ABSTRACT

GRAVER, BRANDON MICHAEL. Measurement, Prediction, and Evaluation of Microscale Energy Use and Emissions for a Plug-In Hybrid Electric Vehicle Based on Real-World Driving Data. (Under the direction of Dr. H. Christopher Frey.)

As the effects of climate change continue to concern the world's population, many look to the automobile industry to research and create technology that will help to combat increases in anthropogenic greenhouse gas emissions. Over the past decade, hybrid automobile transmissions have been commercially available that allow for lower fuel use and, therefore, lower emission rates. In recent years, some corporations have started to retrofit existing hybrid vehicles, creating plug-in hybrid electric vehicles (PHEVs), which include a second battery that can be plugged into any electrical outlet. This allows for travel on an electrical current discharged from a battery without combusting a single drop of fuel for a set distance. When this battery has completely discharged, the PHEV returns to its roots as a hybrid vehicle; its engine providing greater driving range. To develop a prototype of a framework for quantifying PHEV energy use and emissions at a microscale (approximately second-by-second), field measurements were conducted using a Toyota Prius retrofitted with an A123 Hymotion plug-in battery system. Three systems were used for in-use monitoring of the PHEV: (1) electronic download from the hybrid control system interface for factors such as battery charge, voltage, and current, and on-board diagnostic (OBD) data such as vehicle speed, engine RPM, and fuel flow rate; (2) portable emission measurement system (PEMS) measurement of exhaust gas concentrations; and (3) GPS monitoring of coordinates and altitude using a barometric altimeter. PHEV operating modes were defined based on engine status, vehicle speed, battery status, and vehicle acceleration. PHEV energy use and emissions were estimated with respect to estimated vehicle specific power. Data were

collected over seven routes for which there were two to eight repeated runs each. Depending on the route, there was substantial variability in the number of engine starts per mile. The indirect emissions from the electricity grid were substantial for CO_2, NO_X, SO_2, and particulate matter (PM), but were very small for CO and hydrocarbons (HC). Fuel economies based only on direct consumption of gasoline were quantified, as was the equivalent fuel economy based on the sum of direct gasoline consumption plus energy consumed to provide electrical power from the grid. Implications of the field results for estimation of the activity, energy use, and emissions of PHEVs are discussed. A model was created to predict future operation modes and to estimate instantaneous fuel use and emissions for the vehicle based on easily accessible parameters, such as vehicle speed and engine RPM.

Measurement, Prediction, and Evaluation of Microscale Energy Use and Emissions for a Plug-In Hybrid Electric Vehicle Based on Real-World Driving Data

by
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BIOGRAPHY

Brandon M. Graver was born in New York's picturesque Hudson Valley in April 1986. He received his Bachelor of Science in Environmental Engineering and Science, Technology & Society from the oldest technological university in the English-speaking world – Rensselaer Polytechnic Institute – in May 2008. He joined the Department of Civil, Construction and Environmental Engineering at North Carolina State University in August 2008 to pursue a Master of Science degree. His research focuses on the estimation and measurement of energy use and emissions in the transportation sector. This thesis completes the requirements for that degree.

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PART I
INTRODUCTION

1.0 Overview

This chapter provides an overview of this thesis including introduction, objectives, major research tasks, and organization.

1.1 Introduction

In 2007, there were 254 million personal vehicles on U.S. roadways in 2007, of which 53 percent were passenger cars and 39 percent were sport utility vehicles and light trucks. On average, each vehicle traveled 48 miles each day (BTS, 2010). Transportation accounts for 28 percent of U.S. energy use, and contributes 33 percent of national carbon dioxide (CO_2) emissions. Approximately two-thirds of transportation fuels consumed in the U.S. are imported (EIA, 2010). Highway vehicles contribute 40 percent of national annual nitrogen oxides (NO_X), 56 percent of carbon monoxide (CO), and 28 percent of volatile organic compounds (VOCs) emissions (EPA, 2008). Plug-in hybrid electric vehicles (PHEVs) could alleviate two critical transportation problems, air pollution and energy security, because of higher energy efficiencies compared to conventional vehicles (Markel and Simpson, 2006; Gonder and Brooker, 2009).

