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Emissions Modeling and Implementation into CORSIM

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ABSTRACT

The objective of this project was to develop a micro-scale model for the energy use and emissions of light duty gasoline vehicles, based on in-use measurements, and incorporate the resulting fuel and emissions model into the CORSIM traffic simulation program. Portable Emission Measurement Systems (PEMS) were used to measure the exhaust emissions of 10 passenger cars and 5 passenger trucks during driving on routes in the Research Triangle Park, NC region, supplemented with data collected in Asheville, NC and Gainesville, FL. Fuel use and emissions during cold starts were also measured using PEMS. The PEMS data were used to quantify fuel use and emission rates for 14 Vehicle Specific Power (VSP) modes. VSP is an indicator of engine power demand based on speed, acceleration, and road grade. Cold start increments for fuel use and emissions were quantified. The VSP-based approach was implemented into CORSIM. To demonstrate a method for evaluating emissions estimates from the revised CORSIM, a pilot study was conducted for the I-4 corridor near Orlando. VSP modal emission rates for a test vehicle were used to calibrate CORSIM, and CORSIM was used to predict the emissions for the same road segments traveled by the vehicle. The project successfully demonstrated that real-world vehicle emissions data can be incorporated into a traffic simulation model, and that the revised model can predict trends in vehicle emissions consistent with real-world data.

EXECUTIVE SUMMARY

Transportation accounts for 28% of U.S. energy use (EIA, 2006). Highway transportation accounts for 32% of national annual emissions of nitrogen oxides (NO_x), 50% of CO, and 22% of volatile organic compounds (VOC) (EPA, 2012). NOx, CO, and VOC are precursors to tropospheric ozone formation. There is increasing concern regarding air quality, which motivates the need for accurate micro-scale vehicle Energy use and Emissions (EU&E) data. Real-world EU&E data can be measured in the field with Portable Emission Measurement Systems (PEMS) (Frey et al. 2003). In this work, data measured for light duty gasoline vehicles were used to develop a microscale model of EU&E rates, which in turn is incorporated into a widely used, US-based traffic simulation model, CORSIM. This will enable the assessment of how traffic control strategies can improve the environmental performance of urban highway networks.

This research is an extension of prior work at the University of Florida in the area of traffic micro-simulation (McTrans 2012), and at NC State University in the area of PEMS-based measurement and development of EU&E models (Frey et al., 2001, 2002a&b, 2003, 2008, 2010). The EU&E modeling method is founded on the concept of Vehicle Specific Power (VSP), also used in the EPA MOVES model (Jimenez-Palacios, 1999; EPA 2011).

CORSIM is a microscopic, stochastic, traffic simulation software program. CORSIM can model the movement of vehicles in great detail, taking into account a variety of geometric and traffic factors, and doing so at a 1-second time resolution. While CORSIM currently has the ability to generate fuel consumption and emissions estimates, it is rarely used for this purpose, as the underlying data are based on research from the mid-1980's (McGill et al., 1984, Hooker, estimated

1984), and modifying these data by the user is a challenging proposition. CORSIM currently uses look-up tables to define fuel consumption and emissions generation. These tables are indexed by vehicle type, instantaneous speed, and instantaneous acceleration (but not for grades). Fuel consumption and emissions are accumulated every time step for every vehicle. Thus, in this work, the fuel consumption and emissions data are updated based on recently collected PEMS data.

Real-world fuel use and emissions for hot-stabilized running tailpipe exhaust were measured on selected routes for 15 selected vehicles, including 10 passenger cars and 5 passenger trucks (SUV's). Selected routes include four routes in Raleigh and the Research Triangle Park (RTP) in North Carolina, routes in Gainesville, FL and a segment on I-4 in Orlando, FL. Selected vehicles include a Honda Pilot from the University of Florida, and a variety of vehicles recruited from student volunteers and rental agencies. Data were also collected in Asheville, NC to assess the effect of altitude and road grade on emissions. Cold start fuel use and emissions were measured for a selected set of vehicles in the RTP area.

For the hot-stabilized exhaust measurements, an Axion portable emission measurement system (PEMS), a ProScan on-board diagnostics (OBD) system, and 8 Garmin 76CSx tracking global positioning system (GPS) receivers were used to measure exhaust pollutant concentrations and vehicle activities. For the cold start measurement, the PEMS and OBD were used. Exhaust emission rates of CO, CO_2, HC, and NO (in g/s), on a second by second basis, were estimated from the exhaust concentrations based on carbon mass balance and the flow of fuel or exhaust gas. Road grade was estimated using the GPS data at 1 Hz rate. Emissions rates were estimated on the basis of VSP. VSP was categorized into 14 modes. Modes 1 and 2 are for negative VSP which includes deceleration or coasting down a hill. Mode 3 includes idling. Modes 4 through 14 include increasing positive VSP associated with accelerating, cruising at various speeds, or traveling up a hill. Average fuel use and emission rates were estimated in each VSP mode as a modal emission rate. Uncertainty in the average rates was quantified using 95% confidence intervals.

For cold start measurement data, fuel use and emissions were quantified based on a comparison to the hot-stabilized idling rates. Based on the average hot-stabilized idling fuel use and emissions rates, the cold start increments of fuel use and emissions were quantified.

VSP modal fuel use and emission rates are typically lowest at idle, and increase monotonically with increasing positive VSP. Fuel use and CO_2 emission rates typically increase linearly with positive VSP. For the average of 10 measured passenger cars, at the highest VSP mode (Mode 14), these rates are approximately 11 times greater than at idle (Mode 3). Among the other three pollutants, the HC emission rates tend to be the least sensitive to VSP, also increasing by a factor of approximately 11 for the highest observed VSP mode compared to idle. However, tailpipe exhaust emission rates of NO_x, and CO typically increase in a nonlinear manner with positive VSP.

For the average of 5 passenger trucks, the trends in VSP modal average fuel use and emission rates are qualitatively similar to those for passenger cars, but the numerical values are somewhat different. For example, the ratio of the Mode 14 to Mode 3 modal average fuel use and CO_2 emission rates for passenger trucks is approximately 13 compared to approximately 11 for passenger cars. For NO_x, the ratio is 88 compared to 155. For CO, the ratio is 120 compared to 170. The ratio for HC is approximately the same as for fuel use in both cases. However, similar to passenger cars, the NO_x emission rates are more sensitive to VSP for moderate to high demand, whereas the CO emission rates tend to be relatively low except at very high power demand.

The results of the field measurement of cold starts confirms that vehicles in the in-use fleet have significant incremental increases in fuel use and emission rates during the first few minutes after starting the engine, when the engine and exhaust system have previously reached ambient temperature. The average cold start incremental fuel use ranges from 71 grams per start to 91 grams per start for passenger cars and passenger trucks, respectively. For example, if an urban area had 1 million vehicles with cold starts each weekday, the incremental fuel use for the cold start would be between 25,000 and 32,000 gallons, or approximately 6 to 8 million gallons per year if there were 5 starts per week for 50 weeks per year.

Altitude may also affect fuel use and emissions. Many studies have evaluated the effect of altitude on heavy-duty diesel vehicles using dynamometer tests, but there is lack of such study for light-duty gasoline vehicles based on comparison of the same vehicle at different altitudes. Three light-duty gasoline vehicles were measured on low altitude piedmont (LP) routes in the Raleigh, NC area and on high altitude mountainous (HM) routes in the Asheville, NC area. Road grade and altitude were jointly found to have a significant effect on fuel use and emission rates. Cycle average fuel use, CO emission, and NOx emission rates were approximately 10%, 60%, and 40% higher, respectively, for the HM vs. LP areas.

The main steps for implementing the VSP-based EU&E estimation approach into CORSIM were to: (1) replace the current set of look-up tables with the VSP model and the corresponding mode-to-emissions/fuel consumption relationship factors; (2) consider the impact of "cold" starts, which means being able to track a vehicle while it is off the roadway (e.g., in a parking lot); and (3) accumulate the emissions statistics on a route basis. A method for evaluating the revised model is demonstrated. The method is based on simulating light duty vehicle traffic on a selected corridor, and comparing the model estimates with vehicle activity, energy use, and emissions data measured on the same corridor using PEMS.

For the purpose of initial testing of the VSP-based fuel use and emissions estimation methodology for incorporation into CORSIM, a pilot study was conducted on the I-4 corridor near Orlando, FL based on field measurements of a Honda Pilot with the PEMS. The VSP modal fuel use and emission rates for the Pilot were used to calibrate an initial version of the VSP-based fuel use and emissions estimation method within CORSIM, and CORSIM was used to estimate vehicle activity and emissions for the same corridor. The comparison of the results from CORSIM with those of the field measurements for selected segments of the I-4 corridor was a confidence building measure to demonstrate that the combined traffic and emissions model can produce reasonable and realistic estimates of emissions. Differences were found in the amount of time spent in each VSP mode between the field and in the simulation. However, these differences are likely due to constraints imposed by the car-following and possibly lane changing algorithms built into CORSIM, which govern the generation of the acceleration and deceleration rates that are key to estimating the VSP values. Cold start measurements were also added to CORSIM. Due to software architecture limitations, some simplifying assumptions needed to be incorporated for the implementation. Nevertheless, the emissions estimation accuracy of CORSIM is still considerably improved with the simplified treatment of cold starts over the previous condition.

The emissions estimation process in CORSIM has undergone a complete makeover through this project. For one, the emissions and fuel consumption rates are now based on the most current passenger vehicle fleet, and the VSP-based emissions and fuel consumption estimation approach has a much stronger analytical and empirical foundation than the previous approach used in CORSIM, and consequently is more accurate and robust.

The project successfully demonstrated that real-world vehicle emissions data can be incorporated into a traffic simulation model, and that the revised model can predict trends in vehicle emissions consistent with real-world data.

CHAPTER 1 BACKGROUND

Transportation accounts for 28% of all U.S. energy use (EIA, 2006). Highway transportation accounts for 32% of national annual emissions of nitrogen oxides (NOx), 50% of CO, and 22% of volatile organic compounds (VOC) (EPA, 2012). In the latest draft Strategic Plan, the United States Department of Transportation (USDOT) recognized the environmental impacts of the transportation system. Two of its five goals dealt with livability and environmental sustainability (USDOT, 2012). Since so much energy use and emissions come from transportation, there needs to be an accurate way to predict the fuel use and emissions for vehicles along certain routes, as well as testing the impact of transportation strategies on fuel use and emissions.

The Energy Use and Emissions (EU&E) estimation method used in this project is based on Vehicle Specific Power (VSP), the same concept used in the Environmental Protection Agency's (EPA) Motor Vehicle Emissions Simulator (MOVES) (EPA, 2011). VSP is a vehicle activity measure of engine load. VSP is binned into a discrete number of modes, which are correlated to fuel use and emission rates per unit time (Frey et al, 2002). Researchers from North Carolina State University (NCSU), most notably Dr. H. Christopher Frey, have developed VSP-calibrated fuel and exhaust emission models for light duty vehicles, transit vehicles, and heavy trucks. The VSP-based exhaust emissions modal estimates include running and idling modes; however, they do not account for the effect of cold starts, which can contribute up to 40% of trip-based exhaust emissions. Therefore, there is need for in-use measurements of cold starts to supplement the VSP-based modal approach to exhaust emissions estimates.

To estimate fuel and emissions in a traffic micro-simulator, one needs estimations of instantaneous speed, acceleration, road grade, vehicle class, and vehicle starts. If all this information is available, the VSP calibrated models can be used to predict exhaust emissions and fuel use. In traffic micro-simulators, such as CORSIM, the speed, acceleration, road grade, and vehicle class are all known. Therefore, if the VSP model is implemented into CORSIM, it could be used to predict emissions. Cold start emissions would also have to be taken into account in CORSIM, as its current emission estimation algorithm does not consider the effect of cold starts.

PROBLEM STATEMENT

With the increasing concern for air quality, there is a need for accurate measurements or estimates of micro-scale vehicle EU&E. The traffic simulation program used for this project will be CORSIM. CORSIM is currently maintained by the Mc*Trans*™ Center at the University of Florida (UF). The underlying data for the fuel use and emissions in CORSIM is based on research conducted in the mid 1980's (McGill et al., 1984; Hooker, 1984). CORSIM currently defines fuel use and emissions by using look-up tables indexed by vehicle type and instantaneous speed and acceleration. Also, the effects of cold starts are not currently modeled in CORSIM. In this work, the CORSIM code was updated to account for EU&E based on in-use real-world measurements that are typical of vehicle technologies and emission control systems in the on-road fleet. This enables assessment of the environmental effectiveness of traffic and Intelligent Transportation Systems implementations more accurately.

RESEARCH OBJECTIVES AND TASKS

The objective of this project was to develop a micro-scale model for the energy use and emissions of light duty gasoline vehicles, based on in-use measurements, and incorporate the fuel and emissions model into the CORSIM traffic simulation program. If the EU&E can be modeled in a widely used traffic simulation program, transportation analysts will have the ability to estimate the environmental impact of different traffic management strategies. To meet the objective, field measurements were made of real-world vehicle emissions, including hot stabilized tailpipe emissions for a warmed-up vehicle, and the incremental emissions associated with a "cold start" of the vehicle. The hot stabilized emission rates are quantified in terms of 14 VSP modes that represent driving situations such as deceleration, idling, cruising, acceleration, and hill climbing. Measurements were made for both passenger cars and passenger trucks. The CORSIM code corresponding to the fuel use and emissions outputs was modified. The look-up tables for fuel use and emissions were replaced by the VSP approach, with a value for fuel use and emissions rates corresponding to each mode of VSP corresponding to a vehicle type. Mc*Trans*™ will distribute the revised CORSIM to its large network of users in the U.S. and worldwide. The main steps for implementing the new VSP model into CORSIM were to: (1) replace the current set of look-up tables with the VSP model and the corresponding mode-to-emissions and fuel consumption values; (2) consider the effect of cold starts, (3) accumulate emissions statistics on a link, OD, and route basis. The tasks that were undertaken to complete this work are summarized:

- Task 1: Fuel and emissions model extensions – The capabilities of CORSIM were extended to better estimate fuel use and emissions rates.
- Task 2: Data collection and reduction – Data were collected regarding the in-use activity, energy use, and emissions of selected vehicles. The emissions included hot stabilized and cold start tailpipe emissions. The field studies obtained a wide range of speeds, accelerations, and road grades. With regard to road grade, measurements for a selected subset of vehicles were made in a mountainous area. This task involved preparation for field data collection, field measurements, quality assurance and control, data analysis, and reporting.

- Task 3: VSP model implementation and testing in CORSIM – This task included replacing the current look-up tables with the VSP model from the data analysis, verifying implementation against hand calculations, and comparing the CORSIM results to empirical results and identifying parameters that need calibration.
- Task 4: Cold start data analysis and implementation into CORSIM – This task used data collected by the NCSU research team for cold starts. The data included a wide range of vehicles.

CHAPTER 2 LITERATURE REVIEW

OVERVIEW OF PREVIOUS TRAFFIC SIMULATION AND EMISSIONS MODELING INTEGRATION EFFORTS

There have been numerous efforts to incorporate vehicle emissions models directly into travel demand models (TDMs) or Traffic Simulation Models (TSMs), or to manually pass data from TDMs or TSMs to a separate vehicle emissions model. For example, Advanced Interactive Micro-Simulation for Urban and Non-Urban Networks (AIMSUN) is a TSM (Panis *et al*., 2006; David, 1999). AIMSUN has been used in combination with a European modal emissions model, VERSIT+ (Fransen and Drewes, 1999; Ligterink and Lange, 2009). MOBILE6 has been used with the Transportation Analysis and SIMulation System (TRANSIMS), a TSM, and EMME/2, a TDM, for case studies of emissions of different road types in Portland, Oregon (Roden, 2005). MOBILE6 has also been used with PARAMICS, a TSM, for emissions impact of Electronic Toll Collection (ETC) plazas versus traditional toll collection (Bartin *et al*., 2011). MOVES has been used in combination with several TSMs, such as PARAMICS, Dynamic Urban Systems for Transportation (DynusT), and VISSIM (Xie *et al*., 2011; Lin *et al*., 2011, Song *et al*., 2012, Hsu and Jones, 2012, Chamberlin *et al*., 2012). The applications include case studies of evaluating the effect of alternative transportation fuels and Connected Vehicle (CV) technology. More recently, a reduced form version of MOVES, referred to as "MOVES Lite," has been incorporated into DTAlite (Frey and Liu, 2013; Zhou et al., 2015). However, with the exception of the latter, these efforts have been either computationally intensive or time consuming in terms of data exchange between the transportation and emissions models, and few are integrated to enable simultaneous simulation of both vehicle activity and emissions in a single model run. This work involves directly incorporating an empirically-based emissions simulation model within a traffic simulation model.

REVIEW OF CURRENT CORSIM EMISSIONS AND FUEL USE MODELING

In the current version of CORSIM, HC, CO, and NO_x emissions only depend on speed, acceleration, and the vehicle's performance level (also referred to as "performance index"). There are two performance levels for passenger cars (low-performance and high-performance) and five performance levels for trucks. The performance levels affect desired and maximum acceleration and speed values, which generally range from 0 to 110 ft/s (0-75 mi/h) for speed and from −10 to 10 ft/s^2 (−6.82 to +6.82 mi/h/s) for acceleration. The program looks up the speed and acceleration in every second and assigns an emissions rate in mg/s for each pollutant in each second. The previous version of CORSIM did not directly correlate roadway grade and desired speed to engine power demand for the required acceleration rate. Rather, it made simple linear adjustments to the look-up values of acceleration, as further explained below.

Fuel consumption rates are modeled similarly to emissions rates in the current version (6.3) of CORSIM, but the calculation differs for the two different simulation sub-programs within CORSIM. The two sub-programs are NETSIM, which performs the traffic modeling on urban streets, and FRESIM, which performs the traffic modeling on freeways and urban highways. In NETSIM, the fuel consumption value depends only on speed, acceleration, and performance index. The program looks up the speed and acceleration for every second and assigns a fuel consumption value in units of 0.0001 gallons per second. In FRESIM, when there is zero road grade, the program calculates fuel use in the same way. When there is a grade in FRESIM, however, the program makes an adjustment to the acceleration that is looked up. The following equation comes from the current code in FRESIM used to model fuel use:

$$JACC = JACC + ZACEM \times RGRADE \times 100 \quad (1)$$

Where:

$JACC$ = actual (and effective) vehicle acceleration (ft/s/s)

$ZACEM$ = grade correction factor for fuel consumption (value is based on vehicle's speed and performance index)

$RGRADE$ = grade proportion of road (i.e., %grade/100)

The program in effect is creating a new "dummy" acceleration. That is, the program considers the vehicle to have a higher acceleration when traveling on an uphill grade (or lower on a downhill grade) than the vehicle actually does. For example, if a low-performance passenger car (performance index 1) were traveling on a 3% uphill grade at a constant 70 ft/s, the actual acceleration would be zero. The *ZACEM* variable would be equal to 0.305 (for speed 70 ft/s and performance index 1). The *RGRADE* would be equal to 0.03, and the equation to determine the "dummy" acceleration would be:

$$JACC = 0 + 0.305 \times 0.03 \times 100 = 0.915 \quad (2)$$

The program then treats this "dummy" acceleration as the real acceleration, goes into the lookup table for fuel consumption, and assigns a value for fuel consumption for every second. With this approach, the "dummy" acceleration serves as a surrogate for engine load, which would certainly increase to keep the vehicle at a constant speed (i.e., zero acceleration) on an upgrade. Obviously, a better approach would be to directly account for the effect of grade on engine load rather than revising acceleration values to different values than the actual vehicle acceleration. Thus the desire to implement the VSP-based approach, which accounts directly for roadway grade. VSP is a good indicator of engine power demand, taking into account changes in kinetic energy, changes in potential energy associated with road grade, rolling resistance, and aerodynamic drag (Jimenez-Palacios, 1999).

OVERVIEW OF EMISSIONS MEASUREMENT TECHNIQUES

Emissions from vehicles are currently measured by a few different methods. The most common methods for light duty gasoline vehicles include chassis dynamometer tests, remote sensing, and portable emissions measurement systems (PEMS). Chassis dynamometers can produce either average or second-by-second data on emissions for a specified standardized driving cycle (EPA 1993). In remote sensing, a sensor captures instantaneous ratios of pollutants in the vehicle exhaust as the vehicle passes through a specific location (Bishop et al., 1998). PEMS can be installed on a vehicle and used to collect micro-scale data on any route driven by the vehicle (Frey et al., 2003). The advantage of PEMS is that it represents actual conditions along any portion of any route, but the measurement methods of a dynamometer are typically more accurate and precise. A PEMS device has been available to the research team for many years and was used for the data collection for this project.

EXAMINATION OF COLD STARTS

Frey, et al. (2002) examined the effects of cold starts on vehicle emissions. Cold starts are a period of high emission rates that takes place when first starting a car that has reached ambient temperature. Because of a combination of factors, including low catalytic converter temperature, low engine temperature and associated effects on cylinder wall temperature, fuel viscosity, and fuel/air ratios commanded by the vehicle electronic control unit (ECU), exhaust emission rates can be relatively higher for a period of typically several minutes (Frey, et al., 2002).

Figure 1 shows the relationship between CO exhaust concentration and coolant temperature for a particular vehicle start. The CO exhaust concentration starts out very high for the first 130 seconds. During that period, the coolant temperature stays lower than 80° F. After about 130 seconds, the coolant temperature and CO exhaust concentration stabilize. Thus, this particular trip has a cold start duration of about 130 seconds. An approach that uses the second by second time series of emissions data can be applied to classify cold starts. (Frey, et al., 2002).

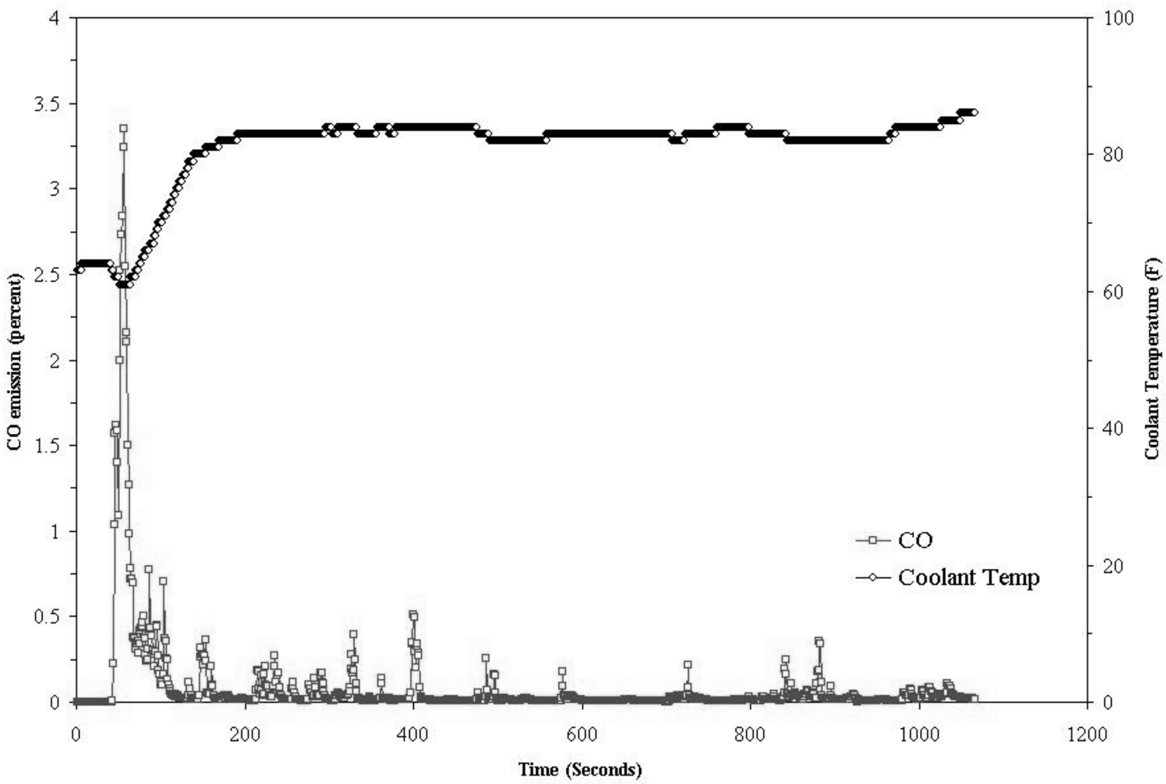

Figure 1. CO exhaust concentration (volume percent) and coolant temperature over time for a cold start (Frey, et al., 2002)

To measure emissions, the research team used a PEMS. The authors used statistical techniques based on non-linear regression to estimate the duration of the cold start by determining the time at which the emissions stabilized. The authors called this time t_c. They wrote a program in Statistical Analysis Software that used non-linear regression to estimate t_c. They used the upper bound of the 95% confidence interval as the assumed t_c in order to reduce the chances that a vehicle would be classified in the hot stabilized operation phase when it was actually in the cold start phase (Frey, et al., 2002).

For the estimation of the duration of cold starts, HC and CO were given more emphasis than NO emissions because HC and CO seem to be more affected by cold starts than NO. For cases in which different values of t_c were found for different pollutants, the highest value was taken to make sure that the cold start data was not recorded as hot stabilized emissions. The authors examined 34 trips that were deemed to experience a cold start, with the duration of the cold starts ranging from 70 to 391 seconds. They wrote a program that determines the driving mode for each second of data and estimates the value of emissions for each mode. One of the modes was the cold start mode. All of the other modes were only defined for the time after the cold start ended. Idle mode refers to zero speed and zero acceleration. Acceleration mode refers to speeds greater than zero accompanied by acceleration of at least 2 mi/h/s. The acceleration mode also includes acceleration of at least 1 mi/h/s for 3 seconds or more, so as not to exclude more conservative accelerations. Deceleration is defined the same way that acceleration is, only for negative values of acceleration. Anything that does not fall into one of these four modes is considered to be in the cruising mode. The program was also able to calculate total trip emissions. Figure 2 shows the average emission rates for each driving mode. The averages were taken for all vehicles and all trips. The cold start mode includes all the activity that took place during the cold start. Some vehicles were driven during the cold start (Frey, et al., 2002).

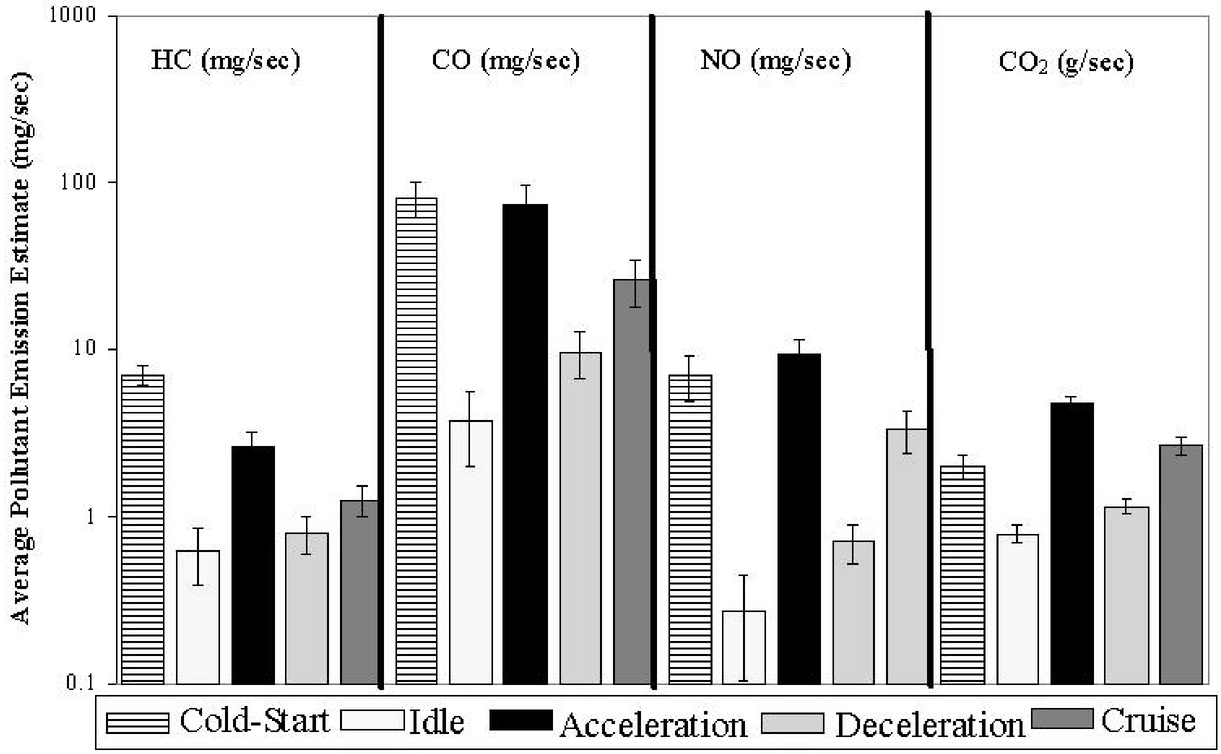

Figure 2. Average emission rate for each mode over all trips in dataset (Frey, et al., 2002)

The cold start emission rate is the highest for HC emissions. For CO emissions, the cold start mode has the highest mean rate, but it is not statistically significantly different from the acceleration rate. The confidence intervals for the two modes also overlap for NO emissions.

The amount of time spent in each mode was also examined. After averaging all of the trips, it was found that cold starts account for about five percent of the trip time but for about 10% to 15% of NO, CO, and CO_2 emissions and more than 20% of HC emissions (Frey, et al., 2002).

COMPARING EMISSIONS FOR DIFFERENT DRIVING MODES

Frey, et al. (2003) developed a study design procedure to measure emissions using PEMS for vehicles fueled by gasoline and E85 (a blend of 85% ethanol and 15% gasoline). This study focused on "real-world hot-stabilized operation on signalized primary arterials" (Frey, et al., 2003). The procedure they developed allowed them to quantify certain aspects of intra-vehicle variability in hot-stabilized emissions. The study aimed to establish modal emissions rates for idle, acceleration, cruise, and deceleration. The authors also present a statistical method for comparing emissions of different drivers. The authors emphasize the importance of on board data because it accounts for the variability encountered in real life driving cycles.

The authors mention that the typical approach for estimating emissions used in models such as MOBILE5b, MOBILE6, EMFAC7, Mobile Emission Assessment System for Urban and Regional Evaluation, and the Comprehensive Modal Emissions Model is dynamometer testing. The emissions data for these models are calculated from average emissions totals per mile over standardized driving cycles. The more recent U.S. EPA MOVES model is also based on dynamometer data, but in this model 1 Hz data are used to estimate VSP-based operating mode bin modal emission rates, thereby enabling estimation of cycle average emission rates for any user specified driving cycle.

This study used the OEM-2100 PEMS for data collection (Frey, et al., 2003). This PEMS includes two five-gas analyzers in parallel. Each five-gas analyzer measures the volume ratio of CO, CO_2, HC, NO, and oxygen (O_2) in the vehicle exhaust. Simultaneously, an on-board diagnostic (OBD) scan tool is used to record selected ECU data via the OBD interface of the vehicle. The OEM 2100 collects the following parameters: manifold absolute pressure, vehicle speed, engine speed (revolutions/min), intake air temperature, coolant temperature, intake mass airflow, percent of wide open throttle, and open/closed loop flag.

The main goal of this particular study was to quantify variability in emissions measurements (Frey, et al., 2003). The design of the study used a small amount of vehicles, drivers, and routes for selected times of the day. There were two primary drivers, who each drove the two primary vehicles on two primary corridors. Most of the data was collected with the two primary drivers driving the same two vehicles on the same two routes to characterize intra-vehicle variability and to compare emissions between drivers. There was also a smaller amount of data collected with secondary vehicles and an additional corridor. These secondary vehicles were driven by the two primary drivers as well as a few other drivers. The purpose of the secondary vehicles and drivers was to assess the strength of the data analysis methodology when applied to different vehicles and drivers. (Frey, et al., 2003).

Figure 3 shows an example of the speed, emission rates of selected pollutants, and fuel consumption plotted against time. For this example, results are reported based on 14 minutes of travel on an arterial corridor, during which speed ranged from 0 to 45 mi/h, and the average speed was about 10 mi/h. The spikes in the graph show that peak emissions rates occur over a very small periods of time. The largest emissions rates coincide with the acceleration from 0 to 40 mi/h, as the vehicle clears an intersection. Most of the spikes in emissions rates coincide with accelerations (Frey, et al., 2003).

