65	0.45	11.3	**7**	4.541920348	0.005672051	0.000322387	0.000964069
37	16.54	2	31.74	0.45	11.7	**7**	4.541920348	0.005672051	0.000322387	0.000964069
38	16.99	3	48.73	0.45	12.1	**7**	4.541920348	0.005672051	0.000322387	0.000964069
38	16.99	4	65.71	0.00	3.7	**4**	2.350747627	0.002346445	0.000189209	0.000492848
39	17.43	5	83.15	0.45	12.5	**7**	4.541920348	0.005672051	0.000322387	0.000964069
39	17.43	6	100.58	0.00	3.9	**4**	2.350747627	0.002346445	0.000189209	0.000492848
39	17.43	7	118.02	0.00	3.9	**4**	2.350747627	0.002346445	0.000189209	0.000492848
38	16.99	8	135.01	-0.45	-4.6	**1**	0.966469428	0.00106315	0.000116251	0.000243875
37	16.54	9	151.55	-0.45	-4.6	**1**	0.966469428	0.00106315	0.000116251	0.000243875
37	16.54	10	168.09	0.00	3.5	**4**	2.350747627	0.002346445	0.000189209	0.000492848
37	16.54	11	184.63	0.00	3.5	**4**	2.350747627	0.002346445	0.000189209	0.000492848
37	16.54	12	201.17	0.00	3.5	**4**	2.350747627	0.002346445	0.000189209	0.000492848
37	16.54	13	217.71	0.00	3.5	**4**	2.350747627	0.002346445	0.000189209	0.000492848
38	16.99	14	234.70	0.45	12.1	**7**	4.541920348	0.005672051	0.000322387	0.000964069
38	16.99	15	251.68	0.00	3.7	**4**	2.350747627	0.002346445	0.000189209	0.000492848
39	17.43	16	269.12	0.45	12.5	**7**	4.541920348	0.005672051	0.000322387	0.000964069
39	17.43	17	286.55	0.00	3.9	**4**	2.350747627	0.002346445	0.000189209	0.000492848
39	17.43	18	303.99	0.00	3.9	**4**	2.350747627	0.002346445	0.000189209	0.000492848
39	17.43	19	321.42	0.00	3.9	**4**	2.350747627	0.002346445	0.000189209	0.000492848
39	17.43	20	338.86	0.00	3.9	**4**	2.350747627	0.002346445	0.000189209	0.000492848
39	17.43	21	356.29	0.00	3.9	**4**	2.350747627	0.002346445	0.000189209	0.000492848
39	17.43	22	373.73	0.00	3.9	**4**	2.350747627	0.002346445	0.000189209	0.000492848
39	17.43	23	391.16	0.00	3.9	**4**	2.350747627	0.002346445	0.000189209	0.000492848
39	17.43	24	408.59	0.00	3.9	**4**	2.350747627	0.002346445	0.000189209	0.000492848
39	17.43	25	426.03	0.00	3.9	**4**	2.350747627	0.002346445	0.000189209	0.000492848
39	17.43	26	443.46	0.00	3.9	**4**	2.350747627	0.002346445	0.000189209	0.000492848
39	17.43	27	460.90	0.00	3.9	**4**	2.350747627	0.002346445	0.000189209	0.000492848
39.23077011	17.54	28	478.44	0.10	5.9	**5**	3.160208607	0.003957501	0.000220933	0.000667733
40	17.88	29	496.32	0.34	10.9	**7**	4.541920348	0.005672051	0.000322387	0.000964069
40	17.88	30	514.20	0.00	4.1	**5**	3.160208607	0.003957501	0.000220933	0.000667733
40	17.88	31	532.08	0.00	4.1	**5**	3.160208607	0.003957501	0.000220933	0.000667733
40	17.88	32	549.96	0.00	4.1	**5**	3.160208607	0.003957501	0.000220933	0.000667733
40	17.88	33	567.84	0.00	4.1	**5**	3.160208607	0.003957501	0.000220933	0.000667733
39.5	17.66	34	585.50	-0.22	-0.3	**2**	1.343227467	0.00154662	0.000102437	0.000305264
39	17.43	35	602.94	-0.22	-0.4	**2**	1.343227467	0.00154662	0.000102437	0.000305264
39.17647171	17.51	36	620.45	0.08	5.5	**5**	3.160208607	0.003957501	0.000220933	0.000667733
40	17.88	37	638.33	0.37	11.3	**7**	4.541920348	0.005672051	0.000322387	0.000964069
40	17.88	38	656.21	0.00	4.1	**5**	3.160208607	0.003957501	0.000220933	0.000667733
41	18.33	39	674.54	0.45	13.3	**8**	5.103227389	0.005665227	0.00038254	0.001072124
42	18.78	40	693.32	0.45	13.7	**8**	5.103227389	0.005665227	0.00038254	0.001072124
42	18.78	41	712.09	0.00	4.5	**5**	3.160208607	0.003957501	0.000220933	0.000667733
42.64286041	19.06	42	731.16	0.29	10.6	**7**	4.541920348	0.005672051	0.000322387	0.000964069
43	19.22	43	750.38	0.16	8.1	**6**	3.939868213	0.004638336	0.000285863	0.000822357
43	19.22	44	769.60	0.00	4.7	**5**	3.160208607	0.003957501	0.000220933	0.000667733
44.25	19.78	45	789.38	0.56	17.1	**9**	5.65819184	0.00743407	0.000519971	0.00117152
45	20.12	46	809.50	0.34	12.5	**7**	4.541920348	0.005672051	0.000322387	0.000964069
45	20.12	47	829.62	0.00	5.1	**5**	3.160208607	0.003957501	0.000220933	0.000667733
46	20.56	48	850.18	0.45	15.5	**8**	5.103227389	0.005665227	0.00038254	0.001072124
47	21.01	49	871.19	0.45	15.9	**8**	5.103227389	0.005665227	0.00038254	0.001072124
47	21.01	50	892.20	0.00	5.6	**5**	3.160208607	0.003957501	0.000220933	0.000667733
47	21.01	51	913.21	0.00	5.6	**5**	3.160208607	0.003957501	0.000220933	0.000667733
48	21.46	52	934.67	0.45	16.4	**9**	5.65819184	0.00743407	0.000519971	0.00117152
49.75	22.24	53	956.91	0.78	25.4	**11**	6.344055652	0.009683494	0.000799617	0.001336255
50	22.35	54	979.26	0.11	9.1	**6**	3.939868213	0.004638336	0.000285863	0.000822357
51	22.80	55	1002.06	0.45	17.8	**9**	5.65819184	0.00743407	0.000519971	0.00117152
52	23.25	56	1025.31	0.45	18.3	**9**	5.65819184	0.00743407	0.000519971	0.00117152
Means							1.92E+02	2.28E-01	1.51E-02	4.06E-02
40.89	18.28									