Hybrid electric vehicles (HEVs) are powered by an internal combustion engine (ICE) and one or more electric motors. The motors use electricity from a battery to provide propulsion in combination with or instead of the ICE. Conversely, one or more of the motors can operate in reverse as a generator, converting shaft output from the engine or from the powertrain during braking to recharge the battery (Toyota, 2008). There are three types of

HEV powertrains available: parallel, series, and mixed. In a parallel hybrid, both the ICE and the electrical motors are connected mechanically to the transmission. In a series hybrid, only the electrical motor is connected to the transmission and the ICE generates power for the motor. A mixed hybrid can act either in parallel or series.

The first commercially available production PHEV, the Chevrolet Volt, is now available (Hirsch, 2010). However, for several years, PHEV retrofit kits have been available for HEVs, such as the Toyota Prius. The retrofit involves installing an additional plug-in battery that can only be recharged by plugging it into the electric grid. The original battery of the Prius, referred to as the "traction" battery, is recharged only during vehicle operation. Charge Depleting (CD) mode occurs until the plug-in battery reaches a state-of-charge (SOC) set point, after which the plug-in battery is no longer used until it can be later recharged from the grid. During Charge Sustaining (CS) mode, the traction battery acts as a reservoir of power. During both CD and CS modes, the traction battery is discharged and recharged depending on vehicle power demand and operating conditions (Bradley and Frank, 2009). The traction battery SOC is maintained between lower and upper set points in order to prolong battery life (Toyota, 2008).

The major components of the retrofitted Prius are shown in Figure 1. The Prius has two motor-generators (MGs) that are referred to as MG1 and MG2. MG1 is used as an engine starter. The planetary gear (PG) system enables the transmission of power among the ICE, MGs, and the drive shaft. The PG system has three sets of gears, including a "sun", or central, gear, planetary gears that revolve around the sun gear, and a ring gear that circumnavigates the planetary gears, as shown in Figure 2. This complex configuration of gears enables operating modes with variations in the power split between the ICE and MGs. Examples of operating modes include, but are not limited to: (a) low speed cruising in which only the traction battery is used to power the drivetrain, (b) moderate speed cruising during which the engine is used to power the drivetrain, either supplemented by the traction battery or from some power that is diverted to recharge the traction battery, and (c) regenerative braking, during which MG2 is operated as a generator to extract power from the drive wheels, thereby slowing the vehicle and recharging the traction battery.

While there is not a standardized definition of operating modes for a PHEV, they can be classified based on whether the vehicle is: (a) at zero versus non-zero speed, and (b) decelerating, cruising, or accelerating. Furthermore, operating modes can be stratified taking into account conditions under which the engine is on versus off, and whether the traction battery is discharging or recharging. Transient engine status is characterized as times when the engine does not consume fuel, but there is an RPM reading. The engine RPM remains around 1000, where it could be easily ramped up if more power is needed or ramped down if battery power can be utilized for an extended time. One example of a transient state occurring is when the driver "tricks" the engine to turn off, while still maintaining speeds where the engine would typically still remain on.