The CO, HC, and NO emissions rates are very low for the first 10 minutes, while the vehicle is in stop-and-go traffic and does not exceed 20 mi/h. The rates are much higher during the high speed portion of the trip, in which there is also a lot of variation in speed. The HC and CO rates are very similar to each other. The peaks occur at about the same times, especially for the first 10 minutes (Frey, et al., 2003).

The trend in CO_2 emission and fuel consumption rates are similar to each other, which is expected since most of the carbon in the fuel is emitted as CO_2. The peaks for CO_2 and fuel consumption occur at similar times to those of HC, CO, and NO emissions, during acceleration and higher speeds.

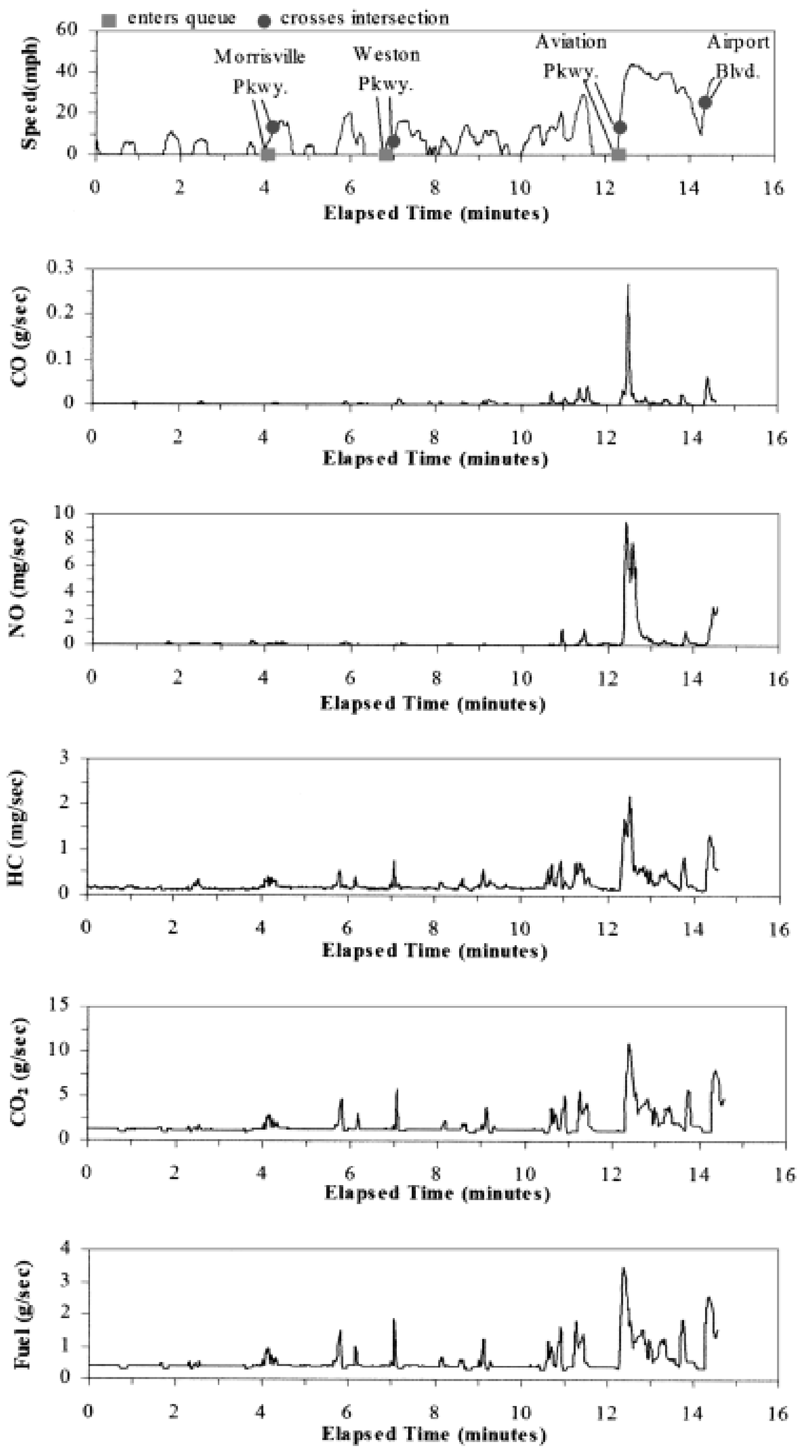

Figure 3. Time traces of vehicle speed, emission rates, and fuel consumption for a 1999 Ford Taurus driven on Chapel Hill Road on August 29, 2000 (Frey, et al., 2003)

The results shown in Figure 3 are similar to those of many other trips in the study. The graphs show that short term events contribute a significant amount to the total emissions in a trip. Identifying such short term events is a precursor to developing strategies to reduce the frequency of such events which, in turn, would reduce overall emissions (Frey, et al., 2003).

An example of variability in measured data and implications for estimation of a mean emission rate is shown in Figure 4. The data in the figure are based on a trip made 141 times using a 1999 Ford Taurus. Figure 4 shows an empirical cumulative distribution function of the average CO emissions for acceleration mode for each of the 141 trips. The average CO emission rate for acceleration mode varies from 2 mg/s to 400 mg/s across the 141 trips. The average for all of the trips is 44 mg/s. The 95% confidence interval is 33 mg/s to 55 mg/s (Frey, et al., 2003).

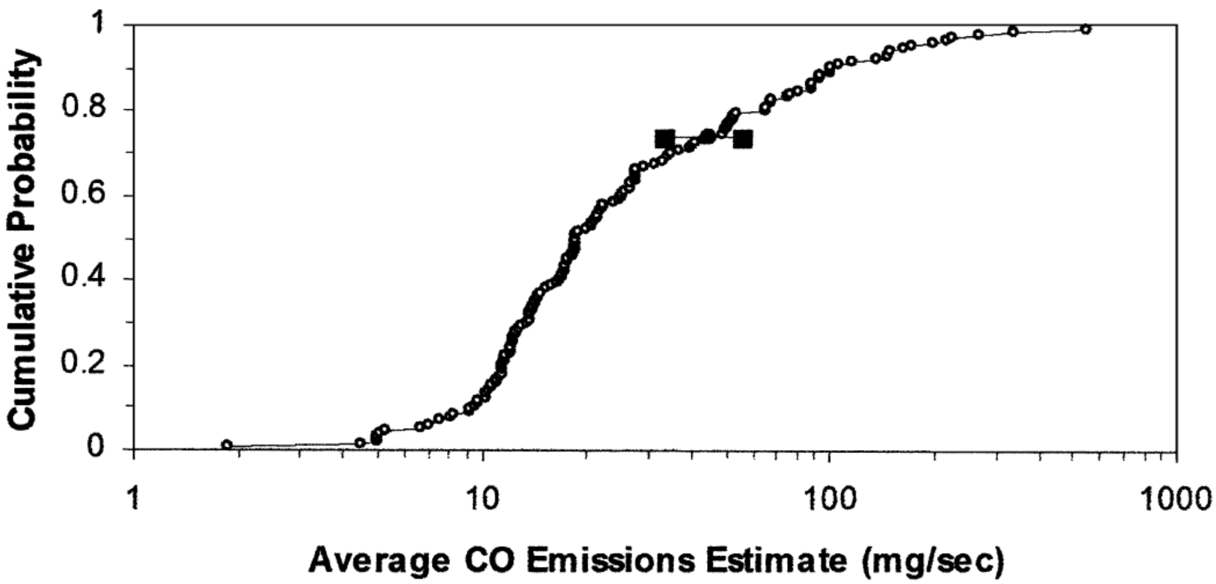

Figure 4. ECDF of CO emissions rates in acceleration mode based on 141 trips (Frey, et al., 2003)

Figure 5 shows the average modal rates for the different pollutants for the 141 trips by the 1999 Ford Taurus. The 95% confidence intervals are also shown. For a given pollutant, the modal means for each driving mode are significantly different from each other. The mean rates for all four pollutants decrease in order from acceleration to cruise to deceleration to idle (Frey, et al., 2003).

Similar results were found when tests were conducted on nine other vehicles. The average emission rate corresponding to acceleration mode was the highest for every vehicle and every pollutant. Cruise mode had the second highest rate for all cases. Deceleration and idle were the third highest and lowest rates, respectively, in almost all cases. The authors conducted t tests to determine if the modal rates were statistically different from each other. Out of 264 possible combinations, 247 of them (94%) were statistically significantly different. The definitions of the driving modes are useful in portraying the variability of different driving styles (Frey, et al., 2003).

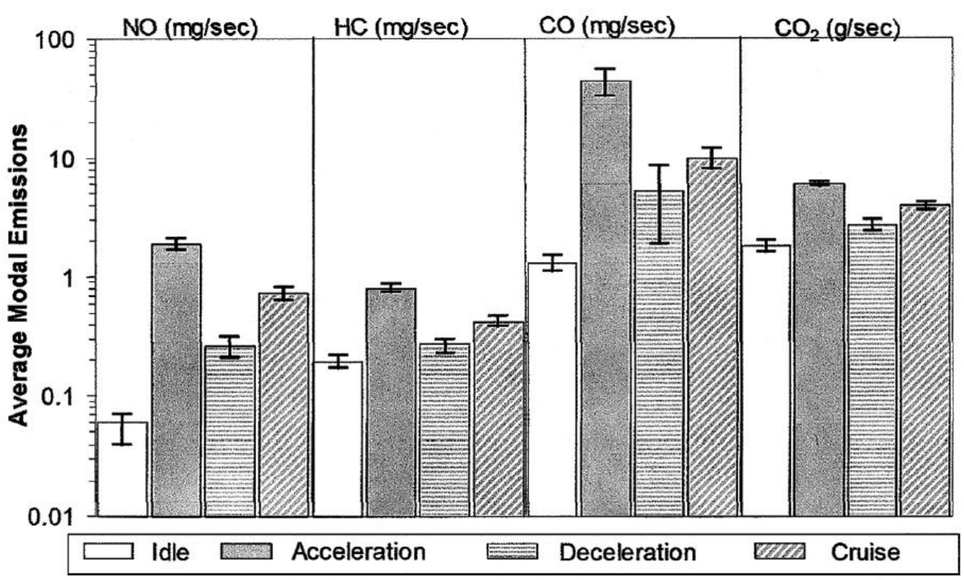

Figure 5. Average model emission rates for 141 trips by a 1999 Ford Taurus (Frey, et al., 2003)

The authors summarized that emissions differ significantly when comparing different vehicles. Therefore, in the implementation of emissions rates into micro-simulation, it is critical to capture the different rates for different types of vehicles.

To quantify the impact of each driving mode, the authors summarize the data based on trip times and total emissions. On average, cruising accounted for over 40% of the total time spent driving. The rest of the time was split almost equally between the other three modes. Idling typically only contributes to 5% or less of the total fuel consumption and emissions, whereas acceleration contributes about 35-40%, even though less than 20% of the time is typically spent accelerating. Deceleration contributes less than 10% of the total emissions, even though about 15% of the time is typically spent decelerating. The main conclusion that the authors draw from this summary is that on signalized arterials, cruise and acceleration modes contribute the most to total emissions (Frey, et al., 2003).

LINK BASED EMISSION ESTIMATION APPROACH

In previous work, team members have developed and applied a link-based approach to linking emissions estimates with a travel demand model. In the link-based approach, link-based driving cycles are selected to match the vehicle type, road type, and link-average speed (Frey et al., 2006, 2008, 2009; Zhai et al., 2008). Based on sampling multiple real world link-based speed versus time profiles by vehicle type, road type, and ranges of link-average speed, and using VSP modal emission rates, as described in the next section, an empirical trend in emission rate versus link average speed was estimated for light duty vehicles, transit buses, and heavy duty diesel trucks. This methodological approach was incorporated into a link-based travel demand model for the purpose of estimating regional vehicle emission inventories at a regional scale. However, the link-based approach cannot take into account variations in driving cycles that have the same cycle average speed. The VSP method implemented in this work is more flexible in that it enables quantification of emission rates for any location on the network based on microscale vehicle activity.

VSP APPROACH TO CLASSIFYING FUEL USE AND EMISSIONS

Frey, et al. (2008) used PEMS to measure the activity, fuel use, and emissions of a sample of 10 light duty gasoline vehicles, including sedan, SUV, and minivan vehicle body types, for the purpose of comparing alternative routes, time of day, and road grade. PEMS complement laboratory-based chassis dynamometer measurements because of the ability of PEMS to measure real world conditions.

Even though PEMS measurements are made under real world conditions, they still vary from one run to another, even with the same vehicle, driver and route. The reason for the variation is the variations in traffic and ambient conditions. One of the main challenges in using data acquired from PEMS is to "quantify the most significant sources of variability from field measurements to help inform field study design" (Frey *et al*., 2008).

Frey *et al*. (2008) considered several factors that would affect the emissions and fuel use in the experiment. These factors included vehicles, routes, road grade, time of day, and drivers (Frey *et al.*, 2008). They collected data primarily for three vehicles, with about 65 hours of data for each vehicle. Routes were selected to include a wide range of road grades and facility classes, and times of day were selected to include a wide range of traffic conditions. The experiment involved three different drivers.

Frey *et al*. (2008) used vehicle specific power as an indicator of engine power demand. For a typical light duty vehicle, VSP is:

$$VSP = 0.278v \times [0.305a + 9.81 \times \sin(a \times \tan(r/100)) + 0.132] + 0.0000065v^3 \quad (3)$$

where

VSP = vehicle specific power (kw/ton)

v = speed (km/h)

a = acceleration (km/h/s)

r = road grade (%)

VSP accounts for changes in kinetic energy, changes in potential energy (e.g., hill climbing), rolling resistance, and aerodynamic drag. Based on Frey *et al*. (2002), VSP is stratified into 14 modes. Average emissions and fuel use rates are assigned to each mode based on statistical analysis of measured data. An average rate for an entire driving cycle can be derived based on how much time the vehicle spent in each VSP mode. The resulting rate is the standardized rate. Comparisons can be made between the observed data and the standardized data to see how well the standardized VSP model predicts emissions and fuel use. Figure 6 shows the 14 VSP modes and the corresponding emission and fuel use rates for one of the vehicles tested. Speed, acceleration, and road grade had substantial effect on intra-vehicle variability in emissions and fuel use. The effects of temperature and humidity were negligible.

VSP mode	definition	NO (mg/sec)	HC (mg/sec)	CO (mg/sec)	CO_2 (g/sec)	fuel (g/sec)
1	VSP < −2	0.12	0.076	1.83	1.30	0.41
2	−2 ≤ VSP < 0	0.092	0.083	1.86	1.43	0.45
3	0 ≤ VSP < 1	0.026	0.056	0.90	0.97	0.31
4	1 ≤ VSP < 4	0.14	0.12	2.59	2.03	0.64
5	4 ≤ VSP < 7	0.21	0.16	3.68	2.74	0.87
6	7 ≤ VSP < 10	0.23	0.20	4.74	3.42	1.08
7	10 ≤ VSP < 13	0.29	0.24	5.73	4.02	1.27
8	13 ≤ VSP < 16	0.32	0.28	6.18	4.56	1.44
9	16 ≤ VSP < 19	0.37	0.31	7.09	5.08	1.61
10	19 ≤ VSP < 23	0.47	0.35	7.81	5.61	1.77
11	23 ≤ VSP < 28	0.59	0.38	8.36	6.05	1.91
12	28 ≤ VSP < 33	0.68	0.42	9.01	6.41	2.03
13	33 ≤ VSP < 39	0.79	0.46	10.5	6.86	2.17
14	39 ≤ VSP	0.97	0.48	10.9	7.41	2.34

[a] The average 95% confidence intervals for these VSP modes in % are ±5, ±2, ±3, ±1, and ±1 for NO, HC, CO, CO_2, and fuel, respectively. The unit for VSP is kw/ton.

Figure 6. Definition of VSP modes and average emissions and fuel use rates for a 2005 Chevrolet Cavalier 2.2L[a] (Frey *et al.*, 2008)

Comparing Routes. For each of two origin/destination pairs, field measurements were made for three alternative routes (Frey *et al.*, 2008). The choice of route was found to significant affect both the rates of fuel use and emissions, and the totals. However, routes with low rates were not necessarily the routes with the lowest totals, since distance and travel time varied among the alternative routes. Furthermore, the choice of route that has the lowest total emissions may differ depending on the pollutant. Therefore, there are trade-offs in choosing a preferred route if the objective is to minimize emissions of each pollutant.

Comparing Drivers. Driver behavior was shown to have an impact on emissions. The average difference in emissions when comparing drivers, for different routes, travel directions, times of day, and vehicles, ranged from 4% to 5% for CO_2, 9% to 11% for HC, 16% to 18% for NO_x, and 102% to 114% for CO (Frey, et al., 2008). The differences are due to different drivers having different desired speeds and accelerations.

Comparing Times of the Day. The emissions and fuel use data were compared for peak and off-peak periods, using the same vehicle, route, and driver. The empirical data showed that fuel use and emissions were higher for the peak periods than the off-peak periods. The average speeds during the peak periods were 10% lower than in the non-peak periods (Frey, et al., 2008).

Comparing Road Grades. Zhang et al. (2006) report that the average NO emission rate for positive grades of 5% or more was 4 times higher than it was for level or downhill terrain, and HC, CO, and fuel use were 40% to 100% higher for the uphill segments.

Zhang and Frey (2006) report that when positive road grades were ignored on the segment level, the VSP-based model underestimated the fuel use by 16% to 22%, and when negative road grades were ignored, they were overestimated by 22% to 24%. Thus, this sensitivity analysis indicates that road grade can substantially affect localized fuel use and emission rates at specific locations along a route. However, the effect of variation in road grade along a path is less pronounced than at specific locations. For example, for measured one way trips that were typically 10 to 18 miles in length, the difference in estimated route total fuel use and emissions ranged from −0.2% to 3.2%. Positive and negative grades along a path tend to compensate in terms of effect on fuel use and emission rates. Thus, the effect of road grade is typically more pronounced for short segments of road than when aggregated over a longer path. In more recent work, Yazdani and Frey (2014) have demonstrated a methodological approach to quantifying road grade based on in-use deployment of GPS receivers with barometric altimeters and statistical analysis of the data for adjacent road segments (e.g., 0.1 mile segments), for which road grade is estimated for each segment.

CHAPTER 3 METHODOLOGICAL APPROACH

VSP EMISSIONS MODEL DEVELOPMENT

This section discusses the study design, instrumentation and data analysis process used to develop the emissions factors for the VSP model.

Study Design

Fuel use and emissions measurements were conducted in three study areas. One is a low altitude piedmont area in the vicinity of Raleigh, NC, at altitudes less than 200 m. This area includes two alternative routes between each of two origin/destination pairs, with a total distance of 110 miles. Another study area is a high altitude mountainous area near Asheville, NC, at altitudes of 600 to 1,800 m. This route is 120 miles, including 55 miles over 1,000 m in altitude. The third study area is a low altitude piedmont area in the vicinity of Gainesville and Orlando, FL, at altitudes less than 200 m. The total distance for these Florida routes is 40 miles. Routes in details are demonstrated in Chapter 3.

Fifteen vehicles, including 10 passenger cars and 5 passenger trucks, were measured in the Raleigh study area. Two passenger cars and 1 passenger truck out of the 15 vehicles measured in the Raleigh study area were also measured in the Asheville study area. For the Gainesville and Orlando study area, a local passenger truck was measured.

Instruments

Instruments used include multiple global positioning system receivers with barometric altimeters (GPS/BA), a portable emissions measurement system (PEMS), and an on-board diagnostic (OBD) scan tool.

Typically, seven GPS/BA receivers were used, including Garmin 76CSx and Garmin Oregon 550 receivers. Each logs 1 Hz data. The GPS receivers measure position to within ±3 meters. Relative changes in elevation are measured within ±1 meter.

OEM-2100 Montana and OEM-2100 Axion PEMS were used to measure exhaust pollutant concentrations. The Montana was used with a 2012 Ford Fusion and a 2012 Toyota Sienna, and the Axion was used with the other vehicles. Each of these functionally similar PEMS includes two parallel five-gas analyzers that measure carbon dioxide (CO_2), CO, and HC using non-dispersive infrared (NDIR), and nitric oxide (NO) and oxygen (O_2) using electrochemical sensors. The analyzers were calibrated before each measurement day at the measurement area. During measurement, the analyzers periodically 'zero' using ambient air to prevent drift (Frey *et al*., 2003).

Battelle compared the exhaust emission concentrations from the same model PEMS to reference method instruments using a chassis dynamometer. There was less than 10% difference for measured driving cycle average emission rates for CO_2, CO, and NO_x. For HC concentrations, the PEMS uses NDIR but the reference method uses flame ionization detection (FID). The HC concentrations from NDIR are lower than for FID by a factor of approximately two (Battelle, 2003; Singer *et al*., 1998; Stephens and Cadle, 1991).

An OBDPro scantool and ScanXL™ Professional software was used to record on-board diagnostic (OBD) data from the vehicle electronic control unit (ECU), including engine speed (RPM), mass fuel flow (MFF), mass air flow (MAF), intake manifold absolute pressure (MAP), intake air temperature (IAT), and vehicle speed (VSS).

Data Analysis Proecedure

GPS/BA, PEMS, and OBD data were synchronized and processed for quality assurance using methods detailed elsewhere (Sandhu and Frey, 2012). These methods include converting the OBD data to a second-by-second basis, time aligning and combining PEMS, GPS/BA, and OBD data, checking errors for the combined data and correcting them if possible. Typical errors included both gas analyzers zeroing, negative pollutant concentrations, and unusual air to fuel ratio. Errant records that could not be corrected were excluded for analysis.

Road grade is quantified for non-overlapping 0.16 kilometer segments per the method demonstrated by Yazdani and Frey (2014), using data from multiple GPS/BA receivers. The precision of estimated grade depends on the number of devices used.

VSP was estimated using OBD speed and acceleration, and GPS-derived road grade at 1 Hz, using typical parameter values for light-duty vehicles (Jimenez-Palacios, 1999):

$$VSP = v(1.1a + 9.81r + 0.132) + 3.02 \times 10^{-4} v^3 \quad (1)$$

Where:

v = Vehicle speed, (m/s)

a = Vehicle acceleration, (m/s^2)

r = Road grade, (slope)

VSP = Vehicle specific power, (kW/ton).

For the high altitude (>1000 m) Asheville area, the aerodynamic drag term in Equation (1) was adjusted to account for decreasing air density associated with higher altitudes:

$$VSP = v(1.1a + 9.81r + 0.132) + \frac{P_{high,avg}}{P_{sealevel}} \times 3.02 \times 10^{-4} v^3 \quad (2)$$

Where:

$P_{high,avg}$ = the average barometric pressure observed for high altitude (>1000 m) measurements, (kPa). $P_{high,avg}$ ranged typically from 85 kPa to 90 kPa.

$P_{sealevel}$ = the barometric pressure at sea level (101 kPa).

VSP values were stratified into 14 discrete modes, as shown in Table 1 (Frey *et al*., 2002).

Table 1. Definition of Vehicle Specific Power Modes (Frey *et al*., 2002)

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

For most of the measured vehicles, MFF was reported by the ECU. Aggregated fuel consumption based on OBD data was compared to gas pump fuel consumption. Emissions rates for CO, HC, and NO_x were estimated based on a carbon mass balance and measured exhaust concentrations (Frey *et al*., 2008).

For the 2012 Dodge Avenger only, neither MFF nor MAF were broadcast by the ECU. Therefore, MAF was estimated using the Speed-Density method (Hendricks and Sorenson, 1991; Vojtisek-Lom and Allsop, 2001). This method estimates the exhaust flow rate based on the ideal gas law, taking into account RPM, MAP, IAT, displacement, compression ratio, and volumetric efficiency (VE). VE is the ratio of actual to theoretical mass flow. From the measured exhaust concentrations, and the weight percent of carbon in the fuel, the air/fuel ratio can be inferred. Thus, MFF can be inferred from MAF. VE was calibrated so that the sum of 1 Hz estimates of MFF was within 10% of the actual fuel consumed. From MFF and MAF, the exhaust flow rate is estimated. Using the measured exhaust concentrations, the mass flow rate of each pollutant is estimated.

For each measurement, average fuel use and emission rates were estimated for each VSP mode. Uncertainty in average fuel use and emission rates was quantified using 95% confidence intervals.

VSP MODEL IMPLEMENTATION IN CORSIM

This section discusses the approach used to implement the VSP-based emissions and fuel use estimation models into CORSIM. Additionally, the process used to account for cold-starts in CORSIM is described.

For initial development of the approach to implement VSP-based emissions models into CORSIM, previously reported VSP modal emission rates reported by Frey et al. (2008) for a 2005 Chevrolet Cavalier were used. These rates were given in Figure 6. The rates were implemented into the code in units specified by the CORSIM data dictionary. According to the data dictionary, emissions rates must be implemented in mg/s, and fuel use must be implemented in gal/s × 100,000 (Mc*Trans*™, 2011). The program does not handle decimals for fuel use and emissions rates inputs. Therefore, the values of emissions rates were all multiplied by 1,000, and the labels for the emissions outputs were adjusted from “grams per mile” to “milligrams per mile.” The reason for the multiplication by 1,000 was because many of the rates (in mg/s) were less than 1 and rounded down to 0 because decimal places were not allowed. Additionally, the software code had to be modified to let the program bypass the current emissions and fuel use calculations and assign rates based on the VSP mode.

Testing of the VSP implementation into CORSIM involved comparison with SwashSim. SwashSim is a microscopic traffic simulation program written in C# and employs an object-oriented architecture. It is developed and maintained by Dr. Scott Washburn, with contributions from various UF graduate students. The car-following and lane-changing algorithms of SwashSim generally replicate the logic of these algorithms in the current version of CORSIM. SwashSim also contains an emissions class, which calculates emissions using the VSP approach. It uses the same modal rates that were implemented into CORSIM for testing (from the 2008 study by Frey, et al.). In SwashSim, a simple network was used for testing purposes. The network is a 1-mile long freeway link. The network was replicated in CORSIM with the same entry volume (2400 veh/h), number of lanes (3), and free-flow speed (50 mi/h).

In CORSIM, emissions output and fuel use statistics on a link, route, and O-D basis can be viewed in the comma separated values (CSV) formatted file that is automatically generated. Emissions outputs are displayed in units of mg/mile/veh for every link in the network after the label modification. With these units, if the user wants total milligrams on a specific link, for example, then the output in mg/mi/veh must be multiplied by the length of the link and total vehicles discharged from the link. If the user wishes to obtain the emissions for a specific route, the emissions on links corresponding to that route can be summed. For emissions analysis in this project, link emissions were summed to estimate emissions totals for a certain route.

In SwashSim, the output is viewed in a CSV file, and there is no aggregation of the emissions into mg per unit distance or mg per vehicle. The emissions outputs that are shown in

SwashSim are the rates that are assigned every tenth of a second for every vehicle. Therefore, in order to estimate the mg/mile/veh, which in this case is the total mg of emissions per vehicle, since the link is 1 mile long, the mg/s values have to be summed for every second that the vehicle is on the link. They must also be divided by 10 because the rates are for every tenth of a second.

To verify that the VSP model was implemented correctly, the CORSIM emissions results were compared to the SwashSim results. SwashSim employs 10 different driver types, with similar adjustments to desired speed and acceleration as the 10 driver types in CORSIM. Three vehicles with different driver types were sampled from SwashSim to ensure that the results for all three vehicles were reasonably consistent with one another. The results from both programs, shown in Table 2 and Table 3, produced very similar emission rates, so it was concluded that the VSP model had been correctly implemented.

Table 2. SwashSim Predicted Emissions (mg/mile)

Vehicle	NOx	HC	CO
Vehicle 1	16.3	12.7	278
Vehicle 2	16.7	12.7	292
Vehicle 3	16.3	12.1	278

Table 3. CORSIM 6.3 Predictions with VSP Implementation (mg/mile)

Vehicle Type	NOx	HC	CO
1	16.3	12.4	278

COLD START IMPLEMENTATION INTO CORSIM

For this task, a method was established within the CORSIM source code to account for the extra emissions and fuel use caused by cold starts, to the output. Unfortunately, the outdated software architecture of CORSIM made it essentially impossible to implement this capability in any kind of robust manner. Thus, a very simple approach had to be used, and furthermore, it could only be applied to NETSIM links (i.e., surface streets). The approach implemented was to designate a fixed proportion of all vehicles that enter the network to be "cold start" vehicles. Each one of these vehicles that enter the simulation network after the initialization period has elapsed are given instantaneous fuel and emissions values equal to the average of the excesses of the 30 tested vehicles discussed in the next chapter. Since the proportion of vehicles to be designated as "cold start" vehicles could be not implemented as a user input, the research team had to select the value to be "hard-coded" into the program. Obviously, this value can be vary significantly depending on the time period and network area being modeled, among other factors. After some discussion and deliberation, the research team selected 10%. This value is intended to be a compromise value that will add a non-negligible amount of emissions outputs and fuel consumption to most simulation scenarios, but not result in cold starts being a dominating factor in the emissions/fuel consumption results.

CHAPTER 4 RESULTS FOR EMISSIONS MEASUREMENTS

APPROACH

For this project, the VSP approach was implemented. The modes of VSP were the same ones defined by Frey et al. (2002; 2008). This approach is preferred over the driving mode approach reported in Frey et al. (2003) because it gives a more specific idea of how much load the engine is experiencing. Also, the effect of road grades needs to be considered, and the driving mode method does not explicitly take road grade into consideration. The lack of an effect of road grade in CORSIM on emissions and fuel use is one of the reasons that the capabilities of CORSIM to estimate EU&E must be extended. The VSP model takes road grade into account, and the VSP is a good indicator of how much effort the engine is exerting.

DATA COLLECTION AND REDUCTION

The most critical factors that impact EU&E are instantaneous speed and acceleration. Road grade can also have an impact, as shown in the literature review. Therefore, the field study obtained a representative range of these factors for several selected routes and vehicles.

EU&E measurements were conducted on selected routes in three areas: Raleigh and Research Triangle Park (RTP), NC, Gainesville and Orlando, FL, and Asheville, NC. Four sets of routes were measured in the Raleigh and RTP area (Frey et al., 2008). These routes are comprised of a variety of road types, including feeder and collector streets, minor arterials, primary arterials, and freeways, with speed limits ranging from 25 to 65 mi/h. The four routes comprise 110 miles of driving distance, and 90 percent of 0.1-mile segments of the routes have grades between −3.7 to +3.7 percent. The Gainesville routes are approximately 40 miles long, including arterial roads and interstate highways with 25 to 70 mi/h speed limits. The Orlando routes are comprised entirely of interstate highway with 55 mi/h speed limits. Relatively flat roads were observed in Florida, with 90 percent of the 0.1 mile segments within ±2.8 percent grade. The Asheville route is approximately 120 miles long, with primarily mountainous arterial roads and a small portion of a state highway. The speed limits of the roads on the Asheville route range from 25 to 45 mi/h. The 90-percent frequency range of road grade for 0.1-mile segments in the Asheville area range from −5.4 percent to +6.1 percent.

Selected vehicles were used for the EU&E measurements in these three areas. For the Raleigh and RTP area, 10 selected passenger cars and 5 selected passenger trucks, which were recruited from student volunteers and rental agencies, were measured. For the Gainesville and Orlando area, an instrumented 2004 Honda Pilot from the University of Florida Transportation Institute (UFTI) and a 2012 Volkswagen Passat from a rental agency were used for measurements. The same Passat was also measured in the Raleigh and RTP area. For the Asheville area, three passenger cars from rental agencies were measured. These three cars were also measured in the Raleigh and RTP area.