Figure 45. Table. Sample VSP and emissions calculations for Type A trajectory, low speed signalized intersection.

VSP		
Mode	Count	% Time
1	10	29%
2	4	11%
3	1	3%
4	6	17%
5	1	3%
6	0	0%
7	7	20%
8	4	11%
9	2	6%
10	0	0%
11	0	0%
12	0	0%
13	0	0%
14	0	0%
Sum	35	

Figure 46. Table. Percent time spend in each VSP mode.

Also, for each of the selected trajectories the actual emission measurements using the PEMS measurement device were available[19]. The total emission values for CO, CO_2, NO_X and HC for each of these trajectory types (total of five trajectories for each Type A, B and C, signal and roundabout) were compared with the results from the computational engine. Below in figure 47 are the values of emissions calculated from the computational engine and the data from the PEMS emission measurement device for each of these trajectories. Since the engine is a macroscopic approach and the field data available were microscopic (PEMS emission measurements for each trajectory), the total emissions (summation of the five trajectories) were compared.

	Trajectory Type	Total seconds	Total Emission Values Over 5 Trajectories			
			CO2 (g/sec.)	CO (mg/sec)	NOx (mg/sec)	HC (mg/sec.)
Low Speed Roundab	A	221	448.235	0.533	0.033	0.095
	B	613	865.982	0.974	0.068	0.186
	C	1217	2034.983	2.307	0.152	0.438
Low Speed Signal	A	197	277.025	0.316	0.022	0.059
	B	726	1197.904	1.242	0.082	0.259
	C	1581	2772.035	3.110	0.217	0.592
Computational Engine Output*						
Trajectory Type		Total Seconds	CO2 (g/sec.)	CO (mg/sec)	NOx (mg/sec)	HC (mg/sec.)
Low Speed Roundab	A	221	483.729	0.564	0.039	0.104
	B	613	772.937	0.908	0.066	0.167
	C	1217	2215.774	2.117	0.143	0.470
Low Speed Signal	A	197	293.114	0.379	0.020	0.061
	B	726	1328.948	1.139	0.075	0.203
	C	1581	2702.025	3.707	0.260	0.520

Figure 47. Table. Validation results for 30 trajectories (15 low speed signal and 15 low speed roundabout).

*The total seconds in each trajectory type was used to calculate the percent time spent in each VSP mode for each trajectory type and then calculate the total emissions results from the computational engine.

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