Most evaluations of PHEV technology focus on fuel economy, with less attention to emissions of NO_X, CO, and HC. Some of the currently available methods and data for evaluating PHEV energy use and emissions (EU&E) are typically based on dynamometer tests that do not take into account real-world activity patterns (Gonder and Brooker, 2009; Karner and Francfort, 2007). Real-world driving cycles are recommended as the basis for estimating fuel economy (Gonder and Simpson, 2007); however, there is a lack of such real-world data. Real-world measurements better describe real-world variability in energy use and emissions based on varying driver behavior and vehicle characteristics (Gonder and Brooker, 2009). GPS-instrumentation has been used to obtain PHEV activity data but without simultaneous measurements of real-world EU&E (Gonder *et al.*, 2007). Selected PHEV designs have been assessed based on hypothetical travel distances and surveys of driver habits based on conventional vehicles (CVs) (Bradley and Frank, 2009). In a cost-benefit analysis of PHEV technology, Markel and Simpson assume a generic PHEV capable of traveling 20 miles in charge depleting mode, but did not use real world activity or EU&E data (Markel and Simpson, 2006). Idaho National Laboratory (INL), under the Vehicle Technologies Program, is conducting an extensive real-world measurement study on focusing mainly on characterizing energy consumption from a fleet of 184 retrofitted HEVs (INL, 2010). Because CO_2 emissions are proportional to fuel consumption, such emissions are estimated in the context of measuring PHEV fuel economy (Bradley and Frank, 2009; Stephan and Sullivan, 2008). Fuel use, CO_2, CO, HC, and NO_x emissions were estimated by Silva *et al.* for two idealized PHEV configurations using the Advance Vehicle Simulator, ADVISOR, software tool (Silva *et al.*, 2009). In-use measurement of activity, energy use, and emissions has been completed on a PHEV school bus (Choi and Frey, 2010). However, PHEV EU&E will vary by vehicle size and weight.

Currently, there is not a fuel economy standard for vehicles that run on both fuel and electric power. The Society of Automotive Engineers suggests calculating “off-vehicle-charge equivalent fuel use” using an electricity-to-gasoline equivalent conversion value of

33,440 W-h/gal that is specified in 10 CFR Part 474 (SAE, 1999). However, this value unrealistically assumes 100 percent power plant and transmission efficiency. Argonne National Laboratory and the National Renewable Energy Laboratory recommend not combining fuel and electricity into a single equivalent MPG result, but rather reporting both MPG and electricity usage, in Wh/mi, separately (Karner and Francfort, 2007; Duoba *et al.*, 2009).

1.2 Objectives

The work of this thesis is motivated by the needs for microscale EU&E models for PHEVs. The main objectives of this thesis are to:

(1) Quantify real-world, microscale energy use and emissions of a PHEV; and

(2) Develop capabilities of predicting real-world, microscale energy use and emissions of a PHEV

1.3 Overview of Major Research Tasks

The following seven major research tasks are needed to achieve the main objectives of this thesis:

(1) Demonstration of an approach for quantifying real-world energy use for PHEV operating modes

(2) Demonstrate an approach for quantifying tailpipe emissions for PHEV operating modes

(3) Assessment of variability in grid emissions during CD mode based on geographical variation in electricity generation resource mixes

(4) Demonstration of a method for quantifying the energy economies of PHEVs

(5) Demonstration of an approach for quantifying when the plug-in battery is in operation

(6) Demonstration of an approach for quantifying when the ICE is in operation

(7) Development of fuel use and emission models for a selected PHEV

1.4 Organization

This thesis consists of four parts, with the main body comprised of two journal manuscripts, Parts II and III. These manuscripts are prepared to be submitted for publishing. For each part of this thesis, there is a separate reference list and supporting information. Appendices are given at the end.

Part I, which is this part, describes general information regarding highway vehicle emissions in the U.S., the current state of the art of vehicle technologies, the needs for development of microscale vehicle-specific emission models, the research objective and tasks of this work, and the organization of this thesis.

Part II gives details regarding instrumentation and experimental design for real-world EU&E measurement of a PHEV. It compares VSP modal EU&E for alternative routes between selected origin and destination pairs in the study area. Comparisons were also done based on geographical variation in electricity generation in electricity generation resource mixes, used to recharge the plug-in battery.

Part III develops a methodology of modeling EU&E of a PHEV based on the in-use measurement described in Part II. Plug-in battery and ICE operation rules were derived and verified. Fuel use and emissions are estimated as the product of average VSP modal EU&E rates and time spent in a corresponding VSP bin, while the engine is on.

Finally, the main conclusions of this study and the recommendations for future studies are presented in Part IV.