Instrumentation

Preparation for field data collection included verification of the status of the PEMS, verification that all the parts and equipment were available, and laboratory calibration of the PEMS. Taking field measurements consisted of the installation of the instrumentation into a vehicle, data collection, and decommissioning. The instruments included the Axion PEMS manufactured by MRVGlobal, ProScan OBD data logger, and Garmin 76CSx tracking global positioning system (GPS). The Axion is made up of two five-gas analyzers. It takes 45 minutes or less to install in a vehicle. The analyzers measure exhaust concentration of CO, CO_2, hydrocarbons (HC), NO, and O_2. CO, CO_2, and HC are measured NDIR. O_2 and NO are measured using electrochemical cells. The system draws less than 6 amps at 12 volts and does not significantly affect engine load. The Axion is calibrated using a reference gas containing known concentrations of CO, CO_2, HC (as C_3H_8), and NO. The instrument holds a calibration within ±5 percent for three months, but is calibrated more frequently. To prevent drift, the two analyzers “zero” approximately every 10 minutes. In order to zero, measurements are made on ambient air, which is taken as a reference gas. The Axion includes a weather station that records ambient temperature, humidity, and pressure.

A ProScan OBD scan tool, software, and dedicated laptop that logs data were connected from the OBD-II interface. Vehicle and engine activity data including Engine revolutions per minute (RPM), manifold absolute pressure (MAP), intake air temperature (IAT), mass of air flow (MAF), mass of fuel flow (MFF), vehicle speed (VS), engine coolant temperature (ECT), catalyst temperature, ambient temperature and pressure, and others were read and recorded. Garmin 76CSx tracking GPS receivers, which record latitude, longitude, and elevation, were used to record the driving routes and to quantify road grade. Photos of the instrumentation can be seen in Figure 20 through Figure 26 in Appendix A.

For each vehicle, the exhaust gas concentrations, engine, and GPS data were measured from different instruments. These data were time-aligned based on trends along time between different sets of data using particular parameters as indicator. First the OBD data was synchronized to PEMS data using engine RPM and CO concentration as indicators. Then the GPS data was synchronized to the synchronized OBD data both using vehicle speed as indicators. The combined data set for each vehicle was screened to check for errors or possible problems. Where possible, such problems were corrected. If correction is not possible, then the errant data were omitted from the final database used for analysis. Exhaust emission rates of CO, CO_2, HC, and NO (in g/s), on a second by second basis, were estimated from the exhaust concentrations based on carbon mass balance and the flow of fuel or exhaust gas. Road grade was estimated using the GPS data at 1 Hz rate. Emissions rates were estimated on the basis of VSP. VSP was categorized into 14 modes. Modes 1 and 2 are for negative VSP which includes deceleration or coasting down a hill. Mode 3 includes idling. Modes 4 through 14 include increasing positive VSP associated with accelerating, cruising at various speeds, or traveling up a hill. Average fuel use and emission rates were estimated in each VSP mode as a modal emission rate. Uncertainty in the average rates was quantified using 95% confidence intervals.

For cold start measurement data, time-based fuel use rate and emissions rates, engine speeds, engine coolant temperatures, and catalyst temperatures were plotted. The cold start increment of fuel use and emissions were quantified based on comparison to the hot-stabilized idling rates. For every vehicle was measured for a cold start, measurements on the Raleigh/RTP routes were also conducted. The hot-stabilized idling rates were summarized based on the Raleigh/RTP routes when the vehicle was idling between each route. Based on the average hot-stabilized idling fuel use and emissions rates, the cold start increments of fuel use and emissions were quantified.

Raleigh/RTP Data Collection

The Raleigh/Research Triangle Park (RTP) routes include four designated routes between NC State University, North Raleigh, and RTP, as shown in Figure 7. These routes are named “A”, “C”, “1”, and “3”, comprising approximately 110 miles (Frey et al., 2008). Routes A and 3 are comprised of arterial roads. The lengths of Route A and 3 are approximately 10 miles and 19 miles, respectively. Routes C and 1 include a significant portion of freeway driving and a small portion of arterial roads, with one way distances of approximately 11 miles for Route C and 17 miles for Route 3. Typical travel times for these routes are listed in Table 4.Table 4

Typically a vehicle started from NCSU, was driven along Route A to North Raleigh and then along Route 1 to RTP. Afterwards, the vehicle returned to North Raleigh and NCSU following Route 1 and A. The vehicle then was driven to North Raleigh and RTP again following Route C and 3, and returned via Route 3 and C. The entire measurement took about 4 hours per vehicle.

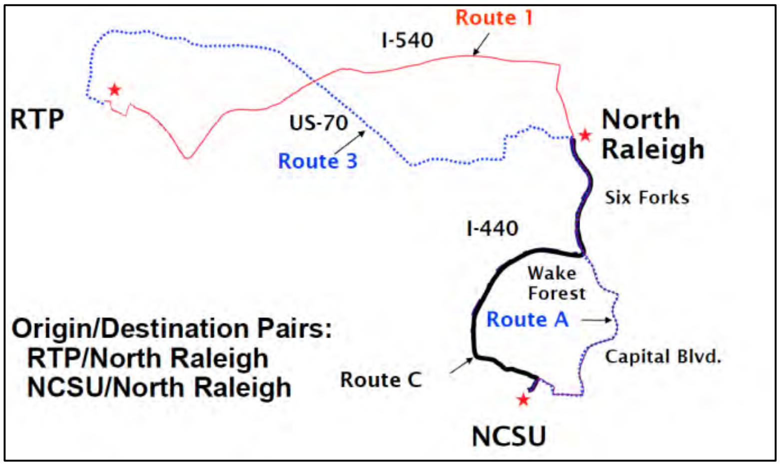

Figure 7. Routes for the Raleigh and Research Triangle Park area measurements

Table 4. Travel Times for Raleigh Routes

Route	Typical Travel Time (min)
A	45
C	55
1	50
3	70

Gainesville Data Collection

The route driven for data collection in Gainesville is about 39 miles long, with 24 miles of freeway and 15 miles of arterial. Emissions from two vehicles, a 2004 Honda Pilot and a 2012 Volkswagen Passat were measured for this route. The Honda Pilot was also measured on the Orlando route (described in the next section). The Volkswagen Passat was also tested on the Raleigh/RTP routes.

The starting point is the intersection of University Avenue and Gale Lemerand Drive. The route continues on westbound University Avenue, which becomes Newberry Road. At the starting point, the road has 2 lanes in the westbound direction, and a lane is added after about 3 miles at the intersection of Newberry Road and NW 8th Avenue. The road continues with 3 lanes to the intersection with I-75. There are several traffic signals on this segment of the route, and the arterial experiences high congestion during peak periods. There is a shopping mall on the south side of Newberry Road about 0.3 miles east of I-75, which contributes to a lot of the congestion. The University Avenue/Newberry Road segment of the route is about 4.2 miles. The route continues northbound on I-75. This is a six-lane divided interstate highway. The driver experienced free-flow conditions for all four runs on this segment of the route. The length of the interstate segment is about 11.8 miles. The next step in the route is to exit eastbound onto M L King Boulevard/US 441. This segment continues for another 11.8 miles. It is a four lane divided highway. There are five traffic signals on this segment. The route continues southbound on NW 34th Boulevard, a two lane road. This segment of the route is about 2.1-miles long. A left turn is made on NW 39th Avenue, which continues eastbound for about 4 miles. This is a four lane road with a median and several traffic signals. A right turn is made on NE 15th Street, which continues southbound for about 1.5 miles. This is a two-lane undivided road. Another right turn is then made on NE 16th Avenue, which runs westbound for about 2 miles to NW 13th Street. NE 16th Avenue is another two-lane undivided road. A left turn is made on NW 13th Street. This segment of the route runs southbound for about 1 mile. It is a 4 lane road with a left turn lane separating the two directions for virtually the entire mile. A right turn is made on University Avenue, which brings the route back to the starting point after about 0.5 miles.

The route was driven four times for data collection. The starting times and travel times of each trip are shown in Table 5. Only a small portion of the route was used for testing with simulation. The portion of the route that was used for simulation testing was a portion along Newberry Road, directly east of I-75. The driving times for this route can be seen in Table 6.

The Gainesville route and screenshots from the in-vehicle cameras can be seen in Figure 27 through Figure 41 in Appendix A. The driving occurred during Spring break for UF students; thus, there was less traffic congestion than usual.

Table 5. Gainesville Route Driving Times

Date	Starting time	Typical Travel time
Monday, March 4th	11:05 AM	61 minutes
Tuesday, March 5th	1:30 PM	60 minutes
Tuesday, March 5th	2:45 PM	56 minutes
Tuesday, March 5th	3:45 PM	62 minutes

Table 6. Driving Times for Portion of Gainesville Route Used for Testing

Run	Time to complete portion of route
1	34 seconds
2	40 seconds
3	45 seconds
4	48 seconds

Orlando Data Collection

Data were also collected on I-4 in Orlando on Monday, March 4th, 2013. A portion of the freeway was already modeled in CORSIM in a previous study conducted at UF, so that particular portion was chosen as the data collection site. This portion spanned from S. Orange Blossom Trail to Maitland Boulevard. The segment is about 8.4 miles long. There are parts of the segment with 3 lanes and other parts with 4 lanes. The route was driven four times in the eastbound direction and four times in the westbound direction. The eastbound segment was the direction that was already coded in CORSIM. Starting times and travel times for the eastbound direction are shown in Table 7. The first two runs experienced nearly free flow conditions, with more congestion on runs three and four. The biggest source of congestion was vehicles getting on and off at toll road 408, the Spessard L. Holland East-West Expressway. The Orlando route and screenshots from the in-vehicle cameras can be seen in Figure 42 through Figure 47 in Appendix A.

Table 7. Orlando Route Driving Times

Starting time	Travel time
2:35 PM	8 minutes 23 seconds
3:01 PM	8 minutes 9 seconds
3:28 PM	9 minutes 10 seconds
3:52 PM	15 minutes 15 seconds

Asheville Data Collection

Data were collected in the Asheville area on 5/17/13, 5/30/13, and 6/21/13. The route began at a gas station on Brevard Rd southwest to City of Asheville. The route followed Brevard Rd for approximately 4.5 miles, and then turned onto Blue Ridge Pkwy. Continuing on Blue Ridge Pkwy for approximately 50 miles, the route turned onto U.S. Route 23. After driving about 6 miles, the route turned to U.S. Route 276. After driving on U.S. Route 276 for approximately 35 miles, a turn was made onto State Highway 280 for 16 miles, and, subsequently, onto Interstate Highway 26 for 9 miles. The route finally returns back to the starting gas station. For each vehicle, the route was driven twice in one day. Data from the two runs were combined for analysis. The route travel times are listed in Table 8.

Table 8. Asheville Routes Travel Times

Vehicle	Run 1 Travel Time	Run 2 Travel Time
2012 Ford Fusion	3 hours 18 minutes	3 hours 16 minutes
2012 Toyota Sienna	3 hours 10 minutes	3 hours 11 minutes
2012 Dodge Avenger	3 hours 18 minutes	3 hours 8 minutes

Synchronization

Because exhaust gas concentrations, engine and GPS data, and recorded videos were measured from different instruments, there was a need to synchronize them to represent simultaneous emissions and vehicle activities. The synchronization was based on trends in time between different sets of data using particular parameters as indicators. The OBD data and the PEMS data were synchronized using engine RPM and CO concentrations as indicators. The GPS and the OBD data were synchronized using speed as the indicator.

Screening

The data were checked for errors and problems. To do this, the NCSU research team has developed a series of Macros in LabView (Sandhu and Frey, 2013). The data were processed using these macros to identify any problems in the data. If possible, the problems were corrected. If not, the data with errors were omitted from the final dataset. Typical data errors include invalid data, unusual engine RPM values, unusual intake air temperature, both analyzers zeroing at the same time, analyzer freezing, negative emission values, inter-analyzer discrepancy, and air leakage.

Data Processing

The emissions rates of CO, CO_2, HC, and NO were estimated from the exhaust concentrations based on carbon mass balance and the flow of fuel or exhaust gas. Road grade was estimated using the GPS data at 1 Hz rate. The data were processed by another series of Macros in Labview developed by NCSU (Sandhu and Frey, 2013). To quantify hot stabilized emissions and fuel use, VSP were separated into 14 modes. Average fuel use and emissions rates were estimated for each VSP mode. Uncertainty was quantified at the 95% confidence level. These rates were implemented into the CORSIM code in the next task. The final modal rates for the 2004 Honda Pilot are in Table 9. These rates can also be seen in graphical form in Figure 48 through Figure 52 in Appendix B.

Table 9. VSP Modal Fuel Use and Emissions Rates for Honda Pilot

VSP mode	VSP Range	Sample Size	Fuel	NO as NO_2	HC	CO	CO_2
	(kW/ton)		(g/s)	(mg/s)	(mg/s)	(mg/s)	(g/s)
1	Below −2	441	0.49	0.33	0.41	2.1	1.6
2	−2 – 0	111	0.74	0.62	0.48	2.8	2.3
3	0 – 1	119	0.61	0.18	0.48	1.4	1.9
4	1 – 4	278	0.98	0.36	0.63	4.8	3.1
5	4 – 7	225	1.38	0.74	0.85	6.5	4.4
6	7 – 10	270	1.78	1.27	0.98	5.2	5.6
7	10 – 13	292	2.19	1.25	1.20	7.5	6.9
8	13 – 16	231	2.59	2.31	1.40	5.1	8.2
9	16 – 19	127	2.81	1.89	1.70	6.8	8.9
10	19 – 23	138	2.89	2.47	1.50	6.2	9.1
11	23 – 28	138	3.13	2.39	1.80	5.9	9.9
12	28 – 33	66	3.46	2.04	2.00	7.0	11.0
13	33 – 39	21	3.69	1.62	2.40	3.5	11.7
14	Over 39	4	4.01	1.50	2.80	8.1	12.7

The modal rates for the 2012 VW Passat driven on the Gainesville route can also be found in Table 26 in Appendix B. These rates were measured from two separate runs on the Gainesville route. The rates can be seen in graphical form in Figure 53 through Figure 57 in Appendix B. However, since this vehicle was not driven on the I-4 route in Orlando like the 2004 Honda Pilot, those results are not used in the latter sections of this report.

In summary, the empirical fuel use and emission rate data for this project include VSP modal emissions and fuel use rates based on the average of each of 10 passenger cars and 5 passenger trucks. The average modal rates for passenger cars and passenger trucks are given in Table 10(a) and (b), respectively.

VSP modal fuel use and emission rates are typically lowest at idle, and increase monotonically with increasing positive VSP. Fuel use and CO_2 emission rates typically increase linearly with positive VSP. For the average of 10 measured passenger cars, at the highest VSP mode (Mode 14), these rates are approximately 11 times greater than at idle (Mode 3). Among the other three pollutants, the HC emission rates tend to be the least sensitive to VSP, also increasing by a factor of approximately 11 for the highest observed VSP mode compared to idle. However, tailpipe exhaust emission rates of NO_x, and CO typically increase in a nonlinear manner with positive VSP. For example, the average NO_x emission rate increases from 0.03 mg/s to 0.37 mg/sec as VSP increases from Mode 3 to Mode 8, an emissions range of 0.34 mg/sec for a VSP range of approximately 16 kW/ton. However, as VSP further increases, the NO_x emission rate increases more substantially. For example, the NO_x emission rate for Mode 10, 0.69 mg/sec, is higher than that of Model 8 by 0.32 mg/sec, for a VSP increase of approximately 7 kW/ton. As engine power demand further increases, the NO_x emission rate increases at a greater rate. For example, the average NO_x emission rate at Mode 14 is 4.64 mg/sec, which is a factor of 155 higher than for idle. The CO emission rates tend to be slightly less sensitive, compared to NO_x, to increases in VSP for Modes 10 to 13, but more sensitive for Mode 14. For example, for Mode 13, the average CO emission rate is 55 times greater than that at idle, whereas for Mode 14, the average CO emission rates is nearly 170 times greater than that at idle. Thus, engine power demand has a different effect on emission rates depending on the pollutant, both in terms of the relative magnitude and the trend.

For the average of 5 passenger trucks, the trends in VSP modal average fuel use and emission rates are qualitatively similar to those for passenger cars, but the numerical values are somewhat different. For example, the ratio of the Mode 14 to Mode 3 modal average fuel use and CO_2 emission rates for passenger trucks is approximately 13 compared to approximately 11 for passenger cars. For NO_x, the ratio is 88 compared to 155. For CO, the ratio is 120 compared to 170. The ratio for HC is approximately the same as for fuel use in both cases. However, similar to passenger cars, the NO_x emission rates are more sensitive to VSP for moderate to high demand, whereas the CO emission rates tend to be relatively low except at very high power demand.

For an equally weighted average of the 14 VSP modes, the average fuel use and CO_2 emission rates of the passenger trucks are approximately 80% higher than for the passenger cars, which is consistent with the difference in weight between the two vehicle groups. The HC emission rates of the passenger trucks are nearly six times higher than for the passenger cars, and the CO emission rates are approximately twice as high. However, the NO_x emission rates are over 40 percent lower. The passenger trucks and passenger cars are certified to the same emission standard, and therefore the emission rates of NO_x, CO, and HC are expected to be somewhat comparable. Some of the large relative differences between the two groups are because the emission rates of the passenger cars are low. These results imply that there is value in differentiating between passenger cars and passenger trucks with respect to fuel use and CO_2 emission rates, and that there can be some differences in emission rates of NO_x, CO, and HC between the two vehicle types.

Altitude may also affect fuel use and emissions. Many studies have evaluated the effect of altitude on heavy-duty diesel vehicles using dynamometer tests, but there is lack of such study for light-duty gasoline vehicles based on comparison of the same vehicle at different altitudes. Three light-duty gasoline vehicles were measured on low altitude piedmont (LP) routes in the Raleigh, NC area and on high altitude mountainous (HM) routes in the Asheville, NC area. Table 7(c) shows the average fuel use and emission rates for 3 selected vehicles measured on Asheville Routes. Road grade and altitude were jointly found to have a significant effect on fuel use and emission rates. Cycle average fuel use, CO emission, and NOx emission rates were approximately 10%, 60%, and 40% higher, respectively, for the HM vs. LP areas. Road grade and altitude each affect fuel use and emission rates and thus, affect emission estimates, which may lead to biases in gasoline light duty vehicle emission inventories and impact estimates of near road air quality and human exposure to air pollution. The method illustrated here is recommended for application to a larger vehicle sample.

Table 10. VSP Based Average Fuel Use and Emission Rates for Selected Vehicles in Selected Routes

(a). 10 Selected Passenger Cars Measured in Raleigh and Research Triangle Park Routes

VSP Mode	VSP Range	Sample Size	Fuel	NO as NO_2	HC	CO	CO_2
	(kW/ton)		(g/s)	(mg/s)	(mg/s)	(mg/s)	(g/s)
1	Below −2	21136	0.34	0.12	0.21	1.35	1.12
2	−2 – 0	6969	0.45	0.09	0.20	1.77	1.45
3	0 – 1	30713	0.31	0.03	0.11	0.52	0.98
4	1 – 4	10766	0.72	0.14	0.28	2.95	2.31
5	4 – 7	10206	1.00	0.17	0.35	4.18	3.19
6	7 – 10	10005	1.26	0.21	0.42	4.66	4.03
7	10 – 13	8787	1.52	0.28	0.51	5.48	4.84
8	13 – 16	7229	1.73	0.37	0.57	6.22	5.52
9	16 – 19	5168	1.95	0.53	0.64	7.57	6.18
10	19 – 23	4400	2.16	0.69	0.71	9.31	6.88
11	23 – 28	2960	2.38	0.89	0.75	12.5	7.51
12	28 – 33	1407	2.66	1.37	0.86	17.2	8.39
13	33 – 39	817	3.03	2.73	1.05	28.5	9.53
14	Over 39	469	3.49	4.64	1.25	87.1	11.0

Selected vehicles are a 2005 Mazda 6, a 2011 Chevrolet HHR, a 2011 Toyota Camry, a 2012 Nissan Versa, a 2012 Dodge Avenger, a 2012 Ford Fusion, a 2012 Nissan Rogue, a 2012 Toyota Camry, a 2013 Ford Fusion, and a 2013 Chevrolet Impala

(b). 5 Selected Passenger Trucks Measured in Raleigh and Research Triangle Park Routes

VSP Mode	VSP Range (kW/ton)	Sample Size	Fuel (g/s)	NO as NO_2 (mg/s)	HC (mg/s)	CO (mg/s)	CO_2 (g/s)
1	Below −2	10714	0.65	0.10	0.91	3.19	2.22
2	−2 – 0	2916	0.83	0.10	0.96	2.89	2.76
3	0 – 1	13484	0.49	0.02	0.49	1.56	1.59
4	1 – 4	4797	1.29	0.15	1.50	5.59	4.29
5	4 – 7	4896	1.76	0.20	1.99	6.42	5.81
6	7 – 10	4701	2.20	0.23	2.40	7.67	7.18
7	10 – 13	4049	2.58	0.31	2.82	8.50	8.34
8	13 – 16	3618	3.01	0.40	3.23	9.08	9.60
9	16 – 19	2764	3.36	0.43	3.56	11.9	10.6
10	19 – 23	2429	3.83	0.52	4.18	20.3	12.0
11	23 – 28	1744	4.26	0.81	4.62	22.1	13.2
12	28 – 33	1074	4.67	0.83	5.14	33.7	14.4
13	33 – 39	697	5.34	1.12	5.74	75.7	16.3
14	Over 39	482	6.54	1.76	7.21	180	19.8

Selected vehicles are a 2008 Nissan Xterra, a 2010 Chevrolet Silverado, two 2011 Ford F150s, and a 2013 GMC Yukon.

(c). 3 Selected Passenger Cars and Trucks Measured in Asheville Routes

VSP Mode	VSP Range (kW/ton)	Sample Size	Fuel (g/s)	NO as NO_2 (mg/s)	HC (mg/s)	CO (mg/s)	CO_2 (g/s)
1	Below −2	4,548	0.43	0.11	0.09	0.82	1.35
2	−2 – 0	1,211	0.57	0.08	0.10	1.13	1.82
3	0 – 1	9,280	0.36	0.17	0.18	2.89	1.13
4	1 – 4	2,586	0.79	0.17	0.13	1.66	2.50
5	4 – 7	2,433	1.06	0.22	0.18	2.75	3.34
6	7 – 10	2,283	1.38	0.32	0.23	2.88	4.36
7	10 – 13	2,005	1.58	0.41	0.27	3.03	5.00
8	13 – 16	1,526	1.81	0.64	0.35	3.38	5.73
9	16 – 19	1,055	1.97	0.87	0.37	3.47	6.25
10	19 – 23	855	2.15	1.20	0.40	2.96	6.80
11	23 – 28	616	2.30	1.59	0.44	5.00	7.29
12	28 – 33	278	2.64	2.35	0.57	5.18	8.35
13	33 – 39	119	2.96	4.74	0.63	25.8	9.33
14	Over 39	44	3.78	5.73	0.84	114	11.8

Selected vehicles are a 2012 Dodge Avenger, a 2012 Ford Fusion, and a 2012 Toyota Sienna. The Avenger and the Fusion were also included as part in the selected 10 passenger car list measured in Raleigh/RTP routes.

For the Asheville data, the modal fuel use and emission rates for high altitudes (over 1,000 m) were typically higher than at low altitudes (less than 200 m), but the comparison also includes differences in terrain. For most of the VSP modes for the three vehicles, the modal average speed, acceleration, grade, RPM and MAP, were statistically significantly different for high altitude mountainous (HM) versus low altitude piedmont (LP) vehicle operation. The fuel use rate averaged 11 percent higher for the high altitude mountainous area versus low altitude piedmont area, and the CO and NO_x emission rates were higher by approximately 60 percent and 20 percent, respectively. Variability in fuel use rate is more sensitive to variation in the observed grades than to differences in study area. However, CO and NO_x emission rates appear to be comparably or more sensitive to study area than road grade. More details are given in Appendix C.

COLD START DATA COLLECTION AND ANALYSIS

Because hot stabilized emissions are being reduced through better management of the engine and catalytic converter, the relative contribution of cold starts to overall trip emissions is likely to increase. In a recent study by co-PI Frey, it was found that cold starts make up 30% of total trip emissions for NO_x, 46% for HC, and 12% for CO based on measurement of 7 vehicles. These estimates differ greatly from those made by the MOVES model. The MOVES model may not be providing accurate results for newer vehicles (Frey, et al., 2002). There is a need to characterize cold starts based on real world data and to develop a model that better quantifies the effects of cold starts.

Data Collection

For data collection on cold starts, vehicles were parked for a 12-hour overnight soak period. For each vehicle one cold start was measured after the 12-hour soak period, followed by hot stabilized driving on one of the prescribed routes. The EU&E were compared for the cold start period to the hot stabilized period to estimate the effects of a cold start. The NCSU research team made cold start measurements for 30 vehicles, including 16 passenger cars and 14 passenger trucks, on the Raleigh/RTP area routes. The specifications, including year, make, model, type, test date, age, engine size, odometer, ambient temperature and relative humidity, of these vehicles are given in Table 11.

Table 11. Specifications of 30 Cold Start Measured Vehicles

Veh #	Year	Make	Model	Type [a]	Test Date	Age	Engine (L)	Odometer (miles)	Ambient Temp. (F)	Rel. Humid. (%)
1	2000	Pontiac	Grand Prix	PC	2/17/2013	13	3.8	109,128	30	37
2	2001	Mazda	Protégé	PC	2/16/2013	12	2	157,245	36	90
3	2002	Chevy	Silverado	PT	11/11/2012	10	4.8	154,475	68	38
4	2002	Lexus	RX300	PT	11/6/2012	10	3	135,784	47	54
5	2002	Jeep	Wrangler	PT	11/11/2012	10	4	90,284	72	36
6	2002	Jeep	Wrangler (b)	PT	2/16/2013	11	4	136,114	42	75
7	2004	Toyota	Tacoma	PT	11/11/2012	8	4	136,211	50	75
8	2004	Chevy	Trailblazer	PT	2/16/2013	9	4.2	99,758	41	76
9	2004	Pontiac	Grand Am GT	PC	2/16/2013	9	3.4	93,237	36	92
10	2005	Mazda	6	PC	11/11/2012	7	2.3	79,164	73	44
11	2006	Dodge	Caravan	PT	6/1/2013	7	3.3	123,927	86	46
12	2008	Chevy	Impala	PC	6/9/2013	5	3.5	98,244	79	81
13	2008	Honda	Fit	PC	11/11/2012	4	1.5	55,531	73	44
14	2008	Nissan	Xterra	PT	2/16/2013	5	4	47,807	36	91
15	2010	Chevy	Silverado	PT	9/17/2012	2	4.8	26,551	79	72
16	2011	Chevy	HHR	PC	12/19/2011	0	2.2	21,072	48	52
17	2011	Toyota	Camry	PC	12/20/2011	0	2.5	8,872	57	50
18	2011	Ford	XL150	PT	9/17/2012	1	5	28,779	64	97
19	2011	Ford	XL150 (b)	PT	9/19/2012	1	5	17,208	64	97
20	2012	Nissan	Versa	PC	12/16/2011	0	1.8	615	57	80
21	2012	Fiat	500	PC	1/28/2012	0	1.4	12,875	41	50
22	2012	Toyota	Camry	PC	10/1/2012	0	2.5	18,752	66	81
23	2012	Dodge	Avenger	PC	6/21/2013	1	2.4	38,502	90	45
24	2012	Ford	Fusion	PC	5/29/2013	1	2.5	26,024	86	35
25	2012	Toyota	Sienna	PT	5/20/2013	1	3.5	35,376	78	76
26	2012	Nissan	Rogue	PC	2/16/2013	1	2.5	6,980	36	92
27	2013	GMC	Terrain	PT	5/16/2013	0	2.4	10,268	87	66
28	2013	GMC	Yukon	PT	9/29/2012	0	5.3	4,089	63	100
29	2013	Chevy	Impala	PC	2/23/2013	0	3.6	8,176	38	60
30	2013	Ford	Fusion	PC	2/24/2013	0	2.5	42,966	48	30

[a] *PC is passenger car, PT is passenger truck. Coupes and Sedans are typically classified as PC. SUVs and pick-up trucks are typically classified as PT.*

Data Analysis

To quantify the effect of cold starts, the fuel use rate, emissions rates, engine speeds (revolutions/min), engine coolant temperatures, and catalyst temperatures were plotted against time. The cold start phase was defined as the start time until the parameters were stable. This phase was categorized into three different scenarios based on observations from the data. These scenarios are described below.

Scenario 1

An initial peak in fuel use and emissions rates is followed by a monotonic reduction in rates that reaches a steady-state value. If the steady-state rate within approximately 15 minutes of the cold start is approximately equal to the hot-stabilized idling rate, the cold start is considered to have ended. The cold start increment is quantified as the difference between the cold start mass and the hot-stabilized mass from the engine start to the time when the cold start rate equals hot-stabilized rate. The scenario 1 cold start quantification is illustrated in Figure 8.

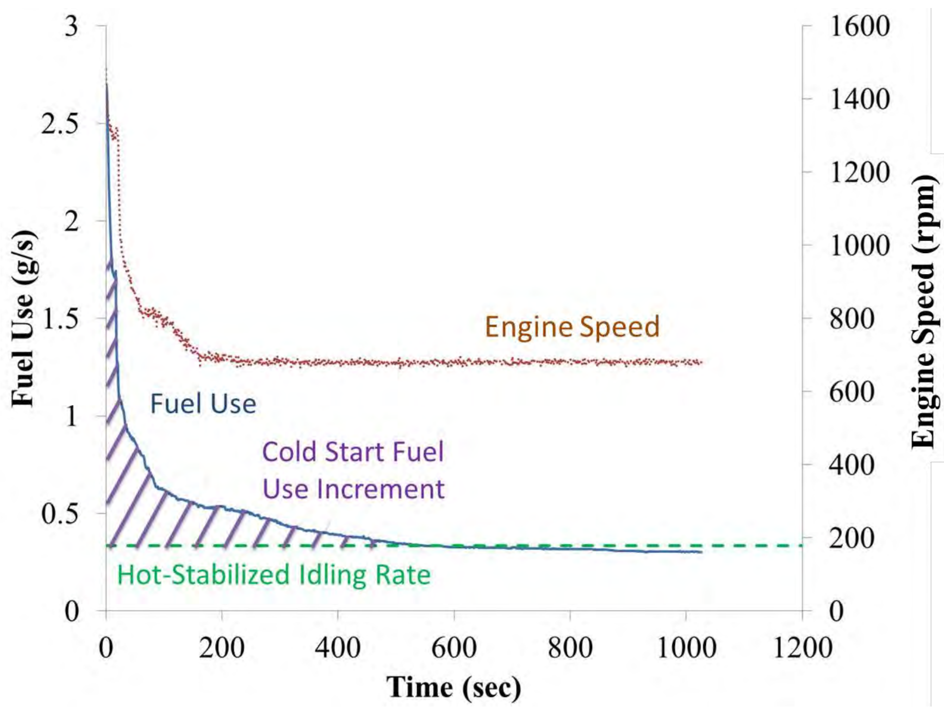

Figure 8. Cold start increment quantification example for scenario 1

Scenario 2

An initial peak in fuel use and emission rates is followed by monotonic reduction in rates that reaches a steady-state value. However, the steady-state rates during the 15 minutes period after cold start are higher than the hot-stabilized idling rates. In this scenario, the cold start increment is quantified as the difference between cold start mass and hot-stabilized mass during the 15 minutes (900 seconds) period. Scenario 2 quantification is illustrated in Figure 9.

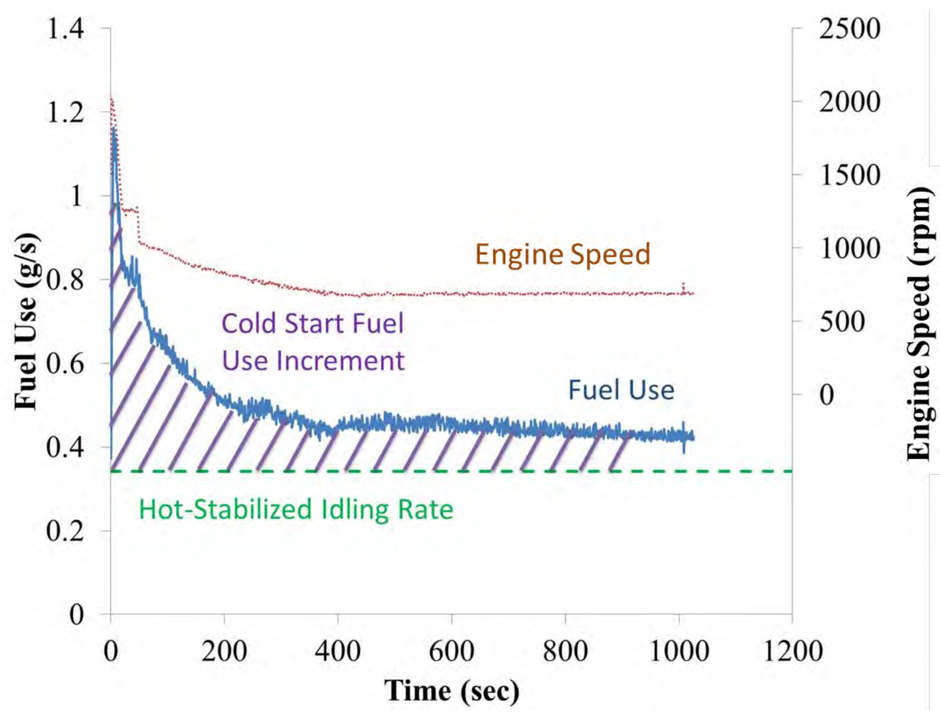

Figure 9. Cold start increment quantification example for scenario 2. The engine speed axis is positioned to avoid data overlap with fuel use.

Scenario 3

Subsequent to a cold start, there is a decrease in fuel use and emissions rates that is followed by or more secondary peaks. The secondary peak(s) are much lower in peak magnitude than the initial cold start, and are typically of low frequency and comparatively longer duration. An example is shown in Figure 10. In Scenario 3, the cold start period includes the secondary peak(s).

The cold start increment is quantified as the difference between cold start mass and hot-stabilized mass from the engine start to the end of the last secondary peak. If the secondary peak cold start rates drops below the hot-stabilized rate, the end of a particular secondary peak is defined as the time at which the rates are equal. If the secondary peak cold start rates do not drop below the hot-stabilized rates, then the end of the cold start is defined as 15 minutes.

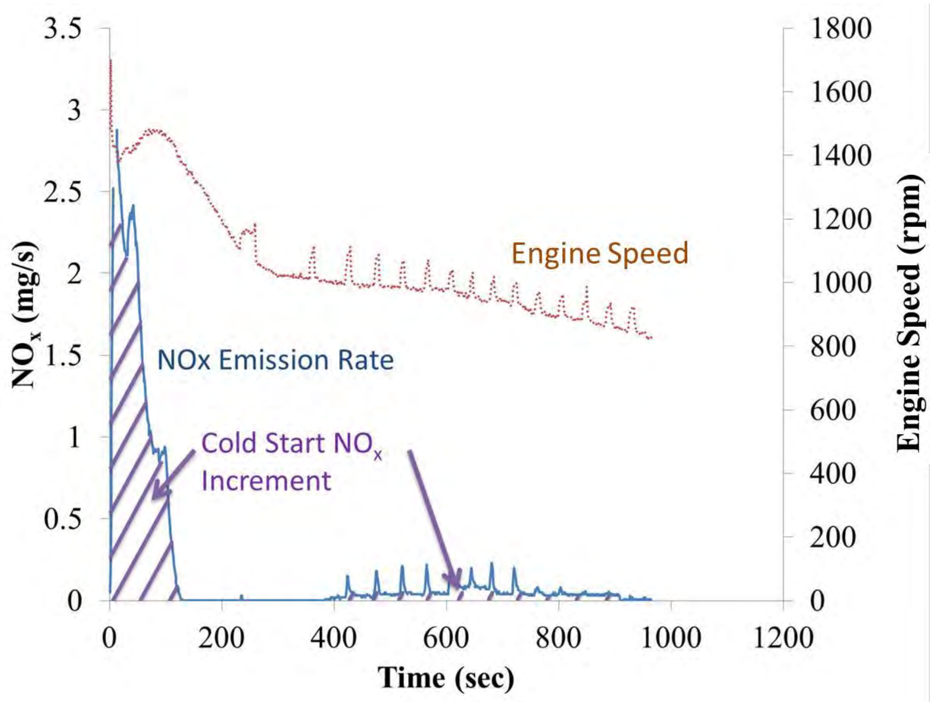

Figure 10. Cold start increment quantification example for scenario 3 situation

Results

The cold start excess fuel use and emissions for each of the 30 vehicles are given in Table 12.

Table 12. Cold Start Excess Fuel Use and Emissions for the 30 Measured Vehicles

Veh #	Year	Make	Model	Empirical Cold Start Excess (Scenario) [b] Fuel (g)	CO (g)	HC (g)	NO_x (g)	CO_2 (kg)
1	2000	Pontiac	Grand Prix	127	54	1.7	0.08	0.33
2	2001	Mazda	Protégé	95	4.0	0.71	2.6	0.29
3	2002	Chevy	Silverado	60	15	1.4	0.17	0.16
4	2002	Lexus	RX300	127	31	0.66	0.16	0.35
5	2002	Jeep	Wrangler	41	3.6	0.27	0.12	0.12
6	2002	Jeep	Wrangler (b)	135	19	0.33	0.15	0.40
7	2004	Toyota	Tacoma	92	5.0	0.21	0.15	0.28
8	2004	Chevy	Trailblazer	116	17	1.8	0.54	0.34
9	2004	Pontiac	Grand Am GT	109	37	0.67	0.06	0.29
10	2005	Mazda	6	39	2.4	0.43	0.25	0.18
11	2006	Dodge	Caravan	85	5.0	0.3	0.1	0.30
12	2008	Chevy	Impala	61	4.4	0.26	0.06	0.18
13	2008	Honda	Fit	14	0.75	0.14	0.03	0.04
14	2008	Nissan	Xterra	97	16	0.76	0.07	0.29
15	2010	Chevy	Silverado	62	3.9	1.9	0.03	0.18
16	2011	Chevy	HHR	80	3.5	0.38	0.02	0.25
17	2011	Toyota	Camry	83	0.21	0.72	0.12	0.26
18	2011	Ford	XL150	117	3.0	1.9	0.14	0.35
19	2011	Ford	XL150 (b)	143	2.9	2.0	0.11	0.43
20	2012	Nissan	Versa	32	0.81	0.31	0.004	0.10
21	2012	Fiat	500	43	2.7	0.51	0.25	0.13
22	2012	Toyota	Camry	93	1.1	0.90	0.09	0.29
23	2012	Dodge	Avenger	31	4.6	0.50	0.1	0.10
24	2012	Ford	Fusion	47	0.8	0.30	0.1	0.10
25	2012	Toyota	Sienna	77	0.8	0.10	0.002	0.20
26	2012	Nissan	Rogue	68	8.6	0.32	0.02	0.22
27	2013	GMC	Terrain	81	0.9	0.10	0.01	0.30
28	2013	GMC	Yukon	44	4.1	1.0	0.05	0.13
29	2013	Chevy	Impala	122	16	0.20	0.03	0.36
30	2013	Ford	Fusion	98	5.6	0.25	0.04	0.30

The cold start fuel use and emissions increments varied widely between vehicles. However, in emission inventories, the total emissions are based on the aggregated effect of the activity of many vehicles. Thus, it is important to base the mean increment on a sample of vehicles, as is done here, rather than on an individual vehicle. The average fuel use and emissions excesses from a cold start across the 30 test vehicles are given in Table 13.

Table 13. Empirical Cold Start Excess: Average for 30 Vehicles

	Mean			
Vehicle Type	Fuel (g)	CO (g)	HC (g)	NOx (g)
Passenger Car	71	9.1	0.52	0.24
Passenger Truck	91	9.1	0.91	0.13

Sample sizes are 16 for passenger car and 14 for passenger truck.

The results of the field measurement of cold starts confirms that vehicles in the in-use fleet have significant incremental increases in fuel use and emission rates during the first few minutes after starting the engine, when the engine and exhaust system have previously reached ambient temperature. The average cold start incremental fuel use ranges from 71 grams per start to 91 grams per start for passenger cars and passenger trucks, respectively. For example, if an urban area had 1 million vehicles with cold starts each weekday, the incremental fuel use for the cold start would be between 25,000 and 32,000 gallons, or approximately 6 million to 8 million gallons per year if there were 5 starts per week for 50 weeks per year. The cold start increment for CO emissions averages 9.1 grams per start for both passenger cars and passenger trucks, which can amount to over 2,000 metric tons of CO released annual for an area with 1 million vehicles that experience 250 cold starts per year. The cold start increment for HC emissions ranges from 0.52 grams per start to 0.91 grams per start for passenger cars and passenger trucks, respectively, amounting to 130 to 230 metric tons annually under similar activity assumptions. The cold start increment for NO_x ranges from 0.24 grams per start for passenger cars to 0.13 grams per start for passenger trucks, or 60 and 30 metric tons annually, respectively. Of course, the actual cold start fuel use and emissions in an urban area will depend on the actual number of vehicles, their distribution by vehicle type, the number of cold starts. Furthermore, additional factors that affect cold start emissions, such as variations in ambient temperature, require further real-world study.

Figure 11 through Figure 14 show the trends of fuel use, engine speed, engine coolant temperature, catalyst temperature, and NO_x emission rates using a 2008 Honda Fit as an example.

The engine speed was high compared to the hot-stabilized rates, and underwent a gradual reduction to a stabilized value. The engine coolant temperature was near the ambient temperature prior to the engine start, and increased monotonically until reaching a steady state value after engine start. The catalyst temperature followed the same trend as the engine coolant temperature. In this case, it took more than 15 minutes for the engine coolant temperature and the catalyst temperature to reach steady state values. However, the fuel use and NO_x emissions rates reached steady-state values within 7 and 3 minutes, respectively.

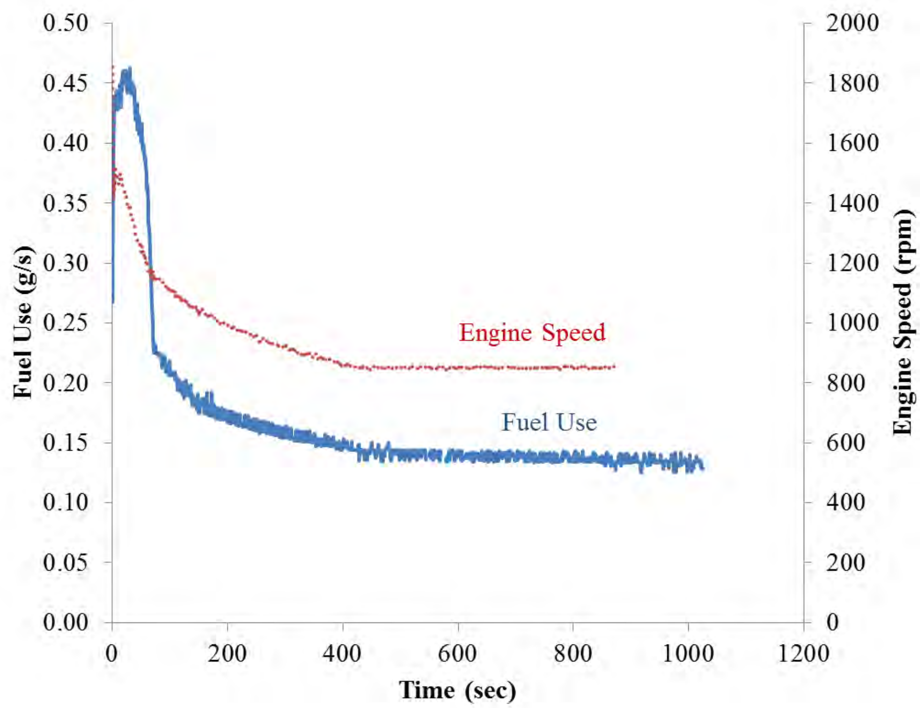

Figure 11. Trend of engine speed and fuel use of the cold start measurement for a 2008 Honda Fit, engine started at time 0

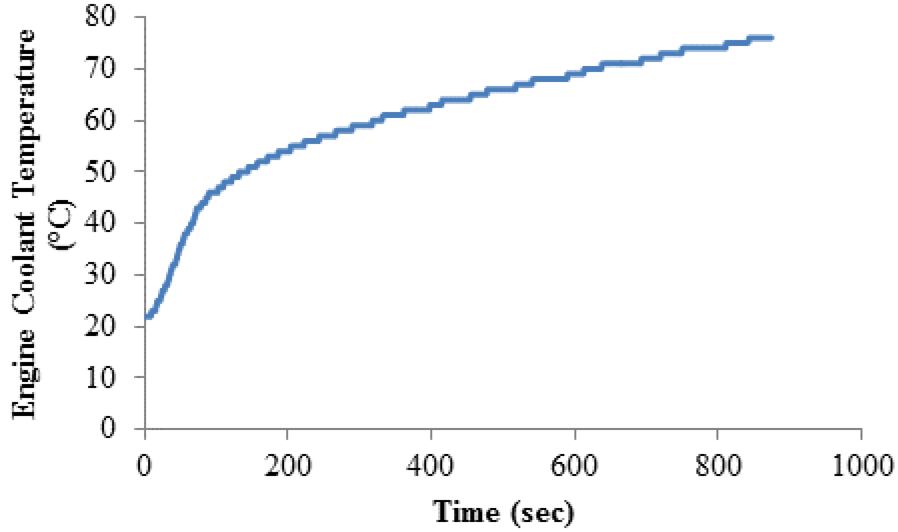

Figure 12. Trend of engine coolant temperature of the cold start measurement for a 2008 Honda Fit, engine started at time 0

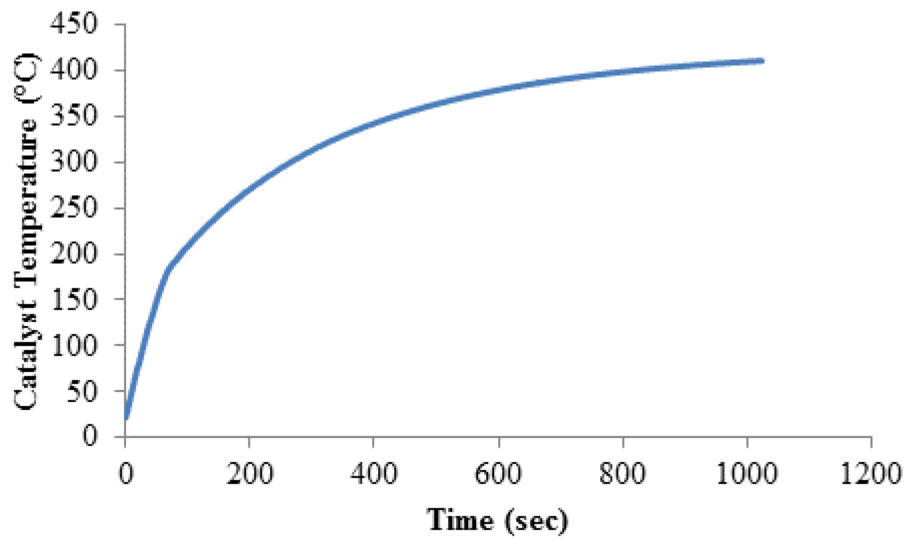

Figure 13. Trend of catalyst temperature of the cold start measurement for a 2008 Honda Fit, engine started at time 0

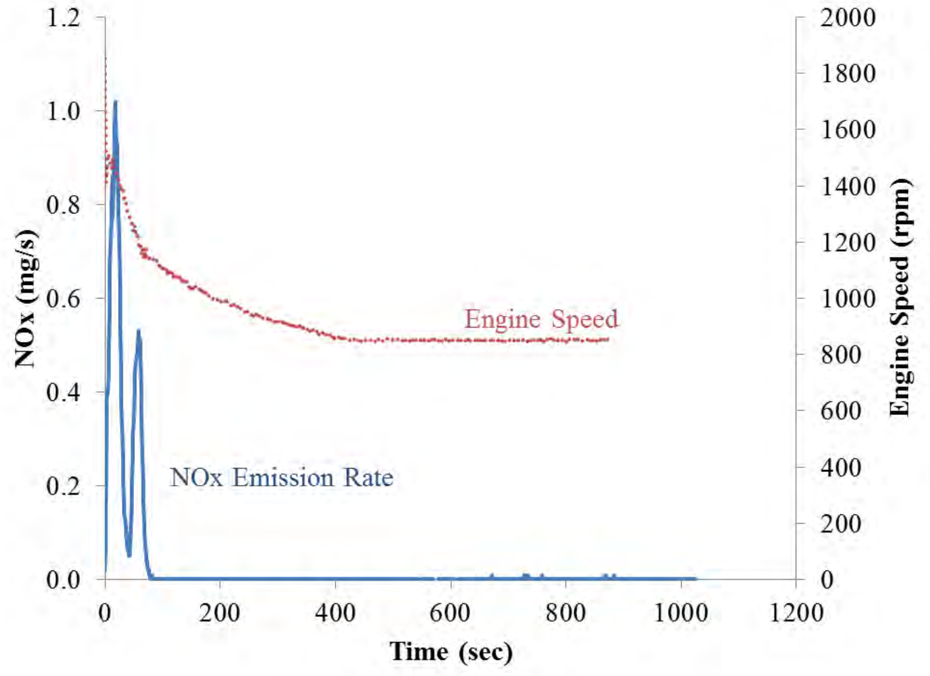

Figure 14. Trend of Nitrogen oxides emission rates of the cold start measurement for a 2008 Honda Fit, engine started at time 0

CHAPTER 5 EMISSIONS AND FUEL USE ESTIMATION TESTING IN CORSIM

TESTING OF I-4 ROUTE IN CORSIM

The CORSIM network file for the eastbound segment of the I-4 route in Orlando was already created as part of two separate FDOT projects. This file served as the starting point for data analysis on this project. To obtain traffic volume data that would replicate field conditions, the UF research team used the UFTI Statewide Transportation Engineering Warehouse for Archived Regional Data (STEWARD) (Statewide Transportation Engineering Warehouse for Archived Regional Data, 2013). In this archive, transportation engineers can look at a specific day and time and get traffic volumes, speeds, and occupancies on I-4, as well as many other roads, as recorded by detectors. For the first run, the data from STEWARD appeared to be faulty. The reported volume increased significantly from one detector to the next, when there was only a single off-ramp between the two detectors. For the other three runs, the data from STEWARD seemed logical.

The traffic volumes were entered into the CORSIM input file. The average I-4 route simulation travel time was calculated by summing the average link travel time outputs for all links that comprised the I-4 route. The goal of the initial testing was to match the travel times in the simulation within 10% of the actual travel times. For runs 2 and 3, this was the case. For run 4, which was by far the slowest and most congested run in the field, the travel time did not match up very well. The field travel time for run 4 was 15 minutes 45 seconds. To get the simulation travel time to match more closely with this travel time, the UF research team tried inputting the volumes that were used in this network in a previous project (Elefteriadou, et al., 2012). These volumes are generally a good representation of the recurring traffic congestion on I-4 during the afternoon peak period. The simulation travel time matched up much more closely with the field travel time when these volumes were used.

Comparing Emissions Totals for Separate Runs

Fuel use and emissions for four runs on a specific segment of I-4 in the Orlando area were measured for a Honda Pilot. The empirical fuel use and emissions for these four runs were estimated in two ways: (1) based on summing 1 Hz reported fuel use and emissions rates inferred from the PEMS measurements only on this segment, for each run; and (2) using a modal model of fuel use and emission rates, calibrated from all measurements of the Pilot on a larger set of routes, weighted by the time in each mode observed on the selected segment of I-4. There is inherent variability in second-by-second (1 Hz) measurements of fuel use and emissions. To obtain a statistically stable estimate of the *average fuel use and emissions* on this segment of I-4 would require far more than four runs. Thus, the use of four runs is intended to be a preliminary illustration of a methodological approach. However, the total amount of 1 Hz data from which modal emission rates were estimated for the Pilot is over 10 hours, which is substantially more than needed to calibrate a VSP-based modal model (Frey et al., 2008). Thus, the modal model for the Pilot is a more robust basis for estimating average emission rates for any road segment, if the vehicle trajectory for that segment is known, than merely extracting a limited number of runs comprising a very small empirical data set.

Table 14 summarizes the observed empirical results of a limited set of measurements on the Honda Pilot. For example, for four runs on I-4, the travel time varies from 8 to 16 minutes, and the NO emissions vary from approximately 250 to 1500 mg. The relative range of variability in the NO emissions of a factor of six (comparing the highest to lowest value) is highly influenced by short-term episodic events such as accelerations that may vary from one run to another.

Table 14. Measurements of Honda Pilot Fuel Use and Emissions on Selected Section of I-4 in Orlando

I-4 Driving Run #[1]	Travel Time	NO (mg)	HC (mg)	CO (mg)	Fuel (g)
1	8 min 23 sec	1500	450	2700	890
2	8 min 39 sec	250	490	3100	990
3	9 min 40 sec	590	600	2800	1060
4	15 min 45 sec	490	920	3400	1240

[1] This refers to the Honda Pilot being driven from the south boundary to the north boundary of the I-4 freeway section used for the freeway driving experiment.

Table 15 presents the emissions and fuel consumption values determined from the in-field VSP modes and the modal rates from Table 9. The percentage of time spent in each VSP mode is multiplied by the respective modal average rates that were calibrated from a larger set of measurements of the Honda Pilot beyond the four runs, summed over all modes, and multiplied by total travel time. For NO emissions on the selected segment of I-4, the results range from approximately 800 to 1000 mg. This is a narrower range than the observed individual measurements on this route. This predicted range is more typical of the average result expected on this road segment. In general, there is less relative run-to-run variability in the predictions using the VSP modal model than based on direct use of the 1 Hz data on a given road segment.

Table 15. VSP Modal-Based Estimates of Honda Pilot Fuel Use and Emissions on Selected Section of I-4 in Orlando

I-4 Driving Run #[1]	NO (mg)	HC (mg)	CO (mg)	Fuel (g)
1	670	550	2660	950
2	660	560	2640	960
3	710	600	2830	1030
4	790	760	3940	1240

[1] This refers to the Honda Pilot being driven from the south boundary to the north boundary of the I-4 freeway section used for the freeway driving experiment.

There is inherent variability in short-term measurements of vehicle emissions. For example, the measured NO emission rates range from 250 to 1500 mg among four runs, at least in part because of differences in the distribution of VSP from one second to another that lead to variability in emission rates. In previous work, a data requirement of at least three hours of 1 Hz measurements has been determined to be necessary to develop statistically stable VSP modal average emission rates (Frey *et al*., 2008). Thus, the recommended approach is to use a VSP modal model calibration from at least three hours of measured data for a given vehicle, combined with observations or estimates of the distribution of time spent in each VSP mode, such as based on a measured or simulated speed trajectory, respectively, to estimate an average, vehicle specific emission rate for the trajectory. For the example of the Honda Pilot, the VSP modal model that was obtained from the field data represents an aggregate of a large portion of data (over 10 hours). The key indicator of model performance is whether, on average over many runs, the model predicts trajectory average emission rates that are similar to those observed in the field. However, it is not expected that a model based on VSP modal averages can exactly predict the run-to-run variability for short duration trajectories. However, it is not necessary to do so either, since traffic emissions are based on the aggregated effect of multiple vehicles operating on a road segment. Thus, an accurate estimate of how the trajectory average emissions rates respond to changes in the trajectory is desirable and achievable. Here, a comparison is made for only four trajectories, based on comparing modal model results in Table 15 versus observational measurements in Table 14. For example, the mean of the four observed runs in Table 9 is 710 mg for NO emissions. However, given a standard deviation between the runs of 550 mg NO and sample size of only 4, the 95% confidence interval for the mean observed emissions will range from 60 mg to 1360 mg NO. This interval encloses the modal model average estimate of 900 mg NO. There are two key findings from this comparison: (1) the magnitude of the modal model-based estimate is similar to that from the average of observed measurements for four runs; (2) the statistical power of the comparison is low based on only four runs. Likewise, the 95% confidence intervals of the mean estimates for HC emissions and fuel use enclosed the predicted mean from the VSP modal model.

Simulations corresponding to the field conditions for runs 1-3 were performed in CORSIM. A total of six replications were performed using a set of inputs in CORSIM that produced similar travel times to those observed in field runs 1-3. The average emissions and fuel consumption results for vehicle types 1 and 2 were obtained from the outputs. Since both vehicle types 1 and 2 are passenger cars, the emissions and fuel consumption values for these vehicle types were averaged to obtain average values for a typical passenger car. The average results from the three field runs (runs 1, 2, and 3) and six simulation replications are shown in Table 16.

Table 16. Average Emissions and Fuel Consumption from Field and Simulation Runs

	Average Travel Time (min)	NO (mg)	HC (mg)	CO (mg)	Fuel Consumption (g)
Field	8.90	780	520	2860	980
Simulation	9.14	420	380	1830	814

This table shows that the emissions and fuel consumption values from the field and simulation replications, while somewhat different, have the same general magnitude. These differences are largely due to the fact that the field runs were based only on three runs of a single vehicle, while the simulation replications were based on all passenger cars across all six replications.

Comparing Percent Time Spent in Each VSP Mode

To evaluate how well the traffic simulation program can replicate real world vehicle activity, the percentage of time several simulated vehicles spent in each VSP mode over the length of the I-4 study section was compared to the same values for the Honda Pilot. With this approach, the validity of using the VSP based emissions calculations in CORSIM can be examined. Histograms showing the percent of time spent in each mode can be seen in Figure 15, Figure 16, and Figure 17. CORSIM employs ten driver types, with driver type 1 corresponding to a very conservative driver and driver type 10 corresponding to a very aggressive driver. These driver types affect the relative acceleration rates of the simulated vehicles.

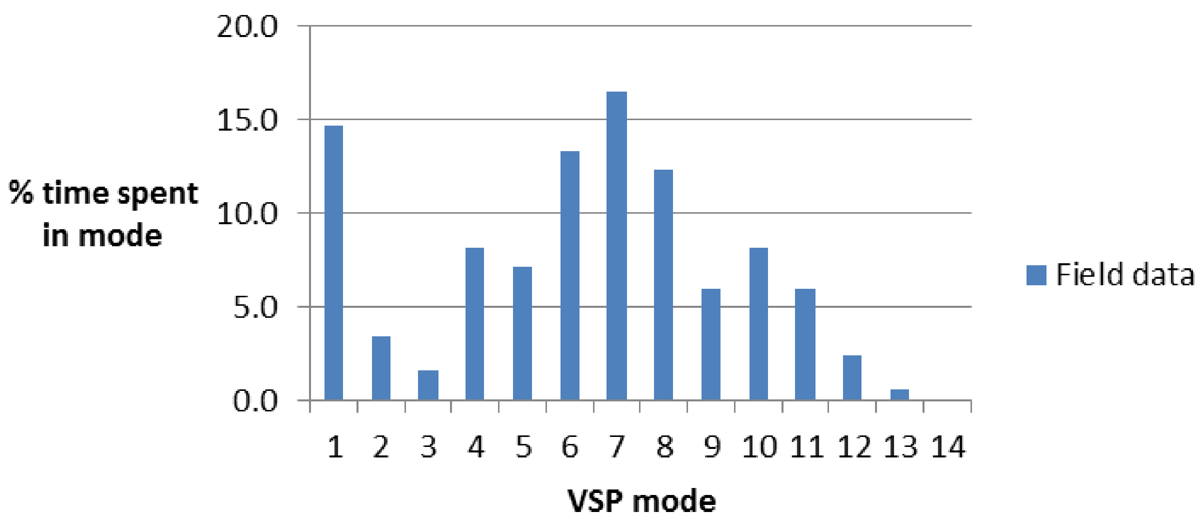

Figure 15. I-4 Freeway Run 1 VSP mode frequencies (Honda Pilot only)

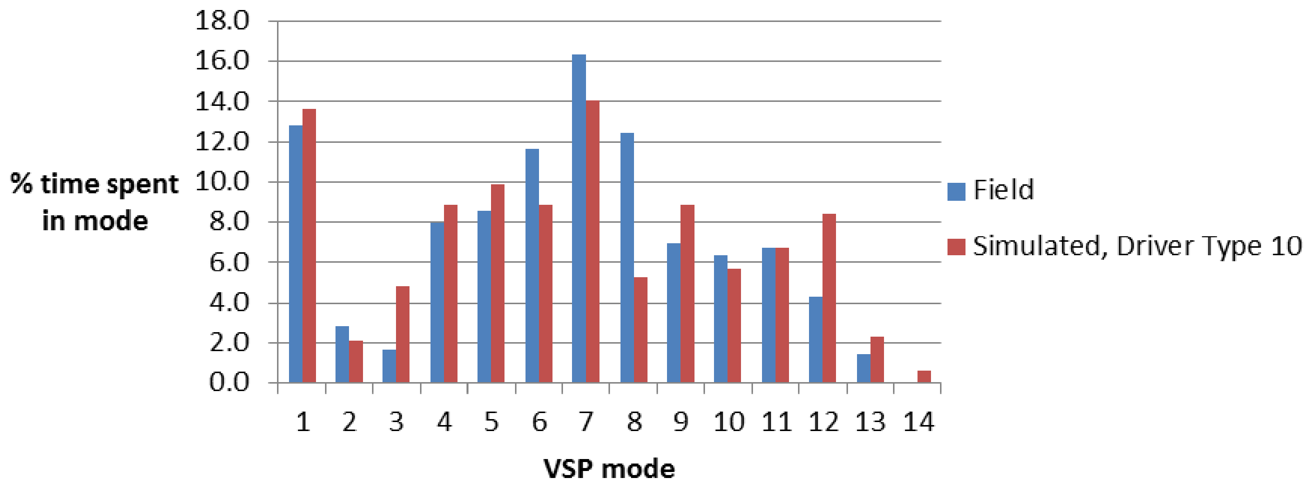

Figure 16. I-4 Freeway Run 2 VSP mode frequencies (Honda Pilot and Simulated Vehicle, Driver Type 10)

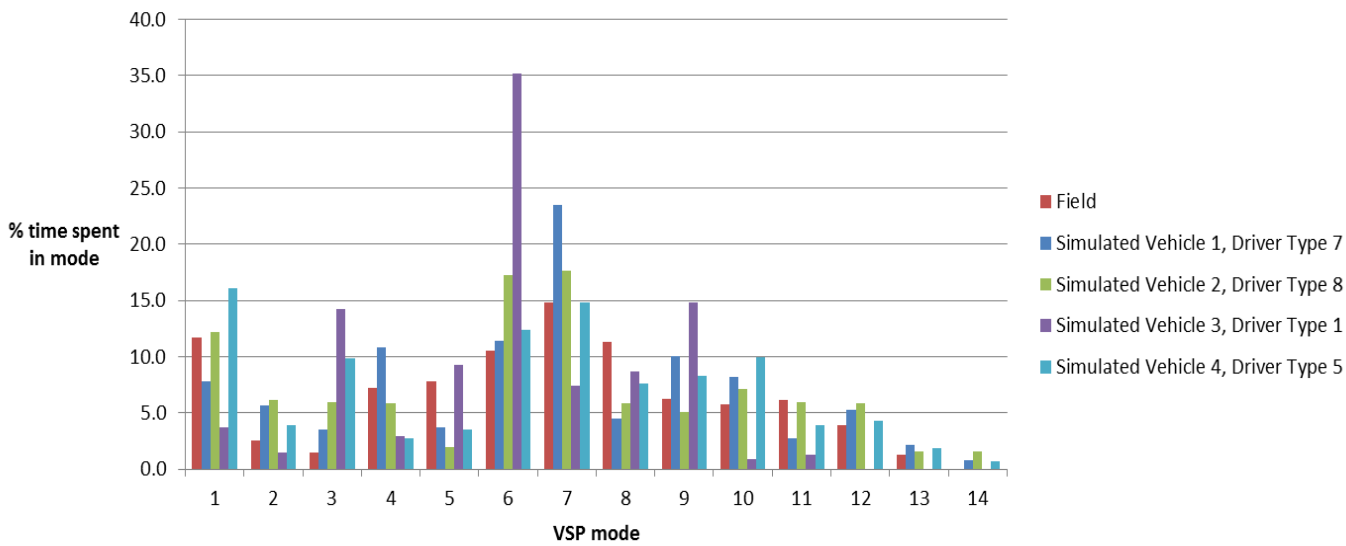

Figure 17. Freeway Run 3 VSP mode frequencies (Honda Pilot and Multiple Simulated Vehicles)

Analysis for this approach was only done for the uncongested runs (1-3). To simplify the process of calibrating the simulated facility travel time to the facility field travel time, the simulation period was limited to 15 minutes. The drawback to this approach is that there was a limited number of vehicles that traversed the entire length of the facility during this simulation period. However, several vehicles were identified for comparisons: one for simulated run 2 and four for simulated run 3.