Ten appendices are given in this thesis. Appendix A provides turn-by-turn directions of the eight routes tested with a PHEV. Appendix B describes the precision, accuracy, and calibration of the PEMS. Appendix C presents a schedule of the routes driven each of the seven test days. Appendix D provides a comparison of fuel use reported by the OBD and refueling amount reported by gas receipts, and plug-in battery electricity use reported by the OBD and recharging amount reported by a Watt-meter. Appendix E presents state average emission factors of CO_2, NO_x, and SO_2 from electricity generation. Appendix F compares emission rates for each route depending on average emission factors for electricity generation in California, Idaho, Indiana, North Carolina, and Vermont. Appendix G provides graphs of tailpipe emissions versus Vehicle Specific Power. Appendix H describes PHEV operating mode characteristics and associated emission rates. Appendix I presents a matrix of transitions between PHEV operating modes. Appendix J provides time traces of vehicle activity and emission rates for a selected route on a selected test day.

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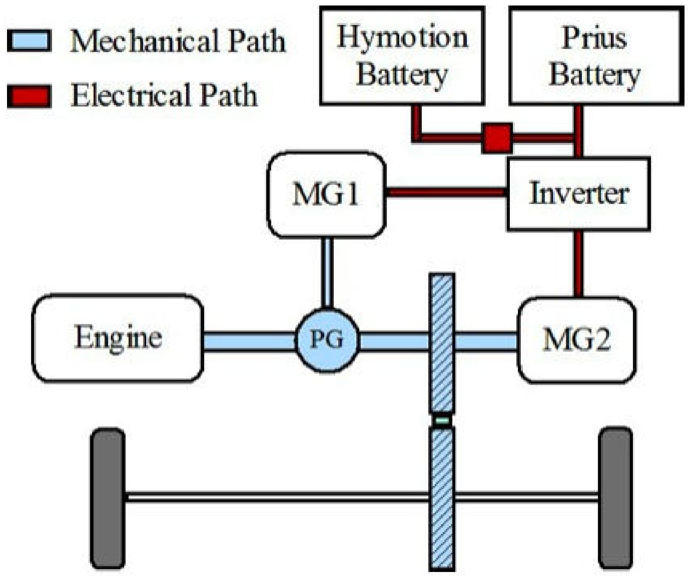
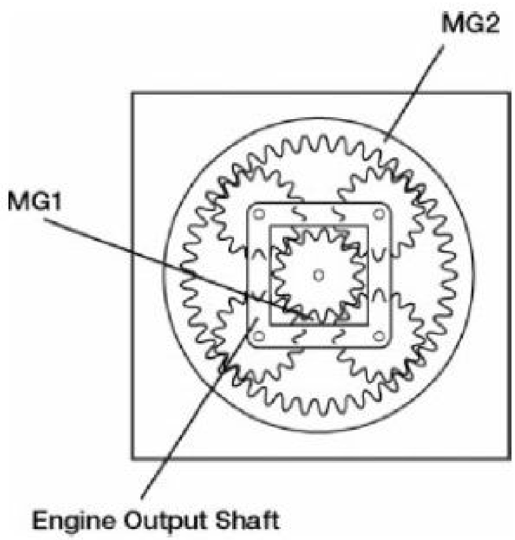


MG: Motor-Generator, PG: Planetary Gear

FIGURE 1 Power flow diagram for plug-in hybrid Toyota Prius.



Sun Gear: MG1, Ring Gear: MG2, Carrier (Planetary Gears): Engine Output Shaft

FIGURE 2 Planetary gear system diagram (Toyota, 2008).