Reviewing the histograms, there are differences between the field vehicle and the simulated vehicle for percent time spent in each VSP mode. This can account for some of the differences in comparing simulated data to empirical data. The differences were studied on a mode by mode basis for the simulated versus the field vehicles. Figure 16 shows that the simulated and field vehicle for run 2 spent approximately the same amount of time in each VSP mode. To further analyze the differences between the simulated and field vehicles, the average absolute difference in the amount of time a simulated vehicle spent in a VSP mode versus the field vehicle was computed for each simulated vehicle. This value was obtained by calculating the absolute difference for each VSP mode and then averaging across all 14 VSP modes. Table 17 shows these values for runs 2 and 3.

Table 17. Average Absolute Difference in VSP Modal Times from Field Vehicle for All Modes (I-4 Segment)

Simulated Vehicle	Driver Type	Average Absolute Difference (s)[a]
Run 2	10	9.4
Run 3-1	7	16.5
Run 3-2	8	13.6
Run 3-3	1	33.0
Run 3-4	5	14.9

a. The average (across all 14 VSP modes) of the absolute difference in the amount of time the simulated vehicle spent in a VSP mode versus the field vehicle

Based on the values in Table 17, it would appear that the driver of the field vehicle most closely matched up with driver type 10 (most aggressive) in CORSIM and least closely with driver type 1 (most conservative). This might lead one to think that the lower the driver type in CORSIM, the higher the average difference would be, but that is not the case, as the vehicle that has driver type 5 has less difference than the vehicle that has driver type 7.

The average VSP mode, which can be seen in Table 18, is actually similar for most of the runs. For run 2, the average mode of the field data only differs from the simulation data by 0.01. For run 3, the average mode of the field data differs from the average mode of the 4 simulated runs by 0.31. While there are differences in the percentages of time spent in each VSP mode for simulated versus field data, the average modes come out to be quite comparable.

Table 18. Average VSP Mode (I-4 Segment)

Vehicle	Driver type	Average VSP Mode #
Field run 1	N/A	3.25
Field run 2	N/A	6.52
Field run 3	N/A	5.91
Simulated run 2	10	6.51
Simulated run 3	7	6.53
Simulated run 3	8	6.22
Simulated run 3	1	5.97
Simulated run 3	5	6.14
Average of all simulated run 3	N/A	6.22

To further evaluate the differences in the amount of time the field and simulated vehicles spent in each VSP mode, the average amount of time the field and simulated vehicles spent in each VSP mode was computed. This was done by averaging the amount of time in each VSP mode across runs 1, 2, and 3 for the field vehicle and across all 5 simulated vehicles from runs 2 and 3 for the simulated vehicle. These values are shown in Table 19. These values were then used along with the Honda Pilot VSP emissions and fuel consumption factors (shown in Table 9) to obtain predictions of the emissions and fuel consumption for each VSP mode based on the field VSP mode travel times and simulation VSP mode travel times.

Table 19. Average Amount of Time Field and Simulated Vehicles Spent in Each VSP Mode

VSP Mode	Average Field Travel Time in VSP Mode on the Segment (s)	Average Simulation Travel Time in VSP Mode on the Segment (s)
1	67	55
2	15	20
3	8	40
4	40	32
5	40	29
6	60	89
7	81	80
8	61	33
9	33	49
10	34	33
11	32	21
12	18	24
13	6	8
14	0	4
Total	495	517

The NO, HC, and CO emissions predictions for each VSP mode are shown in Table 20. The CO_2 and fuel consumption predictions are shown in Table 21. These tables show that the amount of emissions and fuel consumption predicted for each VSP mode using the field and simulation VSP mode travel times generally agree with one another. While there are some differences in the emission or fuel consumption predictions for certain VSP modes, these differences did not have a large impact on the total predicted emissions and fuel consumption values. The total field and simulation emission and fuel consumption predictions were all within approximately 4 percent of one another.

Table 20. Field and Simulation Predicted NO, HC, and CO Emissions by VSP Mode

	Predicted NO (mg)		Predicted HC (mg)		Predicted CO (mg)	
VSP Mode	Field	Simulation	Field	Simulation	Field	Simulation
1	20	20	30	20	140	120
2	10	10	10	10	40	60
3	0	10	0	20	10	60
4	10	10	30	20	190	150
5	30	20	30	20	260	190
6	80	110	60	90	310	460
7	100	100	100	100	610	600
8	140	80	90	50	310	170
9	60	90	60	80	220	330
10	80	80	50	50	210	200
11	80	50	60	40	190	120
12	40	50	40	50	130	170
13	10	10	10	20	20	30
14	0	10	0	10	0	30
Total	660	650	570	580	2640	2690

Table 21. Field and Simulation Predicted CO_2 and Fuel Consumption by VSP Mode

	Predicted CO_2 (g)		Predicted Fuel Consumption (g)	
VSP Mode	Field	Simulation	Field	Simulation
1	110	90	30	30
2	30	50	10	10
3	20	80	0	20
4	120	100	40	30
5	180	130	60	40
6	340	500	110	160
7	560	550	180	180
8	500	270	160	90
9	290	440	90	140
10	310	300	100	100
11	320	210	100	70
12	200	260	60	80
13	70	90	20	30
14	0	50	0	20
Total	3050	3120	960	1000

TESTING OF NEWBERRY ROAD ROUTE IN CORSIM

The portion of the Gainesville route that was used for testing was a portion along Newberry Road, directly east of I-75. A CORSIM network had already been set up from a previous study (Washburn and Kondyli, 2006) that included the 3 traffic signals immediately to the east of I-75. Traffic volumes from the previous study were also used because the UF research team did not have access to detectors, as they did for the I-4 segment. The research team did, however, obtain the traffic signal timings from the City of Gainesville Traffic Management office. These actuated timings were input into the CORSIM file, and the research team again took the approach of comparing the amount of time spent in each VSP mode for the simulated versus the field data. Simulation travel times can be seen in Table 22.

Table 22. Simulation Travel Times (Newberry)

Vehicle	Driver Type	Travel Time (s)
1	5	37
2	8	35
3	2	38
4	6	34

In the field, the driver did not have to stop at any of the three signalized intersections that were part of the CORSIM network in any of the four runs. Also, the driver did not stop at the two signalized intersections immediately upstream of these intersections for any of the four runs. This is unusual for this stretch of arterial, but it can be explained by the reduced congestion because of data being collected during spring break for UF students. The four field runs along the stretch modeled in CORSIM were examined for the amount of time in each VSP mode. A histogram showing the percentages for each run can be seen in Figure 18.

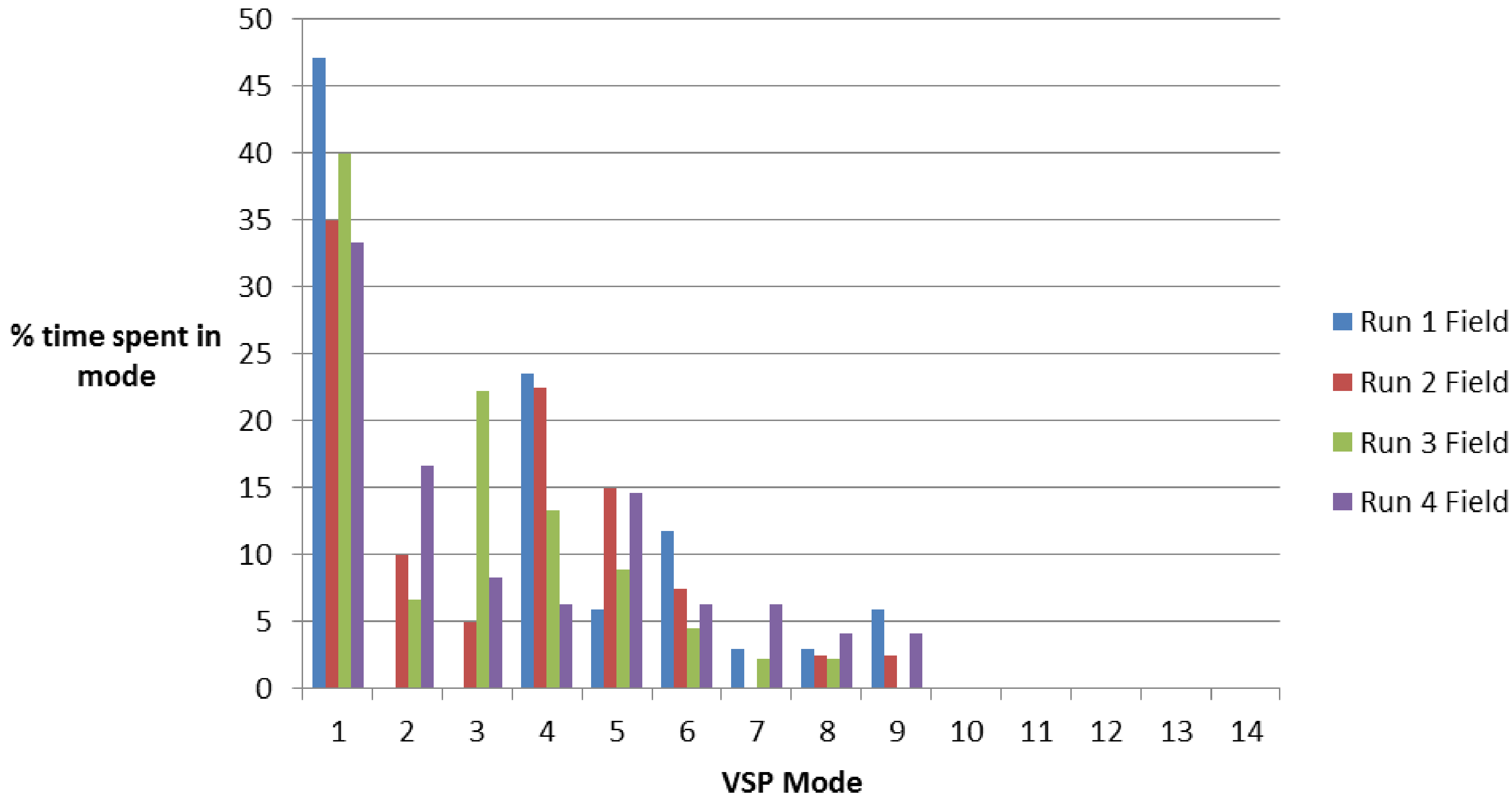

Figure 18. VSP mode frequencies, all field runs (Newberry Road segment)

Because the driver did not experience any stops at the signalized intersections in the field, simulated vehicles that did not experience stops were also examined. Four simulated vehicles, all of different driver types, were analyzed for VSP mode frequencies. To see how well the simulated vehicles match up with field driving, they were compared to the average of the field vehicles in terms of percent time in each mode. This comparison can be seen in Figure 19.

From Figure 18 and Figure 19, it is apparent that the simulated vehicles are not replicating the field vehicle very well in terms of VSP modes. In four trips, the field vehicle did not experience a VSP mode over nine for any second. All four of the simulated vehicles experienced VSP modes 12 or greater. This would suggest that simulated vehicles undergo higher accelerations than the driver of the field vehicle does, at least in segments with lower velocities, like on Newberry Road.

For the four field runs, the average field travel time was about 42 seconds. The average amounts of time in each VSP mode were computed for the field runs. Then the difference from that absolute average in each mode for each of the four simulated vehicles was computed, similar to the way it was computed for the analysis of the I-4 segment. For example, the average amount of time spent in mode 1 for the four field runs was 16 seconds. Simulated vehicle 1 spent 9 seconds in mode 1. The absolute difference is 7 seconds, and the differences of the other modes were computed in the same way and averaged for simulated vehicle 1. This average came out to be 2.77 seconds. The average differences from the average time in each VSP mode for the field vehicle can be seen in Table 23.

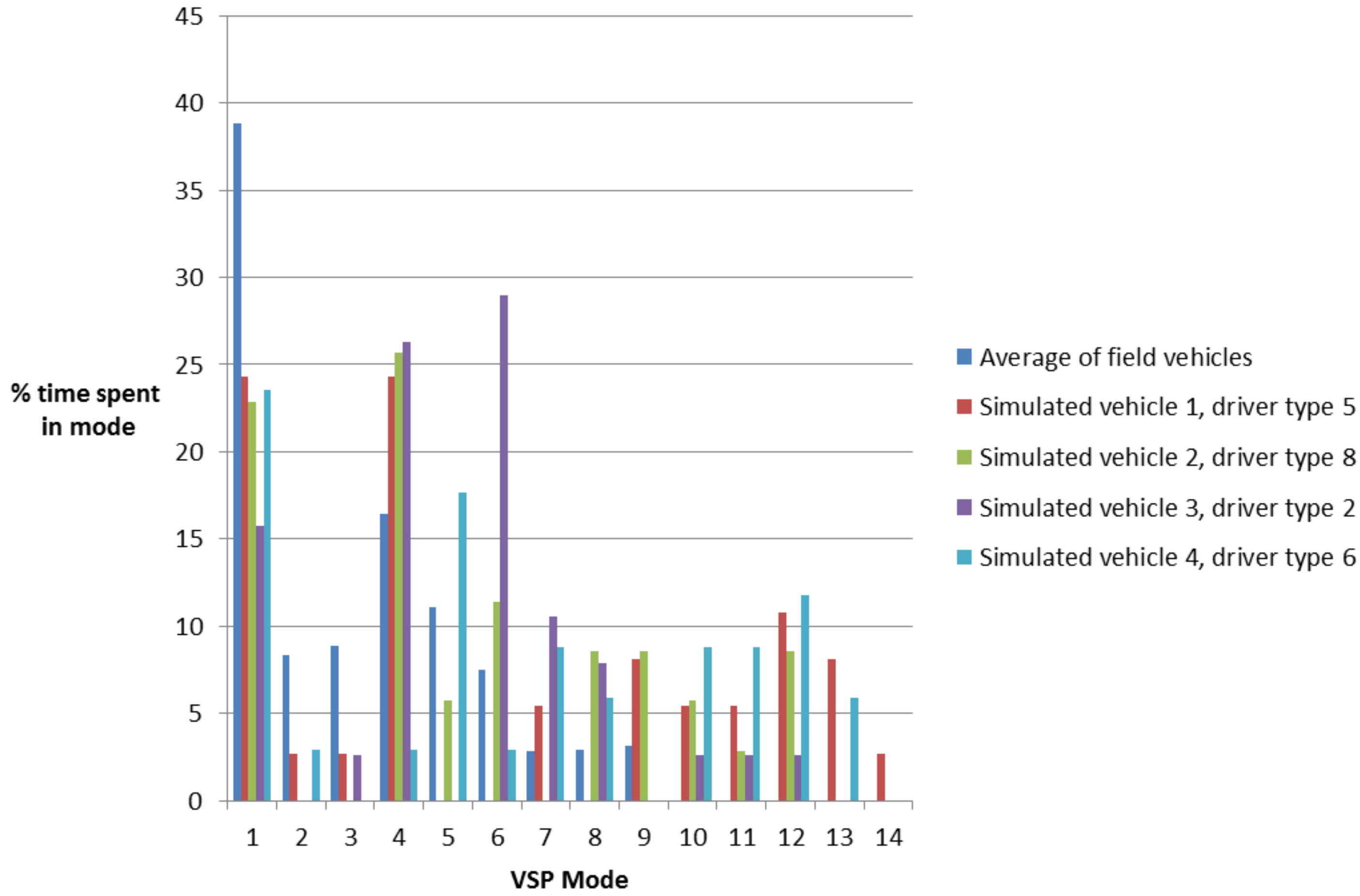

Figure 19. VSP mode frequencies, simulated vehicles and average of field vehicles (Newberry Road segment)

Table 23. Average Absolute Difference in VSP Modal Times from Field Vehicle Average for All Modes (Newberry)

Simulated Vehicle	Driver Type	Average Absolute Difference (s)[a]
1	5	2.77
2	8	2.34
3	2	2.98
4	6	2.80

a. The average (across all 14 VSP modes) of the absolute difference in the amount of time the simulated vehicle spent in a VSP mode versus the field vehicle

Table 23 suggests that the driver in the field is closest to driver type 8, of the four driver types examined. This is somewhat unexpected, considering that the field vehicle did not undergo the high VSP modes, as the simulated vehicles did. Because the field vehicle seemed to have lower VSP modes than the simulated vehicles did, one might think that a conservative driver type might match up most closely, but this is not the case. This is a limitation of this mathematical approach on such a short segment. One big difference in any of the 14 modes can lead to a large average difference.

In Table 24, the average VSP mode can be seen for all four of the field runs and for each simulated vehicle. This is another suggestion that the simulated vehicles along this stretch of arterial are producing VSP modes that are way too high. The field vehicle averaged a VSP mode of 3.2 over four runs, while all four of the simulated vehicles average over 5. In this short arterial section, the VSP-based emissions model in CORSIM is not likely to predict emissions very accurately because it is not predicting the VSP very accurately. In order to get the VSP modes to match more closely, one could experiment with the acceleration settings in CORSIM. It is possible that the default settings are producing unrealistically high accelerations for segments with low speeds, like the Newberry Road segment. If the acceleration rates were lowered, it is possible that the VSP modes would resemble the field driving behavior more closely.

Table 24. Average VSP Mode (Newberry)

Vehicle	Driver Type	Average VSP Mode
Field	N/A	3.20
Simulated Vehicle 1	5	6.32
Simulated Vehicle 2	8	5.60
Simulated Vehicle 3	2	5.26
Simulated Vehicle 4	6	6.59

Based on the vehicle emission and fuel consumption rate testing efforts from this project and other related efforts, the rates for each of 14 VSP modes, shown in Table 25, were recommended to be implemented in the CORSIM executable (version 6.5+) that is distributed publicly to users. The values in this table are based on 15 test vehicles, which correspond to the vehicles represented in Table 10(a) and (b).

Table 25. Average Fuel Use and Emission Rates for 15 Vehicles

VSP Mode	VSP Range (kW/ton)	Sample Size	Fuel (g/s)	NO as NO_2 (mg/s)	HC (mg/s)	CO (mg/s)	CO_2 (g/s)
1	Below -2	31,850	0.44	0.11	0.45	1.96	1.49
2	-2 – 0	9,885	0.58	0.09	0.45	2.14	1.89
3	0 – 1	44,197	0.37	0.03	0.24	0.87	1.18
4	1 – 4	15,563	0.91	0.14	0.68	3.83	2.97
5	4 – 7	15,102	1.25	0.18	0.89	4.93	4.07
6	7 – 10	14,706	1.58	0.22	1.08	5.67	5.08
7	10 – 13	12,836	1.87	0.29	1.28	6.49	6.01
8	13 – 16	10,847	2.16	0.38	1.46	7.18	6.88
9	16 – 19	7,932	2.42	0.50	1.61	9.02	7.66
10	19 – 23	6,829	2.72	0.64	1.86	12.98	8.58
11	23 – 28	4,704	3.01	0.87	2.04	15.66	9.42
12	28 – 33	2,481	3.33	1.19	2.29	22.73	10.40
13	33 – 39	1,514	3.80	2.20	2.61	44.24	11.78
14	Over 39	951	4.51	3.68	3.24	118.06	13.95

COLD START TESTING

As discussed in Chapter 3, the percentage of "cold start" vehicles was "hard-coded" to 10%. Thus, 10% of the vehicles that enter the simulation network after the initialization period has elapsed are given instantaneous fuel and emissions values equal to the average of the excesses of the 30 tested vehicles discussed in the previous chapter. Testing of CORSIM confirmed that 10% of the entering vehicles were receiving the cold start excess values.

CHAPTER 6 SUMMARY AND RECOMMENDATIONS

In this project, previous work by the NCSU team on the use of a VSP-based approach to estimating emission and fuel consumption, as well as the analysis of cold starts, was extended. These results were then subsequently implemented into the CORSIM traffic simulation program and contrasted to a set of controlled field observations on a limited number of routes and vehicles.

VSP modal rates were measured for 15 vehicles, including 10 passenger cars and 5 passenger trucks, and cold starts were measured for 30 vehicles. From the field measurements of the 15 vehicles, the typical trend in the rates of fuel use and emissions indicate that the rates are lowest at idle, and increase monotonically with increasing positive VSP. Positive VSP represents conditions such as steady-speed cruising, acceleration, and hill climbing. Emission rates for negative VSP, which represent deceleration, coasting, or descending a hill, are typically much lower than for positive VSP. These qualitative trends are consistent among the measured vehicles. The magnitude of the fuel use rate is related to the size of the vehicle. Since all of the vehicles are certified to similar tailpipe exhaust standards for NOx, CO, and HC, there is not a clear trend in emission rate when comparing among vehicles. For example, it is not the case that an SUV would always have higher emission rates than a compact sedan, since both are certified to a similar standard.

After the successful implementation of the VSP modeling approach within CORSIM, field data collection was conducted for the purpose of further model testing and verification. These data were applied to the VSP model in CORSIM, and comparisons of simulation data to field data was performed. Although these tests were not extensive, they were sufficient to assure the research team that the VSP estimation approach was working as intended in the CORSIM simulation program.

Differences were found in the amount of time spent in each VSP mode between the field and in the simulation. However, these differences are likely due to constraints imposed by the car-following and possibly lane changing algorithms built into CORSIM, which govern the generation of the acceleration and deceleration rates that are key to estimating the VSP values. The differences also appear to have been dependent on the assigned driver type in the simulated vehicle, since it is very difficult to match one of the ten specific driver types in CORSIM with the actual behavior of the drivers who were involved in the field experiments.

Cold starts are known to contribute a significant amount of additional vehicle emissions, and prior to this project, neither CORSIM, or for that matter none of the widely used microscopic traffic simulation models (to the authors' best knowledge) accounted for the impact of cold start emissions. Cold start data were collected, and the average cold start excess emissions were inferred for 30 vehicles for each pollutant. CORSIM now has the ability to add an average cold start excess to each pollutant once a vehicle with a cold start is generated in the network.

The emissions estimation process in CORSIM has undergone a complete makeover through this project. For one, the emissions and fuel consumption rates are now based on the most current passenger vehicle fleet, and the VSP-based emissions and fuel consumption estimation approach has a much stronger analytical and empirical foundation than the previous approach used in CORSIM, and consequently is more accurate and robust. Furthermore, adding the cold start emissions logic to the CORSIM code further improves the accuracy of the emissions estimates. Traffic simulation users looking to also obtain realistic emission and fuel consumption outputs can now consider CORSIM for that task, without the requirement for any additional inputs. CORSIM will provide aggregated outputs for the following pollutants on a link by link basis: CO_2, CO, NO and HC, along with link-based fuel consumption estimates.

Recommendations for Future Work

A useful topic for a future study would be an investigation of how well the car-following model in CORSIM replicates real world driving behavior at the microscale level, and what can be done to improve the match with field measurements. Such a study could use the VSP modal model approach, similar to the testing done in this study. The analysis could start with just one driver type. Researchers could calibrate the input values of a particular driver type and then analyze vehicles from that driver type. Calibration could be based around trying to match VSP mode frequencies. If one was able to calibrate a driver type so that the VSP mode frequencies matched up more closely with a field driver, than the emissions of that field driver could be more closely predicted in CORSIM as well. Extensions to other driver types can be done in a similar fashion. Future studies should also evaluate the emissions and fuel use outputs of CORSIM under a wider range of traffic and roadway conditions.

The methodological approach demonstrated here for measurement and analysis of real-world emissions data can be replicated to incorporate a much larger vehicle sample, other vehicle measurement study areas, and additional vehicle types. Field measurement of vehicle activity, including speed, acceleration, and road grade, is useful to evaluation and calibration of the vehicle activity predictions of traffic simulation models. Field measurement of vehicle emissions is useful for calibrating emission models that are incorporated into traffic simulation models, and for empirically-based evaluation of traffic simulation model predictions. Field study design for data used to calibrate and evaluation traffic simulation models can take into account a wide range of factors, such as driver activity, vehicle type, fuel, study route, travel direction, time of day, day of week, and season, which also have implications for the observation of uncontrollable factors such as traffic congestion and ambient conditions.

This study has also demonstrated that PEMS can be used to measure cold starts, and that cold starts contribute significantly to trip emissions. Further work on real-world cold starts could take into account variability in ambient conditions, duration of soak time prior to an engine start, and vehicle activity during the cold start. The current CORSIM architecture simply does not allow for these types of factors to vary, unless additional vehicle attributes (e.g., soak time before entering the CORSIM network) can be specified.

Finally, with the new emissions and fuel consumption estimation modeling approach implemented in CORSIM, a myriad number of traffic control/ITS strategies can be more accurately evaluated for their environmental impacts.

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APPENDIX A

Figure 20. Gas zeroing tubes and weather station

Figure 21. PEMS device connection running from side window to tailpipe

Figure 22. Side view of instrumented Honda Pilot

Figure 23. PEMS connection to tailpipe

Figure 24. OBD connection

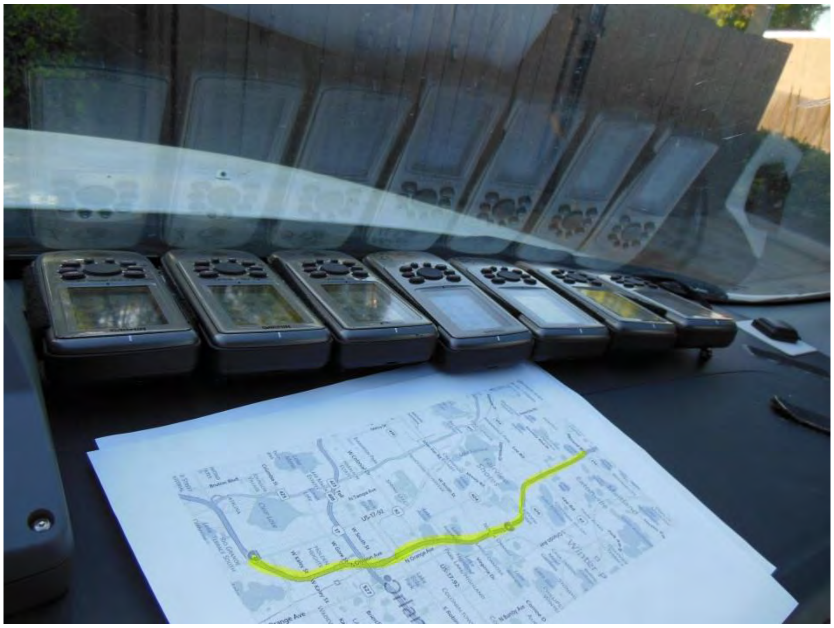


Figure 25. GPS devices

Figure 26. PEMS computer and laptop connected to OBD

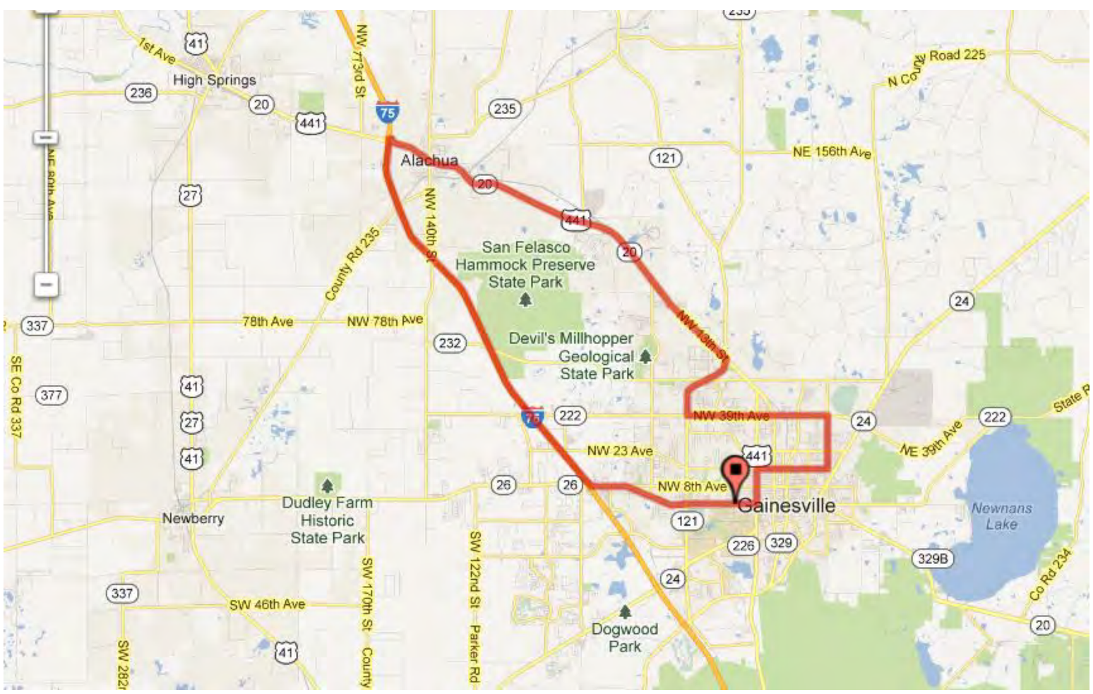


Figure 27. Entire route driven in Gainesville

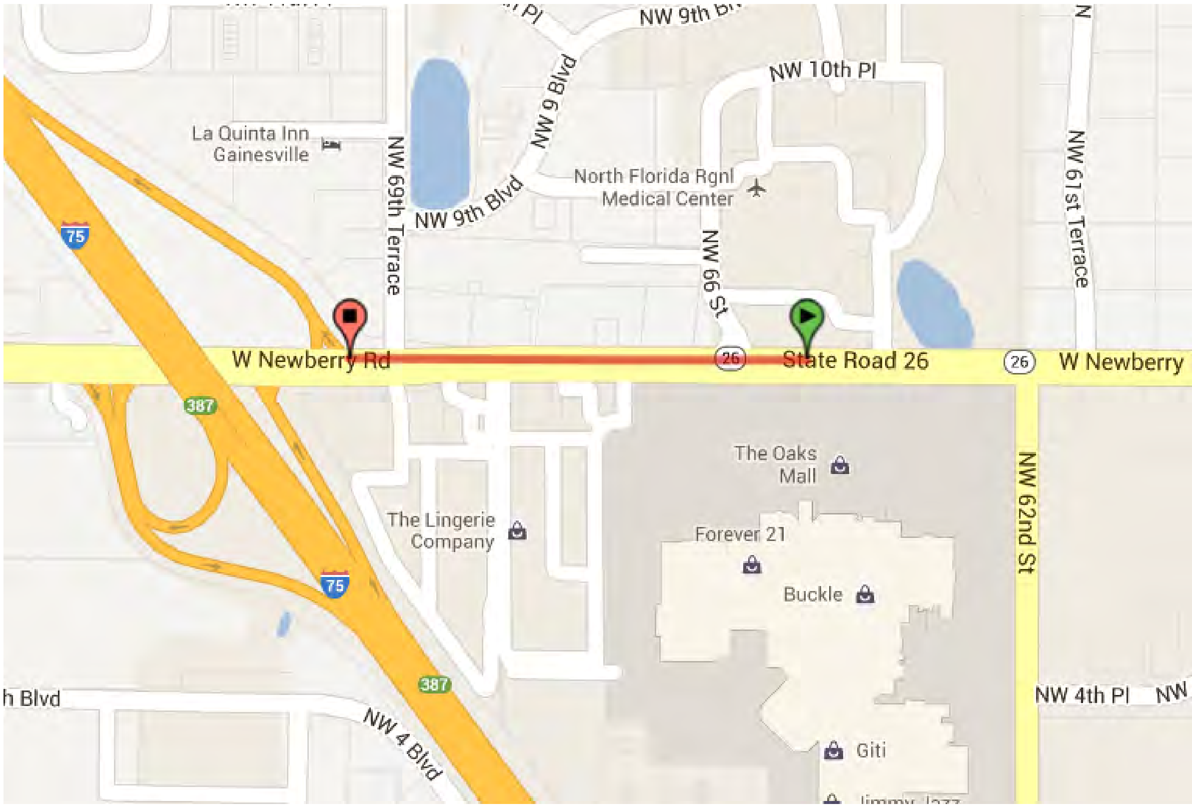


Figure 28. Route in Gainesville used for testing in CORSIM

(A) (B)

Figure 29. University Avenue near starting point. A) Front view, B) Rear view

(A) (B)