PART II
IN-USE MEASUREMENT OF ACTIVITY, ENERGY USE, AND EMISSIONS OF A PLUG-IN HYBRID ELECTRIC VEHICLE

2.0 Overview

Plug-in hybrid electric vehicles (PHEVs) could mitigate two critical transportation problems: air emissions and energy security. However, there is not yet an accepted methodology for estimating on-road emissions of PHEVs. To develop a prototype framework for quantifying PHEV energy use and emissions (EU&E) at a microscale, field measurements were conducted on a Toyota Prius, retrofitted with an A123 Hymotion plug-in battery. Three systems were used for in-use monitoring of the PHEV: (1) electronic download from the hybrid control system interface of energy flow and on-board diagnostic (OBD) data; (2) portable emission measurement system (PEMS) measurement of exhaust gas concentrations; and (3) GPS monitoring of coordinates and altitude. EU&E were estimated with respect to estimated vehicle specific power. Fuel economy is quantified based on (1) direct consumption of gasoline; and (2) the sum of direct gasoline consumption and energy consumed to provide electrical power from the grid. Emissions associated with electricity consumption are estimated based on the mix of fuel sources used in North Carolina and nationally to generate electricity. The indirect emissions from the grid were substantial for CO_2, NO_x, SO_2, and particulate matter (PM), but not for CO and hydrocarbons (HC).

2.1 Methods

A methodology is developed and applied for real-world evaluation of PHEVs to characterize electricity use, fuel use, and emissions. The methodology features the use of a portable emissions measurement system (PEMS) to quantify the activity, energy use, and emissions of vehicles on a second-by-second basis during actual duty cycles. To demonstrate the methodology, field data collection was conducted on a Toyota Prius retrofitted with a plug-in conversion kit operated on eight selected routes in the Research Triangle Park, NC area.

2.1.1 Field Study Design

The field study design consists of the specification of controllable test conditions, including the choice of test vehicle, driver, fuel, initial state-of-charge, driving routes, and time of day for each route.

The test vehicle was a 2005 Toyota Prius HEV retrofitted with an A123 Hymotion plug-in battery system. The vehicle was operated on local retail unleaded gasoline, with an 87 octane rating and a maximum 10% ethanol content as regulated under the Clean Air Act (US Code, 2008). The fuel tank was filled and the plug-in battery was fully recharged overnight prior to each day of field measurements. The gallons of gasoline required to refill the tank at the end of each day were recorded. A watt-hour meter was used to measure the amount of grid electricity consumption during recharge.

The PHEV was operated on eight selected routes, described in Table 1. Six of these routes were used in previous PEMS data collection with conventional light duty gasoline vehicles (Frey *et al.*, 2008a). These routes are based on two origin and destination (O/D) pairs: (1) North Carolina State University (NCSU) to North Raleigh (NR); and (2) NR to Research Triangle Park (RTP). For each O/D pair, there are three alternative routes. Routes A, B, and C from NCSU to NR are comprised primarily of signalized minor and major arterial roads and represent local commuting within Raleigh over a one-way distance of approximately 8 to 11 miles. Routes 1, 2, and 3 from NR to RTP are comprised primarily of major arterial roads and freeways and represent commuting from a residential district to the RTP business district over a one-way distance of approximately 16 to 20 miles. Route D is comprised of major arterial roads and freeways over 12 miles and represent a commute from Southeast Raleigh to NCSU's Centennial Campus. Route E is comprised of minor arterial roads and represents 3 miles of driving within Centennial Campus.

2.1.2 Instruments

Three key instruments were used for field data collection: (1) an electronic control unit (ECU) data logger; (2) a PEMS; and (3) a geographic position system (GPS) with barometric altimeter. Externally observable variables (EOVs) and internally observable variables (IOVs) were measured. EOVs can be characterized, in principle, by an observer outside of the vehicle. These include, for example, vehicle speed, vehicle acceleration, and road grade. IOVs can only be observed within the vehicle, such as engine RPM and electrical current to or from a battery. A combination of both EOVs and IOVs can be used to provide detailed quantitative characterization of EU&E. EOVs could be used to develop modeling approaches for use in traffic simulation and emission factor models.

The Kvaser Memorator ECU data logger was used to record vehicle road speed, voltage and current associated with electricity flow to or from the plug-in and traction batteries, state-of-charge of each battery, engine RPM, and fuel flow rate.

The PEMS used is the OEM-2100 Montana system, manufactured by Clean Air Technologies International, Inc. The Montana system is comprised of two parallel, five-gas analyzers, a particulate matter (PM) measurement system, an engine sensor array, a global positioning system (GPS), and an on-board computer (CATI, 2003). The precision, accuracy, and calibration of the PEMS are described by Frey *et al.* (2003, 2008a, 2008b).