Figure 30. Newberry Road near Oaks Mall. A) Front view, B) Rear view

(A) (B)

Figure 31. Ramp to get on I-75 N. A) Front view, B) Rear view

(A) (B)

Figure 32. US 441. A) Front view, B) Rear view

(A) (B)

Figure 33. Right turn onto NW 34th Blvd. A) Front view, B) Rear view

(A) (B)

Figure 34. NW 34th Blvd. A) Front view, B) Rear view

(A) (B)

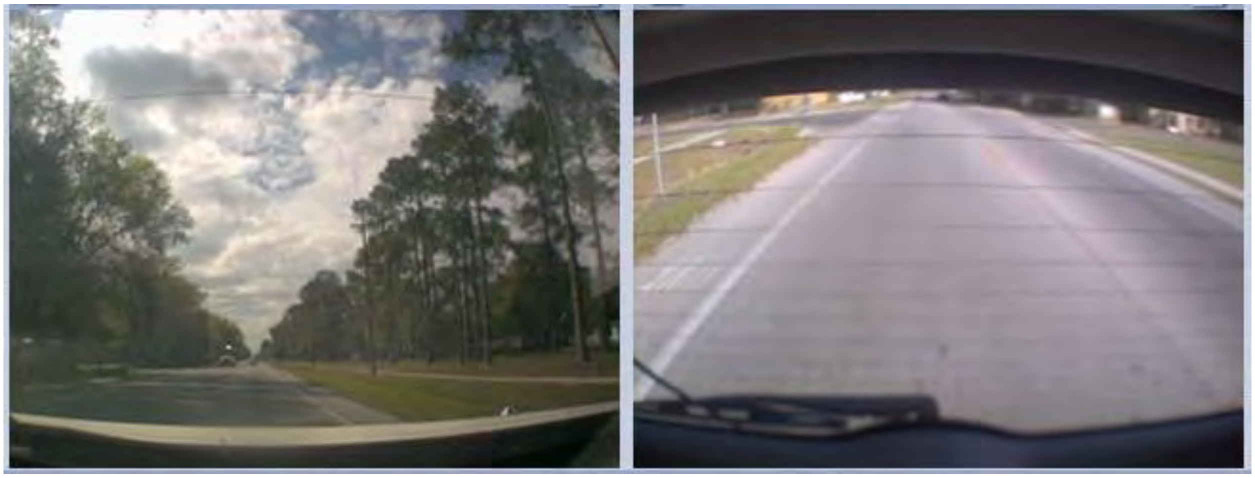
Figure 35. NW 39th Ave. A) Front view, B) Rear view

(A) (B)

Figure 36. Right turn onto NE 15th St. A) Front view, B) Rear view

(A) (B)

Figure 37. NE 15th St. A) Front view, B) Rear view



(A) (B)

Figure 38. NE 16th Ave. A) Front view, B) Rear view

(A) (B)

Figure 39. Left onto NW 13th St. A) Front view, B) Rear view

(A) (B)

Figure 40. NW 13th St. A) Front view, B) Rear view

(A) (B)

Figure 41. Right onto University Ave. A) Front view, B) Rear view

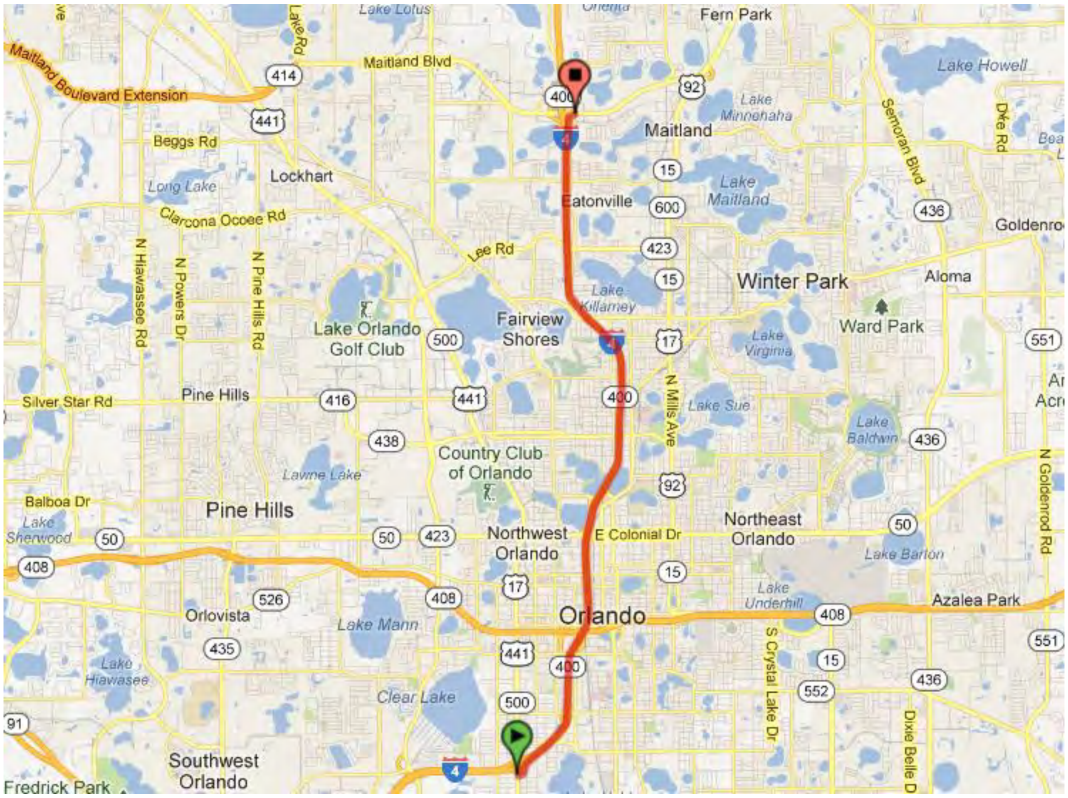
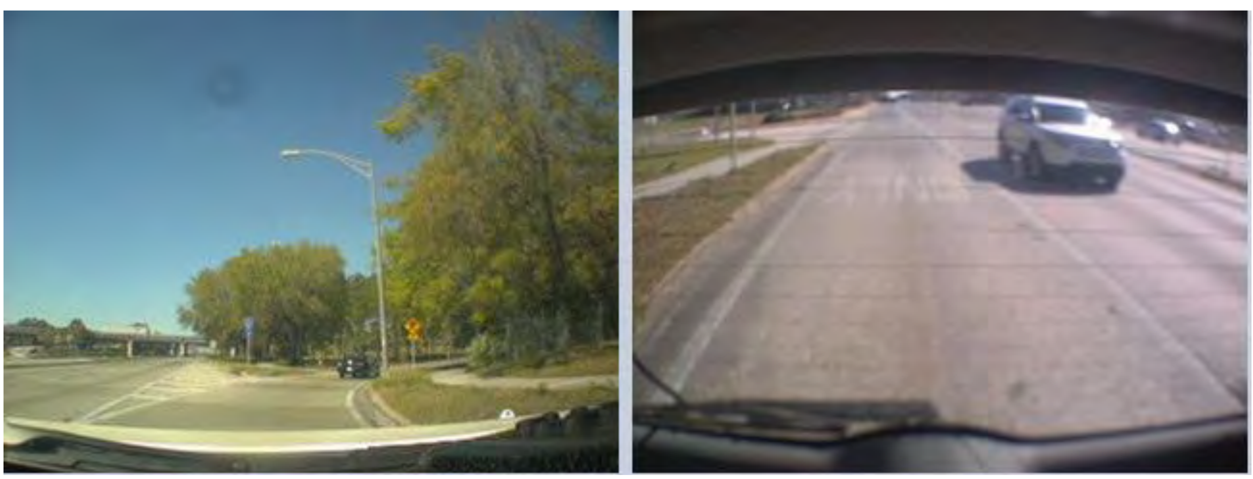


Figure 42. Orlando route (Martin, 2013)



(A) (B)

Figure 43. On ramp for I-4 E at S Orange Blossom Trail. A) Front view, B) Rear view

(A) (B)

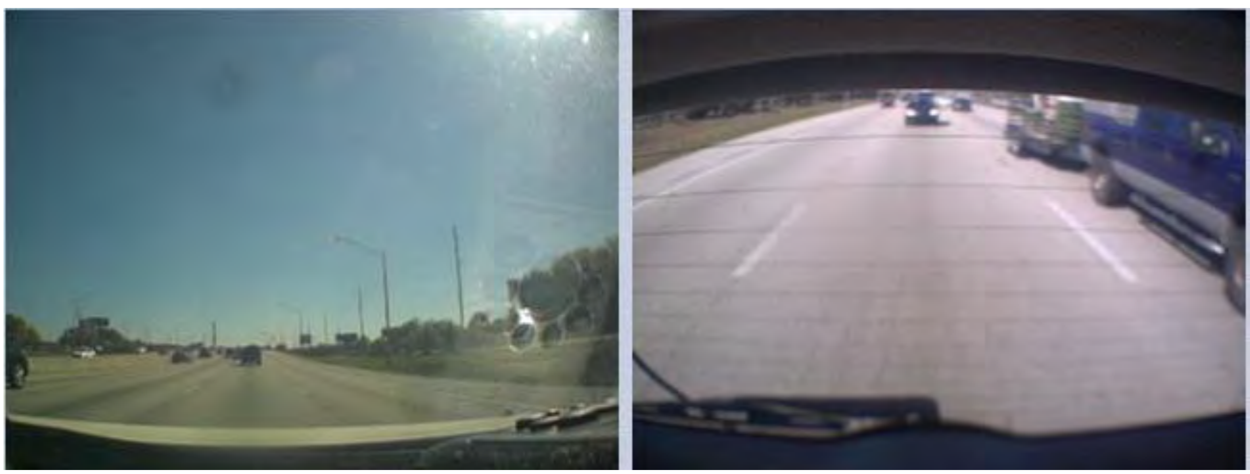
Figure 44. Merging onto I-4 E from S Orange Blossom Trail. A) Front view, B) Rear view

(A) (B)

Figure 45. I-4 E. A) Front view, B) Rear view

(A) (B)

Figure 46. Ramp to get on I-4 W from Maitland Blvd. A) Front view, B) Rear view



(A) (B)

Figure 47. I-4 W. A) Front view, B) Rear view

APPENDIX B

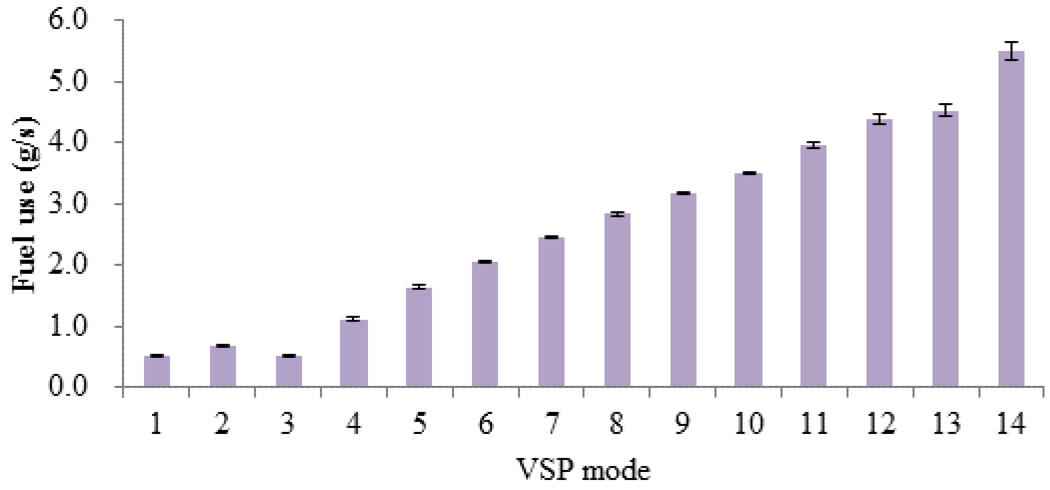


Figure 48. Average fuel use with 95% confidence intervals in each vehicle specific power mode for a 2004 Honda Pilot

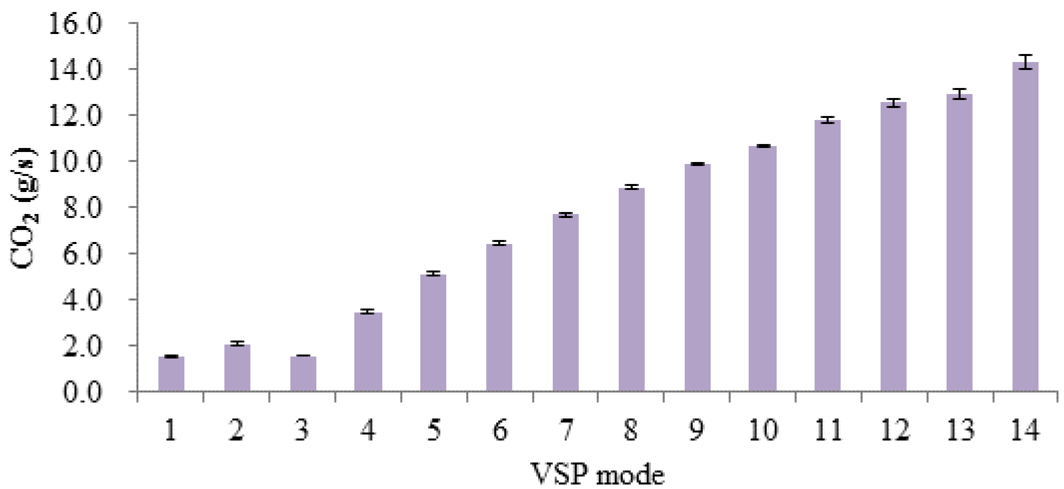


Figure 49. Average Carbon Dioxide with 95% confidence intervals in each vehicle specific power mode for a 2004 Honda Pilot

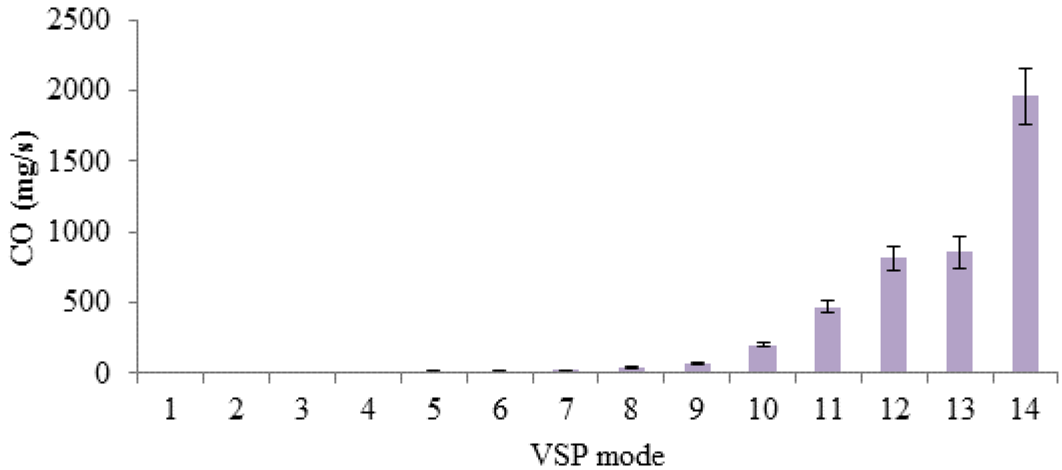


Figure 50. Average Carbon Monoxide with 95% confidence intervals in each vehicle specific power mode for a 2004 Honda Pilot

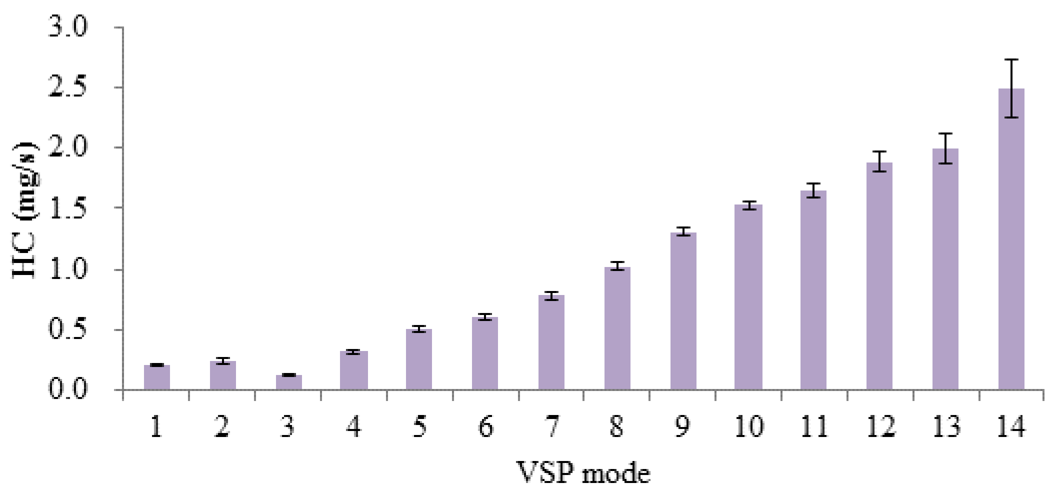


Figure 51. Average Hydrocarbon with 95% confidence intervals in each vehicle specific power mode for a 2004 Honda Pilot

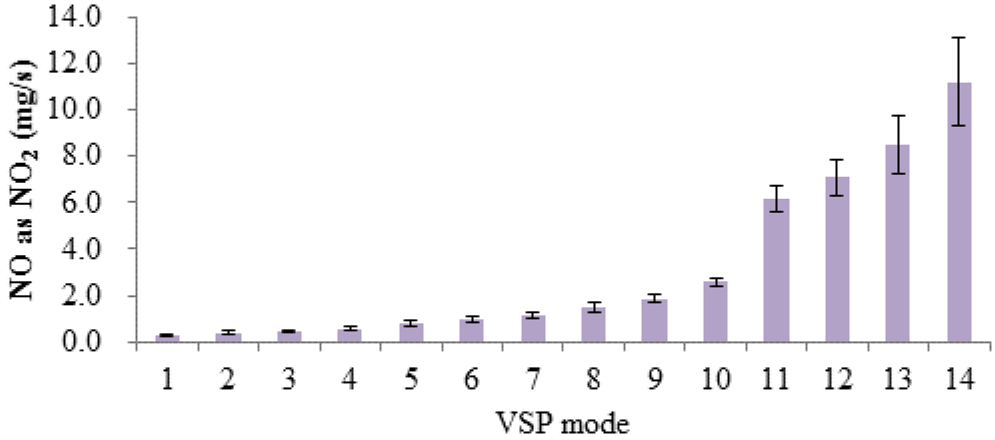


Figure 52. Average Nitrogen oxides with 95% confidence intervals in each vehicle specific power mode for a 2004 Honda Pilot

Table 26. Average Fuel Use and Emissions Rates with 95% Confidence Interval for a 2012 VW Passat

VSP Mode [a]	VSP Range (kW/ton)	Sample Size (s)	Fuel (g/s)			CO_2 (g/s)			CO (mg/s)			HC (mg/s)			NO as NO_2 (mg/s)		
			Mean	±	95%CI [b]	Mean	±	95%CI	Mean	±	95%CI	Mean	±	95%CI	Mean	±	95%CI
1	VSP ≤ −2	1,553	0.25	±	0.01	0.80	±	0.03	0.12	±	0.03	0.14	±	0.01	0.01	±	0.003
2	−2 ≤ VSP < 0	515	0.34	±	0.02	1.06	±	0.07	0.20	±	0.13	0.18	±	0.02	0.02	±	0.01
3	0 ≤ VSP < 1	2,039	0.26	±	0.01	0.83	±	0.02	0.15	±	0.04	0.13	±	0.01	0.003	±	0.001
4	1 ≤ VSP < 4	1,053	0.55	±	0.02	1.74	±	0.07	0.26	±	0.14	0.27	±	0.02	0.01	±	0.004
5	4 ≤ VSP < 7	824	0.84	±	0.03	2.67	±	0.09	0.65	±	0.24	0.40	±	0.03	0.04	±	0.01
6	7 ≤ VSP < 10	837	1.12	±	0.03	3.55	±	0.09	0.79	±	0.19	0.56	±	0.03	0.08	±	0.02
7	10 ≤ VSP < 13	600	1.28	±	0.04	4.06	±	0.12	1.23	±	0.29	0.60	±	0.04	0.12	±	0.09
8	13 ≤ VSP < 16	457	1.54	±	0.06	4.87	±	0.18	0.91	±	0.44	0.65	±	0.06	0.13	±	0.09
9	16 ≤ VSP < 19	371	1.78	±	0.07	5.63	±	0.21	0.89	±	0.29	0.66	±	0.07	0.25	±	0.27
10	19 ≤ VSP < 23	315	2.02	±	0.08	6.40	±	0.25	1.37	±	0.49	0.88	±	0.10	0.12	±	0.06
11	23 ≤ VSP < 28	283	2.40	±	0.09	7.61	±	0.29	1.14	±	0.35	0.97	±	0.11	0.33	±	0.37
12	28 ≤ VSP < 33	134	2.73	±	0.16	8.64	±	0.49	1.08	±	0.47	1.08	±	0.19	0.36	±	0.45
13	33 ≤ VSP < 39	79	3.22	±	0.17	10.19	±	0.55	1.49	±	0.93	1.32	±	0.30	0.31	±	0.38
14	VSP ≥ 39	48	3.94	±	0.22	12.48	±	0.69	4.16	±	6.18	1.62	±	0.41	0.21	±	0.10

[a] *VSP = vehicle specific power*

[b] *CI = confidence interval. The number shown in this table is one half of the 95% confidence interval. The complete interval is mean±95%CI*

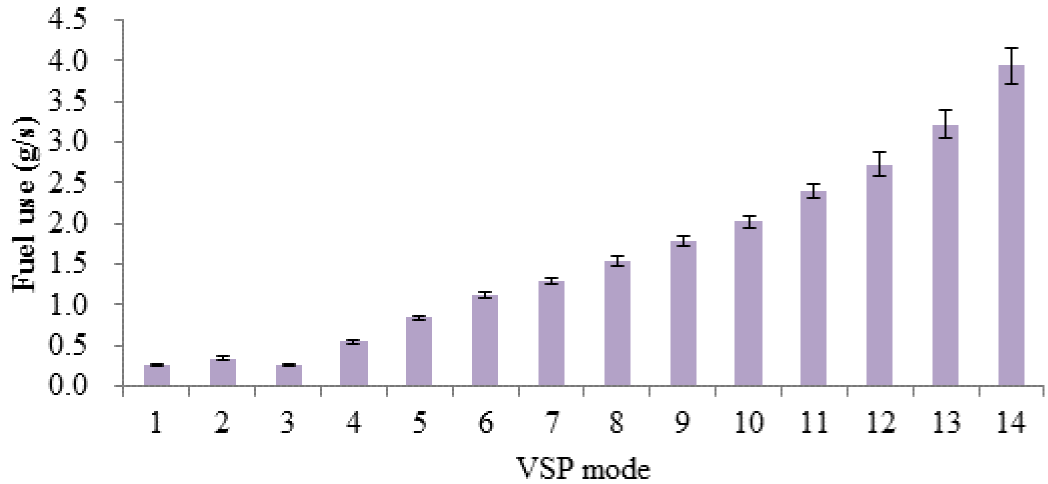


Figure 53. Average fuel use with 95% confidence intervals in each vehicle specific power mode for a 2012 VW Passat

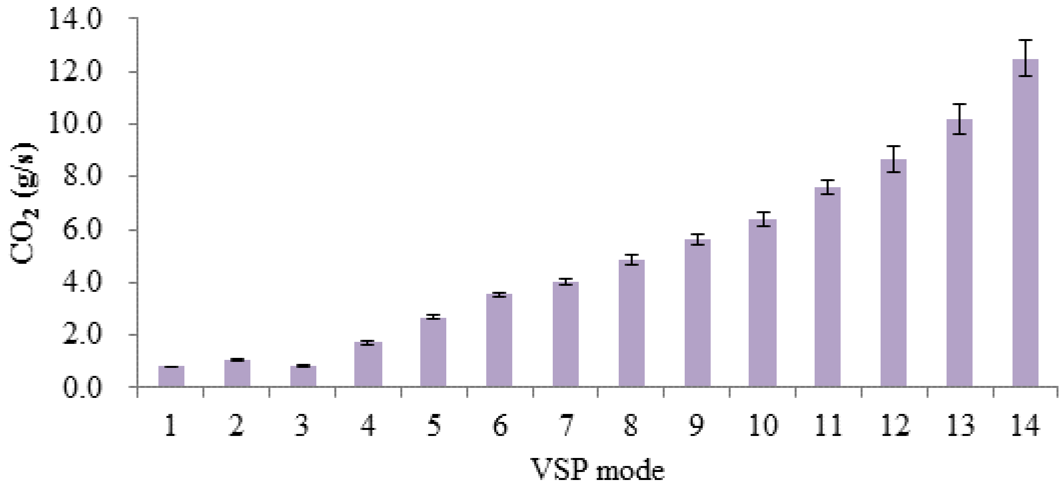


Figure 54. Average Carbon Dioxide with 95% confidence intervals in each vehicle specific power mode for a 2012 VW Passat

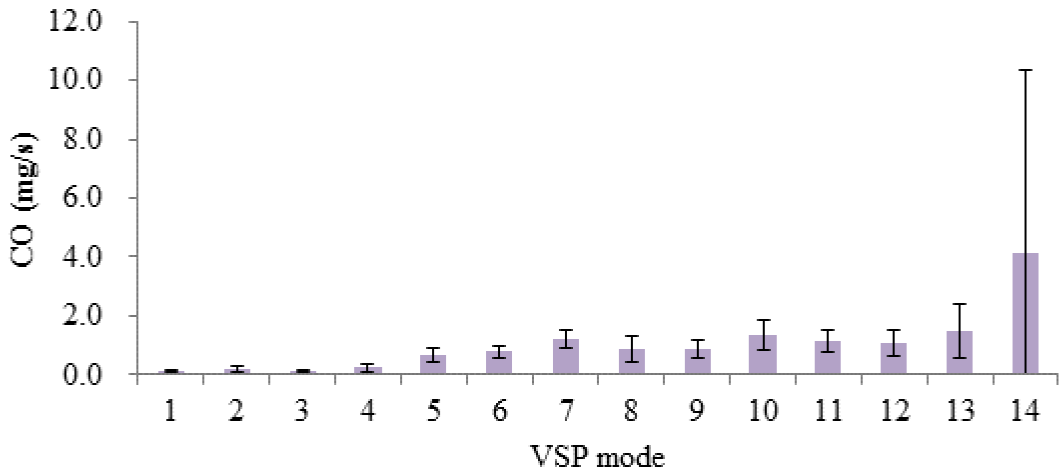


Figure 55. Average Carbon Monoxide with 95% confidence intervals in each vehicle specific power mode for a 2012 VW Passat

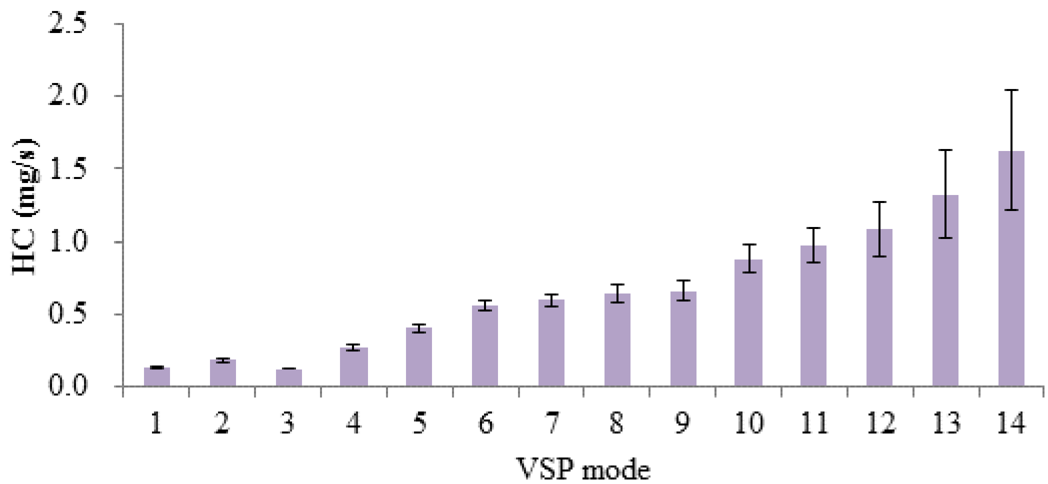


Figure 56. Average Hydrocarbon with 95% confidence intervals in each vehicle specific power mode for a 2012 VW Passat

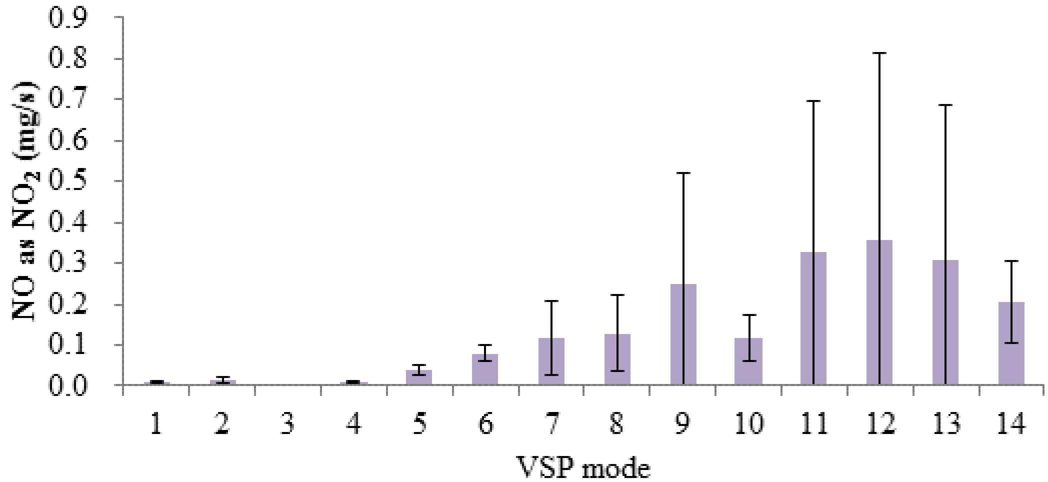


Figure 57. Average Nitrogen oxides with 95% confidence intervals in each vehicle specific power mode for a 2012 VW Passat

This table is complementary to Table 9. This provides the 95% confidence intervals associated with the mean values given in Table 9.

Table 27. 95% Confidence Intervals for VSP Modal Fuel Use and Emissions Rates for Honda Pilot[a]

VSP mode	VSP Range	Sample Size	Fuel	NO as NO_2	HC	CO	CO_2
	(kW/ton)		(g/s)	(mg/s)	(mg/s)	(mg/s)	(g/s)
1	Below −2	441	0.03	0.06	0.02	0.67	0.11
2	−2 – 0	111	0.11	0.51	0.06	1.29	0.34
3	0 – 1	119	0.06	0.08	0.05	0.41	0.19
4	1 – 4	278	0.08	0.11	0.06	1.37	0.25
5	4 – 7	225	0.10	0.26	0.08	1.57	0.31
6	7 – 10	270	0.10	0.52	0.08	1.79	0.31
7	10 – 13	292	0.08	0.40	0.07	2.20	0.24
8	13 – 16	231	0.09	0.85	0.10	1.29	0.30
9	16 – 19	127	0.14	0.98	0.14	4.63	0.44
10	19 – 23	138	0.13	1.11	0.15	2.22	0.42
11	23 – 28	138	0.13	1.01	0.15	3.11	0.40
12	28 – 33	66	0.17	1.00	0.23	4.96	0.55
13	33 – 39	21	0.36	1.04	0.50	1.95	1.13
14	Over 39	4	0.57	2.50	1.37	24.15	1.77

[a] *For each VSP mode, the 95% confidence intervals in average fuel use and emission rates equal to ± the numbers shown here.*

This table is complementary to Table 10. This provides the 95% Confidence Intervals associated with the mean values given in Table 10.

Table 28. 95% Confidence Intervals for VSP Based Average Fuel Use and Emission Rates for Selected Vehicles in Selected Routes

(a). 10 Selected Passenger Cars Measured in Raleigh and Research Triangle Park Routes[a,b]

VSP Mode	VSP Range	Sample Size	Fuel	NO as NO_2	HC	CO	CO_2
	(kW/ton)		(g/s)	(mg/s)	(mg/s)	(mg/s)	(g/s)
1	Below −2	21136	0.04	0.06	0.27	1.13	0.15
2	−2 – 0	6969	0.04	0.04	0.22	1.76	0.14
3	0 – 1	30713	0.05	0.02	0.11	0.43	0.16
4	1 – 4	10766	0.06	0.07	0.30	2.97	0.18
5	4 – 7	10206	0.10	0.10	0.36	4.05	0.27
6	7 – 10	10005	0.13	0.13	0.43	4.32	0.39
7	10 – 13	8787	0.18	0.19	0.50	5.19	0.53
8	13 – 16	7229	0.20	0.30	0.56	6.10	0.58
9	16 – 19	5168	0.22	0.41	0.62	7.98	0.69
10	19 – 23	4400	0.26	0.60	0.66	9.76	0.76
11	23 – 28	2960	0.31	0.81	0.70	11.91	0.99
12	28 – 33	1407	0.38	1.40	0.80	17.69	1.19
13	33 – 39	817	0.43	2.82	0.98	24.61	1.37
14	Over 39	469	0.60	4.91	1.23	80.51	1.81

[a] *Selected vehicles are a 2005 Mazda 6, a 2011 Chevrolet HHR, a 2011 Toyota Camry, a 2012 Nissan Versa, a 2012 Dodge Avenger, a 2012 Ford Fusion, a 2012 Nissan Rogue, a 2012 Toyota Camry, a 2013 Ford Fusion, and a 2013 Chevrolet Impala*

[b] *For each VSP mode, the 95% confidence intervals in average fuel use and emission rates equal to ± the numbers shown here.*

(b). 5 Selected Passenger Trucks Measured in Raleigh and Research Triangle Park Routes[a,b]

VSP Mode	VSP Range	Sample Size	Fuel	NO as NO_2	HC	CO	CO_2
	(kW/ton)		(g/s)	(mg/s)	(mg/s)	(mg/s)	(g/s)
1	Below −2	10714	0.06	0.07	0.70	2.16	0.55
2	−2 – 0	2916	0.09	0.06	0.64	1.61	0.84
3	0 – 1	13484	0.10	0.00	0.24	1.27	0.63
4	1 – 4	4797	0.10	0.05	0.97	4.30	1.15
5	4 – 7	4896	0.08	0.05	1.24	3.87	1.20
6	7 – 10	4701	0.10	0.07	1.58	3.44	1.53
7	10 – 13	4049	0.13	0.13	1.84	3.80	1.63
8	13 – 16	3618	0.14	0.24	2.15	2.33	1.36
9	16 – 19	2764	0.17	0.26	2.51	4.75	1.40
10	19 – 23	2429	0.27	0.31	2.98	21.84	1.51
11	23 – 28	1744	0.45	0.75	3.28	29.42	2.09
12	28 – 33	1074	0.64	0.82	3.71	42.00	2.62
13	33 – 39	697	0.83	1.29	4.32	141.08	3.25
14	Over 39	482	1.11	2.10	5.77	259.18	4.16

[a] *Selected vehicles are a 2008 Nissan Xterra, a 2010 Chevrolet Silverado, two 2011 Ford F150s, and a 2013 GMC Yukon.*

[b] *For each VSP mode, the 95% confidence intervals in average fuel use and emission rates equal to ± the numbers shown here.*

(c). 3 Selected Passenger Cars and Trucks Measured in Asheville Routes[a,b]

VSP Mode	VSP Range	Sample Size	Fuel	NO as NO_2	HC	CO	CO_2
	(kW/ton)		(g/s)	(mg/s)	(mg/s)	(mg/s)	(g/s)
1	Below −2	4,548	0.02	0.02	0.14	0.29	0.05
2	−2 – 0	1,211	0.05	0.05	0.15	0.63	0.16
3	0 – 1	9,280	0.04	0.04	0.24	1.21	0.12
4	1 – 4	2,586	0.05	0.04	0.22	0.62	0.16
5	4 – 7	2,433	0.06	0.06	0.10	1.22	0.18
6	7 – 10	2,283	0.06	0.07	0.05	1.26	0.20
7	10 – 13	2,005	0.06	0.09	0.09	0.90	0.20
8	13 – 16	1,526	0.07	0.11	0.17	0.98	0.22
9	16 – 19	1,055	0.09	0.12	0.10	1.63	0.28
10	19 – 23	855	0.09	0.18	0.07	1.23	0.27
11	23 – 28	616	0.11	0.28	0.11	1.83	0.37
12	28 – 33	278	0.18	0.37	0.19	2.73	0.58
13	33 – 39	119	0.28	1.09	0.32	6.62	0.87
14	Over 39	44	0.49	3.60	0.67	8.96	1.55

[a] *Selected vehicles are a 2012 Dodge Avenger, a 2012 Ford Fusion, and a 2012 Toyota Sienna. The Avenger and the Fusion were also included as part in the selected 10 passenger car list measured in Raleigh/RTP routes.*

[b] *For each VSP mode, the 95% confidence intervals in average fuel use and emission rates equal to ± the numbers shown here.*

APPENDIX C

Comparison of Real World Light-Duty Gasoline Vehicle Emissions for High Altitude Mountainous Versus Low Altitude Piedmont Study Areas

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Abstract

Vehicle specific power (VSP) quantifies engine load based on speed, acceleration, and grade, and is a useful predictor of vehicle fuel use and emissions. Altitude may also affect fuel use and emissions. Many studies have evaluated the effect of altitude on heavy-duty diesel vehicles using dynamometer tests, but there is lack of such study for light-duty gasoline vehicles based on comparison of the same vehicle at different altitudes. In this study, a method is demonstrated to quantify the effect of road grade and altitude on VSP-based fuel use and emission rates for the same vehicle. Three light-duty gasoline vehicles were measured on low altitude piedmont (LP) routes in the Raleigh, NC area and on high altitude mountainous (HM) routes in the Asheville, NC area. Vehicle exhaust concentrations were measured using a portable emission measurement system (PEMS). Engine activity and fuel use were measured using an on-board diagnostic (OBD) data logger. Vehicle position and elevation were measured using multiple global positioning receivers with barometric altimeters (GPS/BA). VSP-based fuel use rates and emissions rates of carbon monoxide (CO), nitrogen oxides (NO_x), and hydrocarbons (HC) were developed for each study location. Road grade and study location were jointly found to have a significant effect on fuel use and emission rates based on three measured vehicles. For HM vs. LP, there for fuel use, CO emission, and NO_x emission rates were approximately 9 percent, 60 percent, and 20 percent

higher, respectively, for the HM vs. LP study areas. Most of measured HC concentrations were below detection limit. The method illustrated here is recommended for application to a larger vehicle sample.

Keywords: Vehicle emission; Altitude; Road Grade

1. Introduction

More than 90 percent of annual 2008 U.S. carbon monoxide (CO) emissions and 60 percent of annual nitrogen oxides (NO_x) emissions were from on-road vehicles (EPA, 2013a, b). Light-duty gasoline vehicles, including passenger cars and passenger trucks, comprise the majority of the U.S. on-road vehicle fleet (Census Bureau, 2013).

Vehicle specific power (VSP), which takes into account changes in vehicle kinetic and potential energy, rolling resistance, and aerodynamic drag, is well correlated with fuel flow and emission rates (Jimenez-Palacios, 1999). VSP is quantified based on vehicle speed, acceleration, and road grade. VSP has been used for modeling fuel use and emissions for various types of vehicles (Koupal *et al*., 2004; Frey *et al*., 2006; Frey *et al*., 2007; Zhai *et al*., 2008).

A vehicle driven on hilly roads with +1 percent to +6 percent road grades had 5 percent to 20 percent higher fuel consumption rates compared to a flat road (Boriboonsomsin and Barth, 2009). Positive road grades are associated with a substantial increase in vehicle CO, NO_x, and hydrocarbon (HC) emissions rates. For example, CO and HC emissions rates increased by 40 percent to 100 percent for a vehicle on +5 percent or more grades compared to a flat road, and the NO_x emission rates were found to be higher by a factor of 4 (Zhang and Frey, 2006; Frey *et al*., 2008).

Altitude may affect vehicle fuel use and emissions rates. For diesel engines, there is empirical evidence from remote sensing, tunnel, and engine dynamometer studies that higher altitude is associated with higher emission rates of CO, HC, NO_x, and particulate matter (PM) (Bishop *et al*., 2001; Yanowitz *et al*., 2000; He *et al*., 2011). However, for gasoline vehicles, literature regarding the effect of altitude on emissions is scarce (Zavala *et al*., 2009). For example, although gasoline vehicles have been measured at high altitude, such studies do not include comparisons to similar vehicles at low altitude (Bishop and Stedman, 2008). One engine dynamometer test for a narrow range of simulated altitudes of 600 m to 850 m indicated contradictory differences in fuel use rate depend on engine revolutions per minute (RPM) (Shannak and Alhasan, 2002). Many studies of real-world fuel use and emissions rates for gasoline vehicles that use VSP as an indicator of engine load were conducted in low altitude areas (Frey *et al*., 2006; Frey *et al*., 2007; Zhai *et al*., 2008; Frey *et al*., 2009; Frey *et al*., 2003). High altitude is defined as 1000 meters above sea level or more (He *et al*., 2011), and low altitude is defined here as 200 meters above sea level or less. There is lack of data on the simultaneous effect of road grade and altitude on VSP-based fuel use and emissions rates.

The objectives of this study are to: (a) quantify road grade; (b) compare VSP modal fuel use and emissions rates for study areas that have different altitudes and terrains; and (c) compare the average fuel use and emissions during hill climbing, driving downhill, and driving on flat road.

2. Methodology

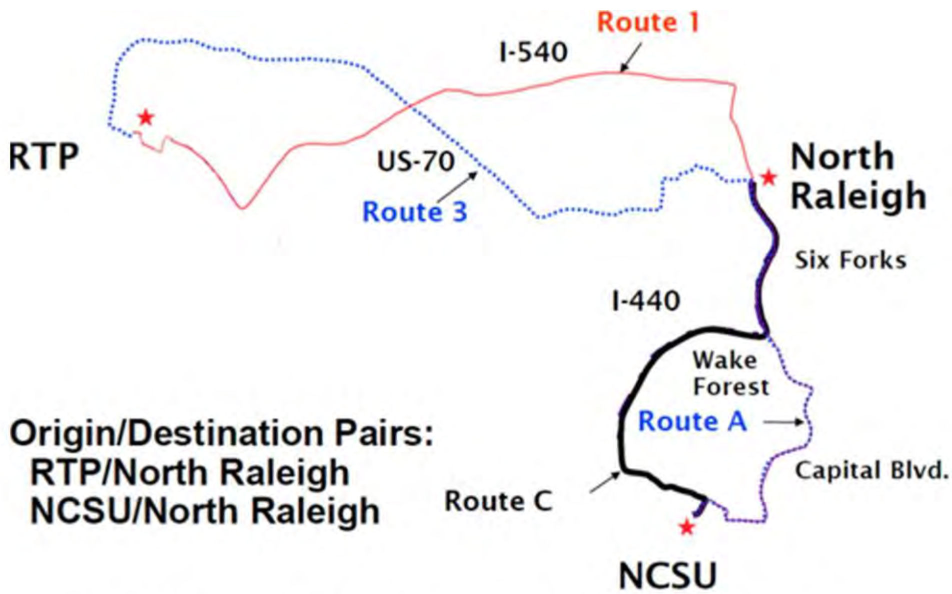
This section discusses study design, instruments, and data analysis.

2.1 Study Design

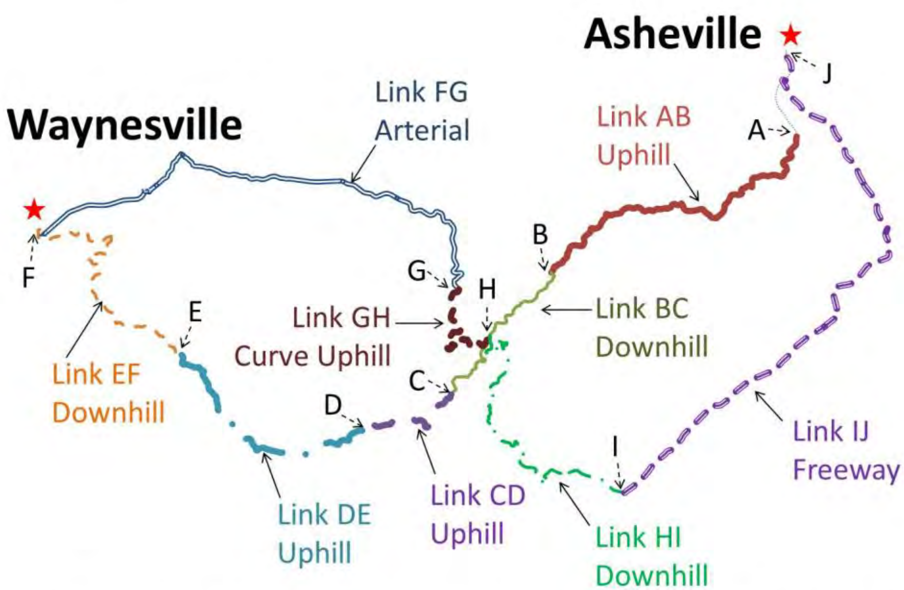
Three light-duty gasoline vehicles were measured, including: a 2012 Ford Fusion sedan with a 175 horsepower (hp) 4 cylinder 2.5 liter engine; a 2012 Dodge Avenger sedan with a 173 hp 4 cylinder 2.4 liter engine; and a 2012 Toyota Sienna minivan with a 266 hp 6 cylinder 3.3 liter engine.

Fuel use and emissions measurements for each vehicle were conducted at two study areas. One is a low altitude piedmont (LP) area in the vicinity of Raleigh, NC that includes two alternative routes between each of two origin/destination pairs, as shown in Figure 58(a). Routes A and 3 are comprised of arterial roads, and routes C and 1 are primarily comprised of freeways. Vehicles were driven outbound and inbound on each route. The total distance is 180 kilometers.

The other study area is a high altitude mountainous (HM) area near Asheville, NC, at altitudes of 600 to 1800 m, shown in Figure 58(b). This route is 190 kilometers, including 85 kilometers over 1,000 m. The lower lying areas, such as valleys, contain arterials and freeway, whereas the mountain roads are two lane arterials. All vehicles were measured once in the LP area and twice in the HM area.



(a) Map for Low Altitude Piedmont Raleigh, NC Area Routes



(b) Map for High Altitude Mountainous Asheville, NC area routes

Figure 58. Maps for (a) Low Altitude Piedmont (LP) Area and (b) High Altitude Mountainous (HM) Area Routes

To differentiate among road types and driving conditions, the HM area route is divided into 8 links. The route begins at an entrance to the Blue Ridge Parkway at point A, and ends at a gas station near Asheville at point J. Details of the elevations, distances, average speeds, upper bound acceleration, and average road grade for each link are shown later in Table 31.

2.2 Instruments

Instruments used include multiple global positioning system receivers with barometric altimeters (GPS/BA), a portable emissions measurement system (PEMS), and an on-board diagnostic (OBD) scan tool.

Road grade is quantified by combining data from multiple GPS/BA receivers for non-overlapping 0.16 kilometer segments (Boroujeni and Frey, 2014). The precision of estimated grade depends on the number of devices used. Typically, seven GPS/BA devices were used, including Garmin 76CSx and Garmin Oregon 550. Each logs 1 Hz data. The GPS receivers measure position to within ±3 meters. Relative changes in elevation are measured within ±1 meter. The elevation of each GPS receiver was calibrated to a known value at a known starting point.

OEM-2100 Montana and OEM-2100 Axion PEMS were used to measure exhaust pollutant concentrations. The Montana was used with the Fusion and the Sienna, and the Axion was used with the Avenger. Each of these functionally similar PEMS includes two parallel five-gas analyzers that measure carbon dioxide (CO_2), CO, and HC using NDIR, and nitric oxide (NO), and oxygen (O_2) using electrochemical sensors. The analyzers were calibrated before each measurement day. During measurement, the analyzers periodically 'zero' using ambient air to prevent drift (Frey *et al*., 2003).

Battelle compared the exhaust emission concentrations from the same model PEMS to reference method instruments using a chassis dynamometer. There was less than 10 percent difference for measured driving cycle average emission rates for CO_2, CO, and NO_x. For HC concentrations, PEMS uses NDIR but the reference method uses flame ionization detection (FID). The HC concentrations from NDIR are lower than for FID by a factor of approximately two (Battelle, 2003; Singer *et al*., 1998; Stephens and Cadle, 1991).

An OBDPro scantool and ScanXL™ Professional software were used to record on-board diagnostic (OBD) data from the vehicle electronic control unit (ECU), including engine speed (RPM), mass fuel flow (MFF), mass air flow (MAF), intake manifold absolute pressure (MAP), intake air temperature (IAT), and vehicle speed (VSS).

2.3 Road Grade Quantification

Linear regression was applied to each 0.16 kilometer segment of each route to estimate the slope of elevation versus distance, which is the estimated road grade. As detailed in Boroujeni *et al*. (2013), data from each of the multiple GPS/BA receivers were synchronized both horizontally and vertically to reference distances and to segment average elevation prior to estimating grade. The latter is to eliminate random error associated with drift in ambient barometric pressure. The precision of the estimated grade is proportion to the square root of the mean standard square error of the fitted regression model and was estimated for a 95 percent confidence interval.

2.4 Data Analysis

PEMS, GPS/BA, and OBD data were synchronized and processed for quality assurance using methods detailed elsewhere (Sandhu and Frey, 2012). VSP was estimated using OBD speed and acceleration, and GPS-derived road grade at 1 Hz, using typical parameter values for light-duty vehicles (Jimenez-Palacios, 1999):

$$VSP = v(1.1a + 9.81r + 0.132) + 3.02 \times 10^{-4} v^3 \quad \text{(C1)}$$

Where:

v = Vehicle speed, (m/s)

a = Vehicle acceleration, (m/s^2)

r = Road grade, (slope)

VSP = Vehicle specific power, (kW/ton).

For the high altitude (>1000m) Asheville area, the aerodynamic drag term in Equation (C1) was adjusted to account for decreasing air density associated with higher altitudes:

$$VSP = v(1.1a + 9.81r + 0.132) + \frac{P_{high,avg}}{P_{sealevel}} \times 3.02 \times 10^{-4} v^3 \quad \text{(C2)}$$

Where:

$P_{high,avg}$ = the average barometric pressure observed for high altitude (>1000m) measurements, (kPa). $P_{high,avg}$ ranged typically from 85 kPa to 90 kPa.

$P_{sealevel}$ = the barometric pressure at sea level (101 kPa).

VSP values were stratified into 14 discrete modes, as shown in Table 29 (Frey *et al*., 2002).

Table 29. Definition of Vehicle Specific Power Modes (Frey *et al*., 2002)

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

For the Fusion and Sienna, MFF was reported by the ECU. Aggregated fuel consumption based on OBD data was compared to gas pump fuel consumption. For all vehicles, the fuel tanked was topped off immediately before and after each data collection run. Emissions rates for CO, HC, and NO_x were estimated based on a carbon mass balance and measured exhaust concentrations (Frey *et al*., 2008).

For the Avenger, neither MFF nor MAF were broadcast by the ECU. Therefore, MAF was estimated using the speed-density method (Hendricks and Sorenson, 1991; Vojtisek-Lom and Cobb, 1998). This method estimates the exhaust flow rate based on the ideal gas law, taking into account RPM, MAP, IAT, displacement, compression ratio, and volumetric efficiency (VE). VE is the ratio of actual to theoretical mass flow. From the measured exhaust concentrations, and the weight percent of carbon in the fuel, the air/fuel ratio can be inferred. Thus, MFF can be inferred from MAF. VE was calibrated so that the sum of 1 Hz estimates of MFF was similar to the actual fuel consumed. From MFF and MAF, the exhaust flow rate is estimated. Using the measured exhaust concentrations, the mass flow rate of each pollutant is estimated.

Modal rates at low altitude for a piedmont topography were developed from the Raleigh area data. Modal rates at high altitude were developed by combining the high altitude portion of the data from the two Asheville area runs. Thus, the comparisons of fuel use and emission rates with respect to altitude are based on 180 kilometers from the Raleigh area and 170 kilometers at elevations over 1000 meters from the Asheville area. Student t-tests were performed to determine whether differences between mean of fuel use or emissions rates for a given VSP mode were statistically significant when comparing the LP and HM areas.

Average vehicle speed, acceleration, road grade, fuel use rates and CO, HC, and NO_x emission rates were estimated for each link of the Asheville route by summing 1 Hz measured data.

3. RESULTS

For each vehicle, approximately 4 hours of 1 Hz data were collected in the LP area and 7 hours in the HM area. Over 99 percent of the collected data were valid for the Fusion and Sienna, and 97 percent of the Avenger data were valid. The sum of 1 Hz fuel use was within 12 percent, 5 percent, and 6 percent of actual fuel use for the Fusion, Sienna, and Avenger, respectively. Results include road grade, VSP-based modal fuel use rates and emission rates, comparison of grades and study areas, and average vehicle activity, fuel use and emissions for different observed driving conditions.

For each vehicle, the average temperature for the HM vs. LP study areas differed by only 2 to 5 C°, and thus is not expected to significantly affect the VSP-based modal rates. For all three measured vehicles, barometric pressure averaged 101 kPa in Raleigh, 90 kPa among all HM road segments, and 85 kPa for HM segments over 1000 meters in altitude.

3.1 Road Grade

The measured elevation and road grade for the Fusion for the LP and HM areas is shown in Figure 59(a) and Figure 59(b), respectively. Results for the Sienna and Avenger are similar. The measured altitudes in both the LP and the HM area are comparable to map-based data (Geocontext, 2013a, b, c).

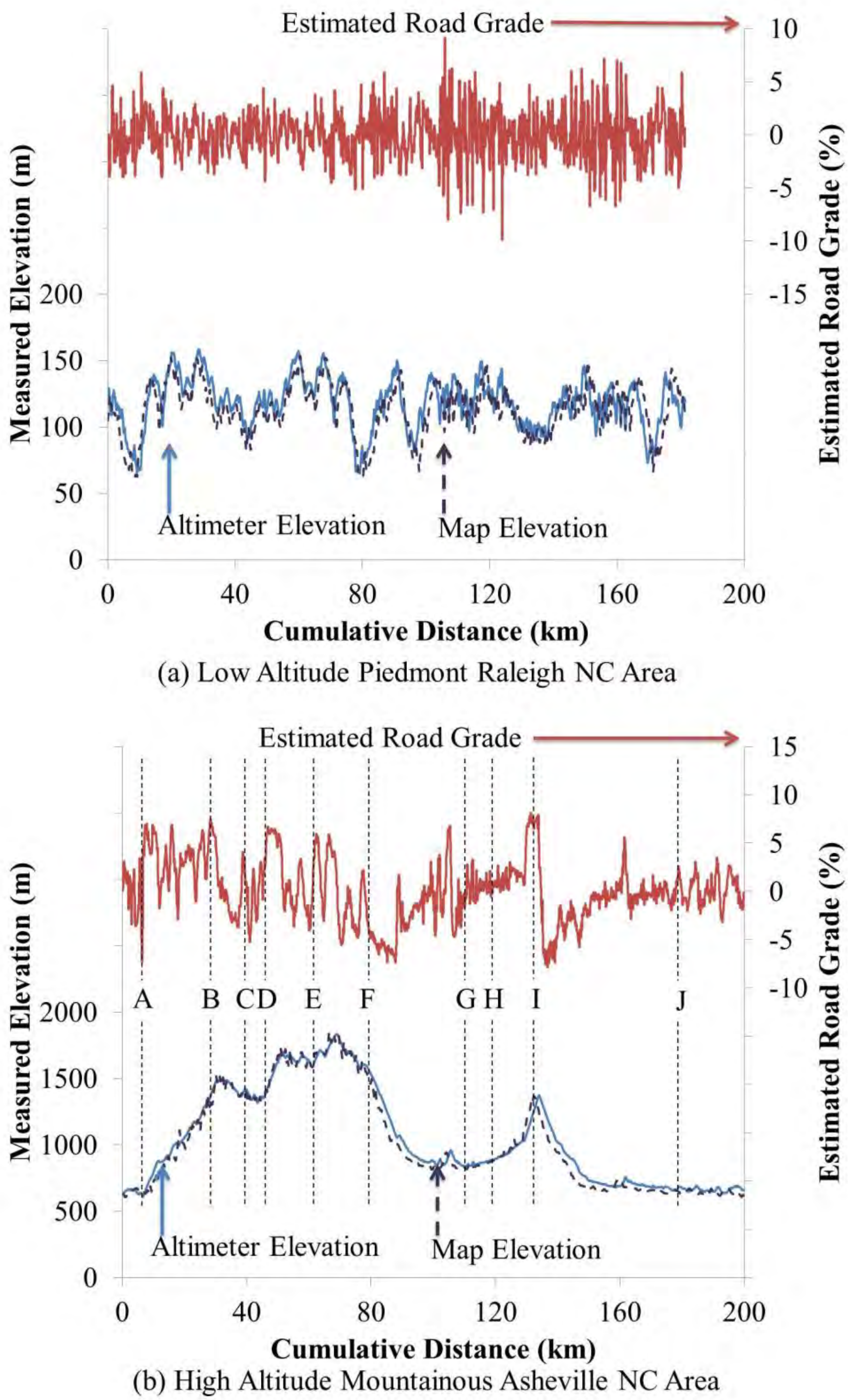


Figure 59. Measured Altimeter Elevation, Map Elevation, and Estimated Road Grade along the Routes for (a) Low Altitude Piedmont (LP) Raleigh Area and (b) High Altitude Mountainous (HM) Asheville Area from the Fusion Measurement, Starts of Links are Labeled

The precision of estimated road grade is 0.5 percent or better for at least 92 percent of the 0.16 kilometer segments for each vehicle in the LP area, and for 39 percent to 61 percent of the 0.16 kilometer segments in the HM area depending on vehicles. For each of the three measured vehicles, the average precision of segment road grade over all 0.16 kilometer segments ranged from 0.2 percent to 0.3 percent in the LP area and from 0.5 percent to 0.7 percent in the HM area. Most of the HM route is under tree cover, which hampers GPS satellite signal reception. The estimated precision is sufficient for assigning 1 Hz data to the appropriate VSP mode.

The 90 percent frequency range of grade in the LP area is approximately ±3.7 percent, compared to a wider range of -5.4 percent to +6.1 percent in the HM area. For the high altitude portions of the HM area route, the 90 percent range is -6.3 percent to +6.8 percent. In the HM area, vehicles spent approximately 9 percent of travel time on grades of 5 percent or higher, compared to less than 2 percent of travel time in the Raleigh area. Thus, vehicles operating on the HM area route encountered steeper grades with higher frequency than in the LP area.

3.2 VSP Modal Fuel Use and Emissions Rates

The VSP modal average fuel use and emission rates for CO, HC, and NO_x were estimated for each vehicle for the LP and HM areas, with the latter focused specifically on only the high altitude portion of the HM area routes.

Because these data were collected in the real-world, the comparison of modal rates for the two study areas is not a controlled experiment in which only altitude was varied. The comparison is between regions which differ by both altitude and terrain. Thus, differences in modal rates between the two areas may be the result of the joint effect of these two key differences, rather than simply because of altitude.

Different combinations of speed, acceleration, and grade can lead to similar estimates of VSP. For example, for the Ford Fusion, using VSP mode 10 as an example, the mean VSP is 20.8 kW/ton for both the LP and HM areas. However, for the HM area, the average speed is lower (66 km/h versus 76 km/h) than for the LP area, the average acceleration is lower (0.54 m/s^2 versus 0.67 m/s^2), and the average grade is higher (+3.6 percent versus +1.1 percent). Furthermore, the performance differs, with higher RPM (2260 versus 2110) and lower MAP (76 kPa versus 81 kPa). All of these differences are statistically significant. Thus, although the power demand is the same, the driving conditions and terrain over which the vehicle is operating, and the response of the engine, differ. Differences in HM vs. LP modal average MAP, RPM, speed, acceleration, and grade were found for most modes for each of the three measured vehicles.

The modal average fuel use rates for both study areas increase monotonically with positive VSP from Mode 3 to Mode 14, as shown in Figure 60(a) for the Fusion. For Mode 12, the LP and HM average of 2.4 g/s and 2.6 g/s, respectively, differ by 9.8 percent but the difference is not statistically significant. In contrast, for Mode 10, the LP and HM average of 2.1 g/s and 2.3 g/s, respectively, differ by only 7.3 percent, but this difference is statistically significant. The modal fuel use rates for the HM area are statistically significantly higher than those for the LP area for 11 of the 14 modes. The sample sizes in Modes 13 and 14 are less than 20 seconds for both study areas; thus, comparisons for these modes are subject to larger random sampling error than for other modes. For a simple average in which all modes are given equal weight, the difference in fuel use rate is 13.1 percent.

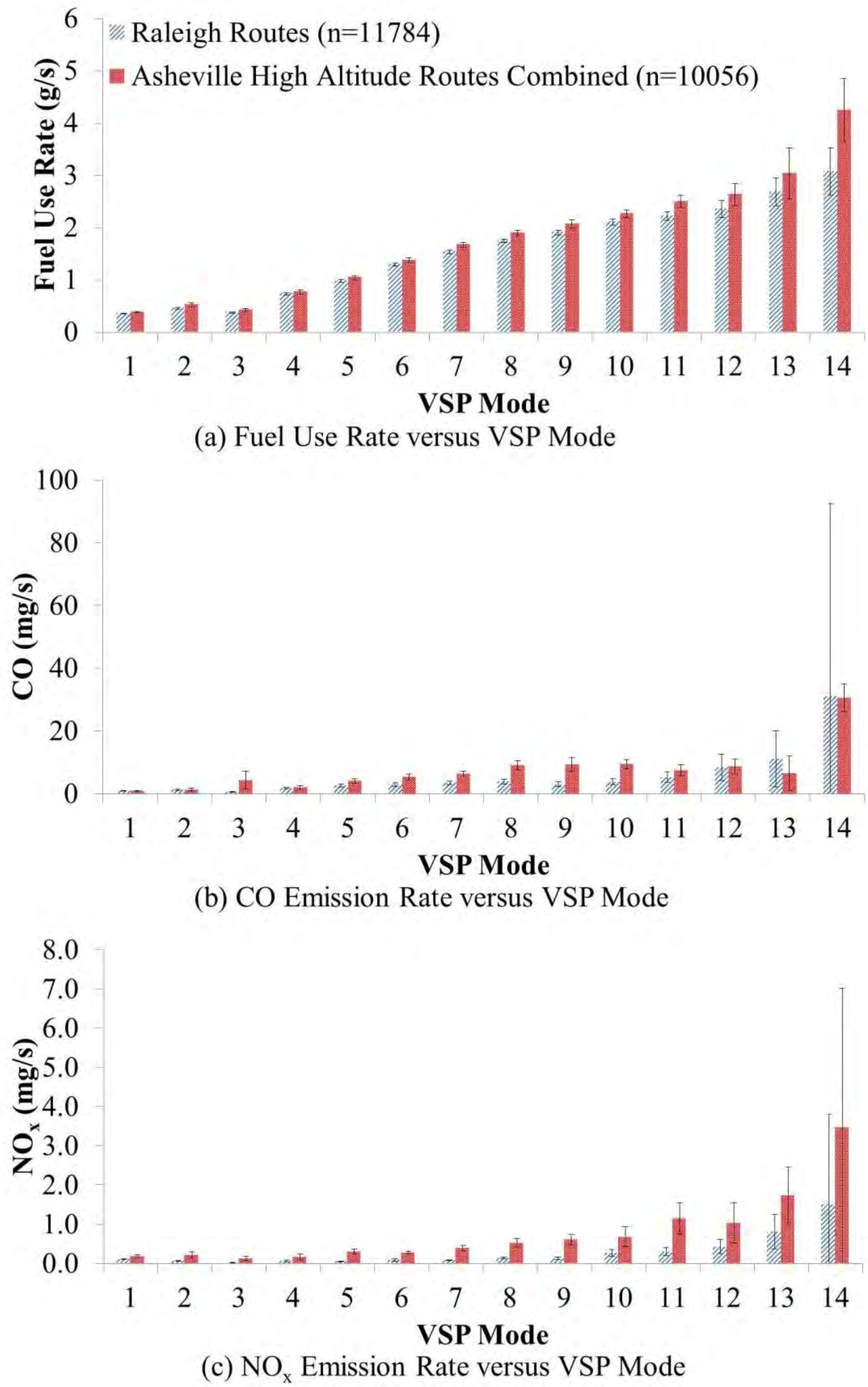


Figure 60. (a) Average Fuel Use Rates, (b) Average CO Emission Rates, and (c) Average NO_x Emission Rates in Each Vehicle Specific Power Mode from the Low Altitude Piedmont (LP) and High Altitude Mountainous (HM) Area for the 2012 Ford Fusion, Error Bar Indicates 95 Percent Confidence Interval

For the Sienna, the comparison of fuel use rates for the HM versus LP areas was similar to the Fusion. There are statistically significant higher fuel use rates for 8 modes. The equally weighted average fuel use rates over the 14 modes are 6.2 percent higher. For the Avenger, there are statistically significant higher fuel use rates for 5 modes, and lower fuel use rates for 4 modes. The equally weighted average fuel use rates are 2.4 percent lower.

The modal CO emission rates for the Fusion are shown in Figure 60(b). The average exhaust CO concentrations in all modes were above the detection limit of 0.008 volume percent. The detection limit is a concentration that is not statistically significantly different from zero as a result of measurement imprecision. For 7 of the 14 modes, the CO emission rates are statistically significantly higher for the HM area. The equal weighted average CO emission rates for the HM area are 31 percent higher than for the LP area.

For the Sienna, the modal average CO exhaust concentrations were above the detection limit for the HM area, except for Mode 3, and below the detection limit for the LP area, except for Mode 14. For the Avenger, the average exhaust CO concentrations were above the detection limit for all modes in both areas. Statistically significant higher HM area modal average CO emission rates were observed for 2 of the 14 modes and lower CO emission rates were observed for 5 modes. The equally weighted HM average CO emission rates were 81.5 percent lower than for the LP area. The large average difference is influenced by large but statistically insignificant differences in Modes 12 to 14 between the HM and LP areas. For example, the CO emission rates for Mode 14 are 332 mg/s and 17 mg/s for the LP and HM areas, respectively, but this difference is statistically insignificant.

The average exhaust NO_x concentrations were above the detection limit of 8 ppm for all modes in both areas for all three vehicles. There were significantly higher NO_x emission rates for the HM versus LP area for 12 modes for the Fusion, 7 modes for the Sienna, and 5 modes for the Avenger. Based on equal weighting of the modes, the differences in average NO_x emission rates for the HM vs. LP areas was +170 percent for the Fusion, +6.5 percent for the Sienna, and -38 percent for the Avenger. For the Avenger, differences in modal average rates were not statistically significant for the other 9 modes. In particular, for Modes 12 to 14, which have large sampling variability and small sample sizes, the differences are not significant but the HM area rates average 52 percent lower than the LP area rates. Thus, when equally averaged over all 14 modes, the Avenger appears to have a lower average rate for the HM area even though none of the individual VSP modes has an HM rate significantly lower compared to the LP rates.

For the Fusion, the average exhaust HC concentrations were below the detection limit of 15 ppm for all modes in the LP area and 2 modes in the HM area. For the Sienna and Avenger, the average exhaust HC concentrations were below detection limit for all modes in both areas. Therefore, HC emissions rates for the Fusion were higher for the LP versus HM areas, while no conclusions can be drawn for the comparison between Sienna and the Avenger.

To evaluate the effect of road grade and altitude on fuel use and emission rates, a sensitivity analysis is shown in Figure 62 for the Fusion. In the sensitivity analysis, VSP is calculated based on zero acceleration for the combinations of constant speed and road grade indicated in the figure. Based on the estimated VSP, the corresponding modal average rates are selected for each of the LP and HM data. The sensitivity analysis is based on ranges of constant speed and road grade that were commonly observed during the measurements. At a given speed, the solid and dashed lines indicate the fuel use and emission rates for the LP and HM areas, respectively. For example, at 80 km/h and +8 percent road grade, the fuel use rate for the HM area is 2.50 g/s, which is 13 percent higher than for the LP area (2.22 g/s). For road grades of less than -4 percent, the estimated VSP is negative for which the estimated rates are not sensitive to either speed or grade. For grades larger than -4 percent, the fuel use rate increases with increasing grade at a given speed. For example, for the HM area at 64 km/h, the fuel use rate increases from 0.4 g/sec at -4 percent grade to 2.3 g/sec at +10 percent grade. At a given grade, fuel use increases with increasing constant speed. For example, for the HM area, at +5 percent grade, fuel use rate increases by 51 percent from 48 km/h to 80 km/h. The fuel use rate is slightly higher for the HM versus LP areas for most of the evaluated combinations of grade and speed. For example, at 64 km/h and 10 percent grade, the HM fuel use rate is 8.0 percent higher. For grades of +5 percent or higher, the HM fuel use rate 6.0 percent to 8.3 percent higher, depending on the speed. The trends are similar for the Sienna and the Avenger. For example, the fuel use rate for grades of +5 percent or more for HM versus LP are higher by 3.5 percent to 13 percent for the Sienna and 1.8 percent to 11 percent for the Avenger, depending on speed.

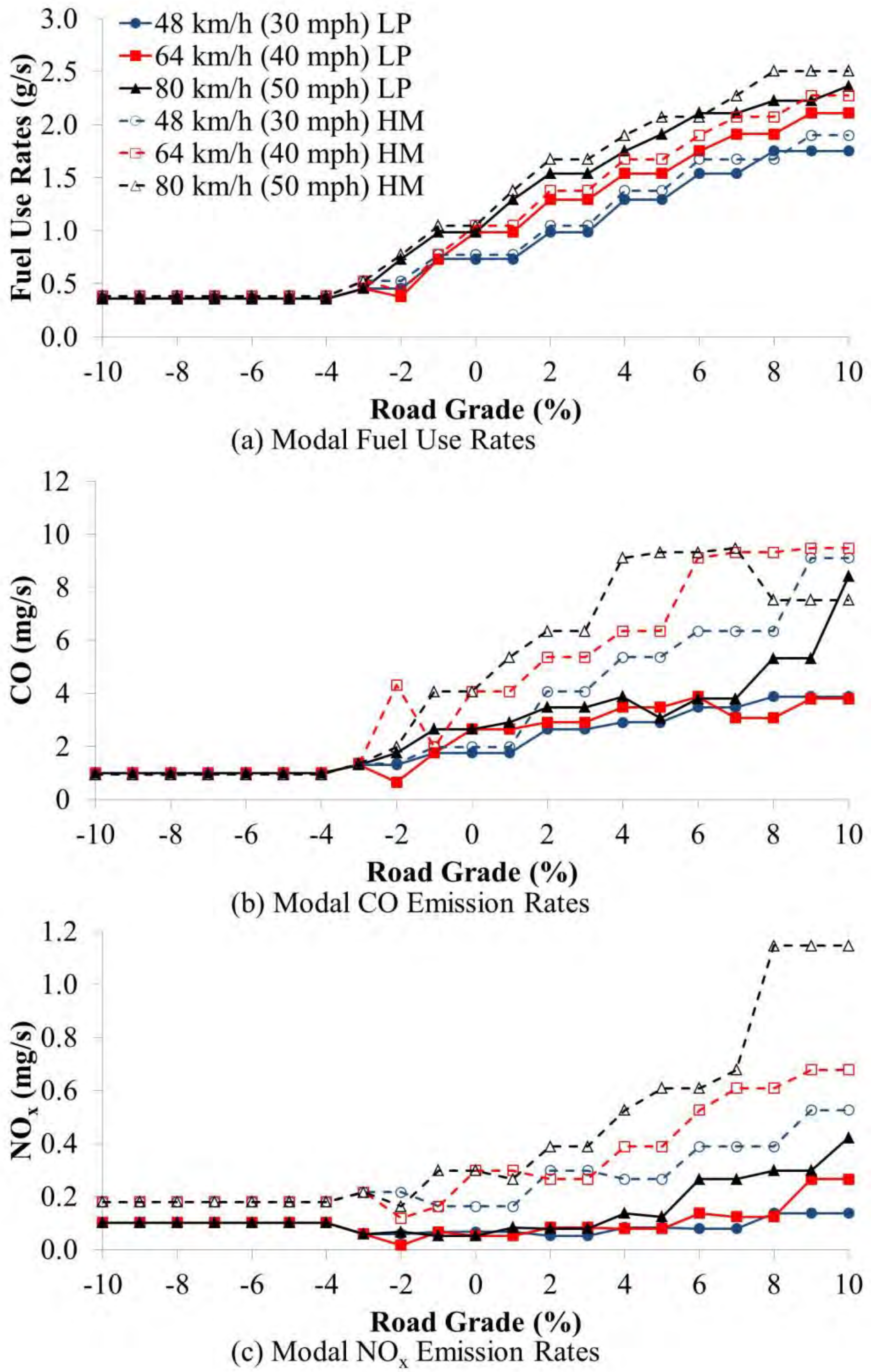


Figure 61. (a) Fuel Use Rates, (b) CO Emission Rates, and (c) NO_x Emission Rates from High Altitude Mountainous (HM) and Low Altitude Piedmont (LP) Areas for the 2012 Ford Fusion at Difference Combination of Speed and Road Grade, Setting Acceleration to Zero

For the Fusion, for the LP area, the CO emission rates appear to be less sensitive to grade than for the HM area. At 64 km/h, the difference in CO emission rates between -4 percent and +10 percent grades are a factor of 4 and 9 for the LP and HM areas, respectively. For +5 percent or more grades, the CO emission rates are 71 percent to 152 percent higher for the LP and HM areas, depending on speed. For the Sienna, the CO emission rates are higher for the HM area by a factor of 5 for +5 percent or more grades. For the Avenger, the CO emission rates are higher for the HM area by 36 percent and 62 percent for at grades of +5 percent or more at 48 km/h and 64 km/h, respectively.

However, the NO_x emission rates are less sensitive than the CO emission rates to changes in road grade between -4 percent and +5 percent at 48 km/h. The road grade at which NO_x emissions increase substantially (by more than 20 percent) from the rate at zero grade varies from approximately 5 percent at low elevations for speeds of 48 to 80 km/h to as little as 1 percent at high altitude and 80 km/h. The estimated HM NO_x emission rates are more than twice as high as for the LP area for grades of +5 percent or more. For the Sienna, the NO_x emission rates are less sensitive to grade than the CO emission rates. The HM and LP rates are within 10 percent of each other for grades of +5 percent or more. For the Avenger, the HM and LP NO_x emission rates are within 20 percent at 48 to 64 km/h at +5 percent or more grades.

To compare the effect of study area and driving cycles, a comparison is made for four cases taking into account the modal rates measured at each area (Figure 60), and the observed driving cycles in each area, as shown in Figure 62. The HM cycle has approximately 5 percent more time for negative VSP values in Mode 1 than the LP cycle, slightly more time at intermediate VSP values in Modes 5 to 11, and 10 percent less time on idle. Time fractions in the other modes are similar. The differences in activity between the two cycles are a result of more variation in road grade in the Asheville area, leading to more time climbing hills under moderate to high VSP and more time descending hills under no engine load.

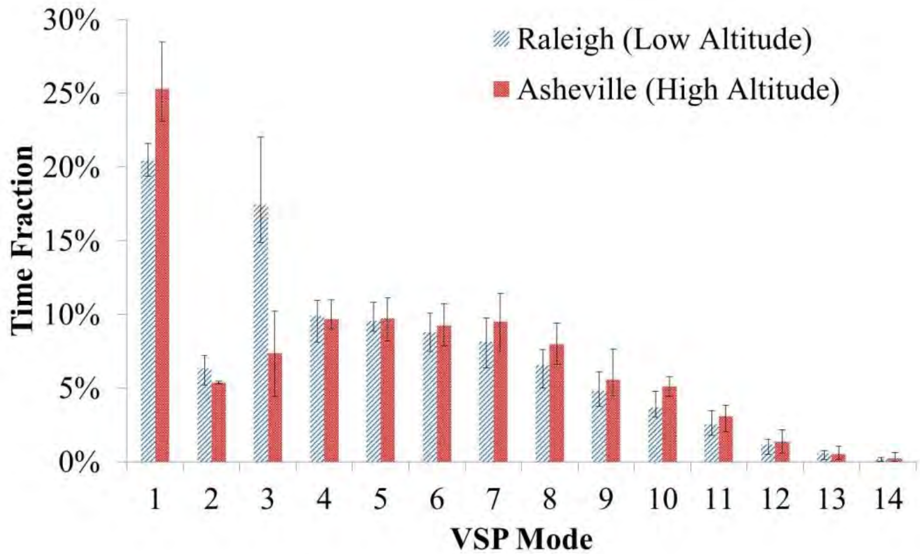


Figure 62. Average Time Fraction in Each Vehicle Specific Power Mode for the Raleigh Low Altitude Piedmont (LP) and Asheville High Altitude Mountainous (HM) Cycles, Error Bar Indicates Minimum and Maximum of Time for Each Vehicle

The estimated cycle average fuel use and emission rates for each vehicle for four combinations are shown in Table 30. The purpose of Table 30 is to evaluate the effect of altitude, road grade, and driving cycle on vehicle fuel use and emissions based on cycle average rates. For each vehicle, cycle average fuel use and emission rates are estimated based on VSP modal rates and observed time in each mode for driving cycles in each of the LP and HM areas. The cycle average rate for each of the LP and HM cycles are estimated using modal rates measured in each of the Raleigh and Asheville areas. The percentage differences based on modal rates for Asheville vs. Raleigh for a given driving cycle indicate the effect of study area on the average rates.

Table 30. Weighted Average Fuel Use Rates and Emission Rates of CO and NO_x for the Measured Vehicles based on Modal Rates from Raleigh Low Altitude Piedmont (LP) and Asheville High Altitude Mountainous (HM) Area and for Raleigh and Asheville Cycles

		Raleigh Cycle			Asheville Cycle		
		Cycle Average Rates			Cycle Average Rates		
Vehicle	Fuel Use or Emission Rates	LP Area [a]	HM Area [a]	Diff. (HM vs. LP)	LP Area	HM Area	Diff. (HM vs. LP)
Ford Fusion	Fuel Use Rate (g/s)	0.95	1.04	8.4%	1.02	1.11	8.2%
	CO Rate (mg/s)	2.18	4.30	97%	2.35	4.37	86%
	NO_x Rate (mg/s)	0.09	0.30	240%	0.10	0.32	260%
Toyota Sienna	Fuel Use Rate (g/s)	1.08	1.26	17%	1.21	1.40	16%
	CO Rate (mg/s)	0.70	4.35	520%	0.87	5.10	490%
	NO_x Rate (mg/s)	0.21	0.28	34%	0.25	0.32	27%
Dodge Avenger	Fuel Use Rate (g/s)	1.08	1.15	6.4%	1.17	1.25	6.8%
	CO Rate (mg/s)	5.45	4.09	-25%	4.68	4.43	-5.3%
	NO_x Rate (mg/s)	0.77	0.82	6.7%	0.99	0.90	-9.6%
Average of Three Vehicles	Fuel Use Rate (g/s)	1.04	1.15	11%	1.13	1.25	11%
	CO Rate (mg/s)	2.78	4.25	53%	2.63	4.63	76%
	NO_x Rate (mg/s)	0.36	0.47	31%	0.45	0.51	14%

[a] *LP is low altitude piedmont Raleigh area, HM is high altitude mountainous Asheville area.*

A comparison was made to evaluate whether differences in modal rates measured in the two study areas lead to differences in cycle average fuel use and emission rates. The comparison was made for each of the Raleigh and Asheville driving cycles, to assess whether the comparison may be sensitive to variation between driving cycles. The cycle average fuel use rates based on the HM modal rates are 11 percent higher than those based on the LP modal rates for both the Raleigh and Asheville driving cycles, taking into account an average over the three vehicles. Similarly, the cycle average CO emission rates averaged 53 percent and 76 percent higher for the Raleigh and Asheville cycles, respectively, when based on modal rates measured in the HM area versus those measured in the LP area. For NO_x, the cycle average rates were likewise 31 percent and 14 percent higher, respectively. Comparisons for HC were not made because most of the measurements were below the detection limit. There is inter-vehicle variability, which implies that any assessment of implications of differences in study area for differences in fleet average rates should be based on multiple vehicles, and not just one vehicle. For example, for the Asheville driving cycle, the Sienna has 490 percent higher CO emission rates based on HM instead of LP modal rates, compared to 5.3 percent lower CO emission rates for the Avenger. Overall, there is evidence that fuel use and emission rates, averaged over the three measured vehicles, were consistently higher when based on measurements from the HM versus LP areas, even when comparisons were controlled for a specific cycle, such as each of the Raleigh and Asheville cycles.

Conversely, a comparison was made between the Raleigh and Asheville cycles, while controlling for modal rates. When averaged over the three measured vehicles, the Asheville cycle has an 8.7 percent higher average fuel use rate than the Raleigh cycle, when using modal rates either from the HM area or the LP area. Similarly, the Asheville cycle CO emission rates averaged 8.9 percent higher than for the Raleigh cycle, averaged over the HM modal rates, and the NO_x emissions were 8.5 percent higher. The slightly higher fuel use and emission rates for the Asheville versus Raleigh cycles are consistent with the higher fraction of time of vehicle operation in positive VSP modes.

Based on the results from the three observed vehicles, the cycle average fuel use rate and emission rates of CO and NO_x are sensitive to both the area-specific modal rates and the driving cycle. The effect of each area-specific modal rates and driving cycle on cycle average fuel use and NO_x emission rates is similar in magnitude. However, cycle average CO emission rates are more sensitive to differences in area-specific modal rates than driving cycles.

To evaluate the effect of altitude on modal fuel use and emission rates, these modal rates were estimated separately based on different altitudes. The approximately 115 miles of data from the LP area for each vehicle are at an altitude of approximately 150 meters, with a range of 60 to 160 meters, and thus are used to characterize low altitude modal rates. The data from the HM area cover altitudes ranging from 550 to 1,800 meters. From these data, it was possible to select a contiguous portion of road with an altitude of approximately 700 meters, ranging from 600 to 800 meters, and to select a contiguous portion of road with an altitude of approximately 900 meters, ranging from 800 to 1,000 meters. Each vehicle was measured twice on each of these latter two portions. The variation in road grade for each of the three portions of road representing altitudes of 150 meters, 700 meters, and 900 meters are similar. For example, over 80 percent of the 0.1 mile segments used for road grade estimation have grades within a range of ±3 percent in each of the three altitude data sets.

VSP-based modal fuel use rates and emission rates of CO and NO_x were developed for each of the three altitude road portions for each vehicle. Figure 64 compares the modal rates for the Ford Fusion. On average over all modes, the differences in fuel use rates were within 5 percent and 4 percent for altitudes of 700 meters versus 150 meters and 900 meters versus 150 meters, respectively. There were more variations in CO and NO_x emission rates compared to fuel use rates. However, for modes 12 to 14, there were insufficient data point to develop stable emission rates. For modes 1 to 11, the CO and NO_x emission rates, on an absolute basis, were low.

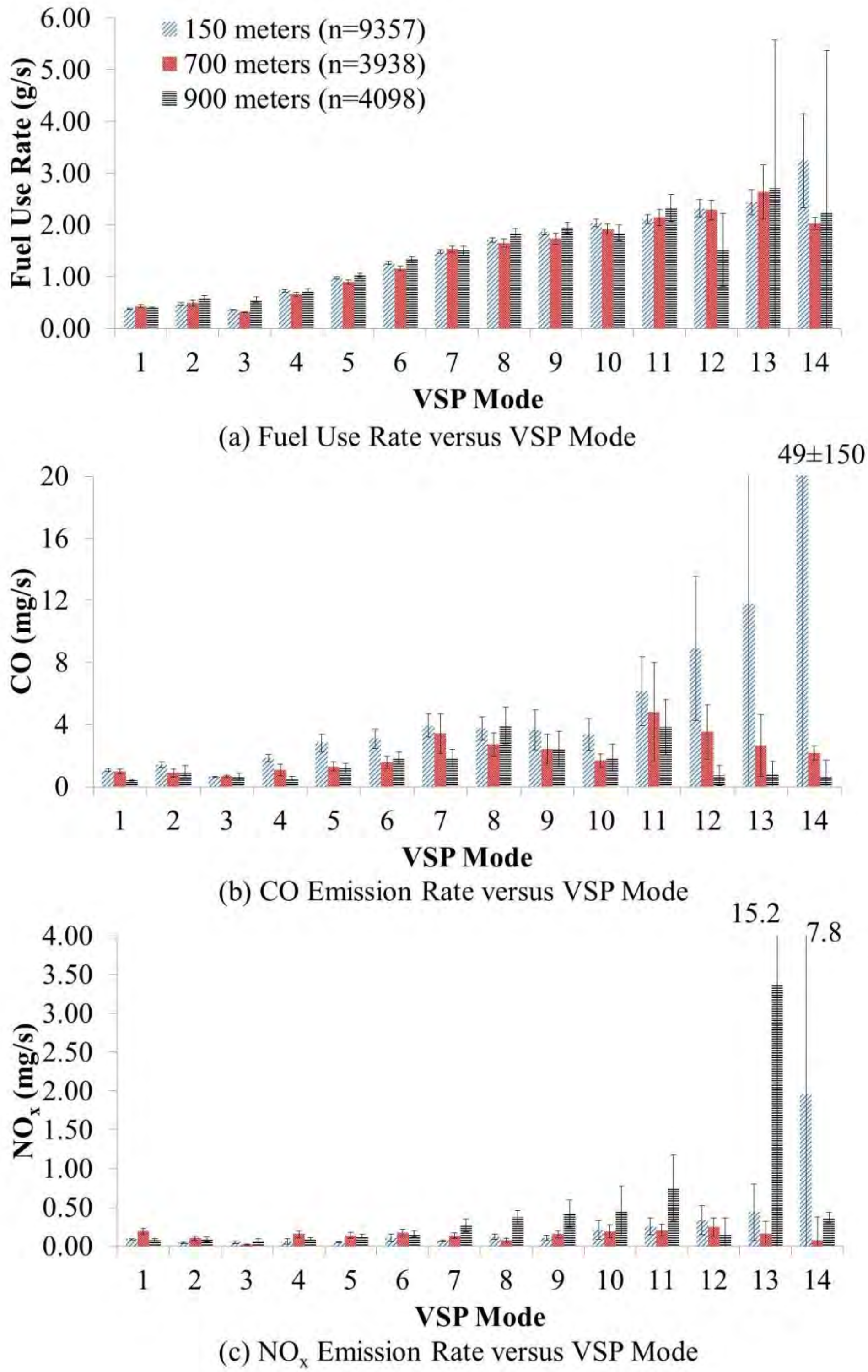


Figure 63. (a) Modal Fuel Use Rates, (b) Modal CO Emission Rates, and (c) Modal NO_x Emission Rates from Altitude of 150 Meters, 700 Meters, and 900 Meters Portions with Similar Road Grades for the 2012 Ford Fusion, Error Bar Indicates 95 Percent Confidence Interval

Table 31. **Average Speed, Acceleration, Road Grade, and VSP for Each Vehicle in Each Link of the High Altitude Mountainous (HP) Asheville Route**

Link\Vehicle	Description	Elevation (m)	Distance (km)	Speed Average (km/h)			Acceleration 95th percentile[a] (m/s^2)			Road Grade Average (%)			VSP[a] Average (kW/ton)		
				F[b]	S	A	F	S	A	F	S	A	F	S	A
AB	Uphill	620 to 1490	23.8	68	72	70	0.52	0.89	0.56	3.7	3.6	3.7	11.4	12.1	11.7
BC	Downhill	1490 to 1320	13.0	62	68	74	0.66	0.89	0.89	-0.9	-0.8	-0.9	2.8	3.1	3.6
CD	Uphill	1320 to 1700	7.9	62	66	68	0.45	0.89	0.45	4.3	4.2	4.4	11.0	11.9	11.9
DE	Uphill	1700 to 1830	17.7	68	71	73	0.55	0.89	0.59	1.2	1.1	1.2	6.8	7.2	7.2
EF	Downhill	1830 to 1040	20.8	64	69	70	0.54	0.89	0.78	-3.5	-3.6	-3.6	-2.1	-2.2	-2.0
FG	Arterial	1040 to 940	34.4	63	62	65	0.88	0.89	0.89	-0.2	-0.2	-0.3	3.9	4.1	4.5
GH	Curves Uphill	940 to 1370	9.7	48	54	55	0.76	1.04	0.76	4.7	4.6	4.5	8.0	9.7	9.1
HI	Downhill	1370 to 680	24.6	60	58	55	0.66	0.89	0.83	-2.7	-2.9	-2.6	-0.4	-0.6	-0.2
IJ	Freeway	680 to 660	41.4	65	72	72	0.59	0.89	0.89	0.0	0.2	0.2	5.4	6.1	6.0

Link\Vehicle	Description	Avg. Fuel Use Rates (g/s)			Avg. CO Rates (mg/s)			Avg. NO_x Rates (mg/s)		
		F	S	A	F	S	A	F	S	A
AB	Uphill	1.91	2.39	2.09	7.31	8.69	9.18	0.47	0.42	1.32
BC	Downhill	0.83	1.17	1.07	0.69	2.87	2.00	0.16	0.23	0.95
CD	Uphill	1.94	2.45	2.23	6.11	7.36	9.03	0.47	0.51	1.56
DE	Uphill	1.23	1.50	1.30	2.01	3.46	3.54	0.16	0.44	1.16
EF	Downhill	0.50	0.78	0.42	1.14	1.88	0.88	0.25	0.20	0.15
FG	Arterial	0.97	1.16	1.05	0.93	1.91	1.90	0.18	0.30	0.95
GH	Curves Uphill	1.48	2.04	1.88	12.8	14.4	9.23	0.69	0.31	1.48
HI	Downhill	0.55	0.77	0.51	0.57	0.65	0.39	0.14	0.25	0.23
IJ	Freeway	0.96	1.29	1.13	1.85	1.48	2.00	0.14	0.18	1.05

[a] VSP = Vehicle Specific Power; [b]F = 2012 Ford Fusion, S = 2012 Toyota Sienna, A = 2012 Dodge Avenger

3.3 Comparison of Vehicle Activity, Fuel Use and Emission Rates in Different Links

To enable comparison among different road types and real-world driving conditions, average speed, acceleration, road grade, VSP, fuel use, emissions rates of CO and NO_x are summarized in Table 23 for each vehicle for each link measured in the HM area.

For 7 of the 9 links, the average speeds range from approximately 60 to 75 km/h. Although link IJ is comprised of freeways, the average speed is about 65 km/h because of congestion on I-26. This road is curvy with short entrance and exit ramps, and associated weaving, which tends to suppress vehicle speed. For the links GH and HI, the average speeds are about 55 km/h, because these links are mainly curvy and hilly roads.

The Toyota Sienna has the highest 95th percentile acceleration rates when driving in mountainous area (i.e. links AB through EF, GH, HI). The Sienna has a power to curb weight ratio of 0.62 hp/lb versus only 0.50 hp/lb for the other two vehicles.

Links AB and CD have similar average VSP values of approximately 12 kW/ton, which is the highest among all links. The fuel use rates on links AB and CD are higher, for each vehicle, than on any of the other seven links. With the exception of link GH, the CO and NO_x emission rates are also typically higher. Thus, as expected, the links with the highest average VSP tend to have the highest fuel use and emission rates. Although link GH does not have the highest average VSP, it has the highest average positive road grade and thus represents a hill climbing scenario. CO emission rates are particularly sensitive to short episodes of high power demand, and thus the average CO emission rates are highest for this link. For the links with negative average VSP, such as links EF and HI, the average fuel use rates for each vehicle are lower than for any other link, as expected. The NO_x emission rates are typically among the lowest compared to other links. The

CO emission rates for link HI are lower than for any other link, but are somewhat higher for link EF.

The Sienna, with the largest engine and weight, had higher fuel use rates compared to the other vehicles for all links. Although the Avenger and Fusion have similar engine power, displacement, and number of cylinders, and similar vehicle weight, the Avenger had the highest CO emission rates for four links, and the highest NO_x emission rates for most links. This is an indication that CO and NO_x emission rates do not necessarily correlate with fuel use rates.

Links AB and HI have comparable elevation range, distances, and average speeds, but have road grades that are approximately opposite in magnitude. The average fuel use rates were higher by a factor of 3 to 4 for the uphill link AB compared to the downhill link HI. The average CO and NO_x emissions rates were higher by factors of 13 to 24 and 2 to 6, respectively. The inter-vehicle variability in CO emission rates is larger than for fuel use rates or NO_x emission rates.

Links DE and IJ have similar average VSP but differ in altitude by over 1,000 m. For all three vehicles, the average fuel use rates and emission rates of CO and NO_x are higher by 19 percent, 30 percent, and 69 percent for the high altitude link DE.

The fuel use, CO emission, and NO_x emission rates for uphill links (i.e. links AB, CD, DE, GH) were higher than for the approximately flat link FG by 74 percent, 370 percent, and 54 percent, respectively, averaged over the three vehicles. For downhill links (i.e. links BC, EF, HI) compared to the approximately flat link FG, the fuel use, CO emission, and NO_x emission rates were lower by 36 percent, 33 percent, and 47 percent, respectively.

The sample correlation of link average fuel use rate versus link average road grade is 0.95, 0.96, and 0.98 for the Fusion, Sienna, and Avenger, respectively. On average, for every 1 percent increase in road grade, the fuel use rates increase from 0.17 to 0.22 g/s, for the observed average speeds of 55 to 75 km/h. The correlation of link average fuel use rate versus link average speed or link average acceleration is less than 0.2 for each vehicle.

4. Conclusions

A method has been demonstrated to evaluate the joint effect of road grade and altitude on fuel use and emission rates for light-duty gasoline vehicles based on real world measurements of in-use vehicles.

Changes in elevation in the LP and HM areas were accurately measured, leading to distributions of estimated grade that were more variable in the HM area, as expected. The Asheville cycle also had a higher frequency of hill climbing. The precision of the road grade estimates was better in the LP area, which may be partly associated with less tree cover over the roads. The precision could be improved by using more GPS/BA receivers.

The modal fuel use and emission rates for high altitudes (over 1,000 m) were typically higher than at low altitudes (less than 200 m), but the comparison also includes differences in terrain. For most of the VSP modes for the three vehicles, the modal average speed, acceleration, grade, RPM and MAP, were statistically significantly different for HM versus LP vehicle operation. Thus, future work in which vehicle activity is measured for similar ranges of grade at each of high and low altitude areas could provide a more controlled basis for evaluating the effect of altitude.

When comparing the Asheville to Raleigh driving cycles, the rates of fuel use, CO emissions, and NO_x emissions were higher by an average of 9, 2, and 17 percent, respectively. Thus, as expected, the cycle with more variation in grade and more frequency of hill climbing had higher average rates. The higher altitude may also be a contributing factor to the difference.

As expected, the link average fuel use and emission rates were sensitive to road grade. For speed ranges of 80 km/h or less, road grades of -4 percent or less have no effect on fuel use and emission rates, since there is no power demand on the engine. Fuel use rates increase approximately linearly with grade for grades over -4 percent. CO and NO_x emissions rates also typically increase with road grades.

The fuel use rate averaged 11 percent higher for the HM versus LP areas, and the CO and NO_x emission rates were higher by approximately 60 percent and 20 percent, respectively, for either of the Raleigh and Asheville cycles. Variability in fuel use rate is more sensitive to variation in the observed grades than to differences in study area. However, CO and NO_x emission rates appear to be comparably or more sensitive to study area than road grade. Results for HC emission rates were generally inconclusive because most of the modal average exhaust concentrations were below detection limit. However, there was evidence that the HC emission rates for one vehicle were higher for the HM versus LP area.

The sample size of three vehicles is small, and thus it is not advisable to generalize these results to a larger fleet. However, the apparent sensitivity of light duty gasoline vehicle fuel use and emission rates to the joint effect of terrain and altitude merits further evaluation.

5. Acknowledgement

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