Exhaust gas concentration from the PEMS and fuel flow rate from the ECU were used to estimate the exhaust flow rate of each pollutant (Vojtisek-Lom and Allsop, 2007). From the measured data, the air-to-fuel ratio, inlet air flow and exhaust gas flow rates are estimated. Based on the exhaust gas flow rate and the exhaust gas concentrations, the mass per time emission rates were estimated.

A Garmin GPSmap 76CSx GPS unit with barometric altimeter was used to record coordinates and elevation on a second-by-second basis. The coordinates were used to match vehicle location relative to each test route, and to estimate distances between elevation measurements. The differences in elevation over a distance were used to estimate road grade.

2.1.3 Vehicle Specific Power

Vehicle specific power (VSP) has typically been used to estimate the fuel consumption of conventional light duty gasoline vehicles (LDGV). VSP is an estimate of the power output required of the drivetrain in order to move the vehicle. VSP accounts for the kinetic energy of vehicle movement, acceleration due to gravity, rolling resistance, and aerodynamic drag. Based on typical values of rolling resistance and aerodynamic drag, VSP is estimated as (Jimenez-Palacios, 1999):

$$\mathrm{VSP} = 0.278v\,[0.305a + 9.81r + 0.132] + 0.0000065v^3 \qquad (1)$$

Where VSP = vehicle specific power (kW/ton); v = vehicle speed (km/h); a = vehicle acceleration (km/h per sec); and r = road grade (%).

Here, VSP is used to account for the energy demand of a PHEV, rather than the fuel demand of an LDGV (Choi and Frey, 2010). For a conventional LDGV, vehicle fuel use is typically constant for negative values of VSP, and increases linearly with positive VSP (Frey *et al.*, 2008a). For a PHEV, the battery-motor system will sometimes augment the power output of the engine during plug-in and/or traction battery discharge, and at other times consume some of the engine output for recharging the traction battery.

2.1.4 Direct and Indirect Emissions

ICE fuel consumption is reported by the ECU in microliters (μL) of fuel during each reporting period, approximately a 0.7 second interval. These data were integrated over time and used to estimate fuel consumption on a second-by-second basis. For validation, reported fuel use over the entire test day was compared to the amount of gasoline used to refill the fuel tank after testing.

The electrical power extracted from the plug-in battery was estimated based on ECU-reported voltage and current. For the traction battery, the amount of electricity associated with either discharge or recharge, in Watt-hours, was estimated on a second-by-second basis. Plug-in battery electricity use was compared to the amount of grid electricity used to recharge the battery after each day of testing.

The net electricity obtained from the electric grid to recharge the plug-in battery after a day of data collection was used to estimate the gasoline-equivalent amount of fuel consumed by power plants to generate and deliver the electricity to the grid. The national average heat rate for power plants is 10,132 BTU of thermal energy input per kWh generated (EIA, 2010). Gasoline has a heating value of approximately 115,500 BTU/gallon, and density of 2,790 g/gallon (EPA, 2007a). Thus, each kWh of electricity obtained from the grid corresponds to the potential energy contained in 0.088 gallons of gasoline equivalent. The indirect energy use from power generation is estimated for several geographic locations based on the North American Electric Reliability Corporation (NERC) regions. Gasoline-equivalent fuel economy is estimated when the vehicle is operating in part on electricity stored in the plug-in battery.

2.1.5 Data Quality Assurance

The key steps to process raw data from the data logger, PEMS, and GPS with barometric altimeter are: (1) convert data to a second-by-second basis, if necessary; (2) synchronize the data from multiple instruments into a single database; and (3) screen and evaluate the data for possible errors, correct errors where possible, and remove invalid data that cannot be corrected. Details of the data processing and quality assurance procedure are given by Frey *et al.* (2003, 2008a, 2008b, 2010).

2.2 Results

Based on second-by-second data collected for eight routes in the RTP area, results are given for quality assurance, energy use for both gasoline and electricity from the grid, tailpipe and electric grid emission factors, and fuel and electricity consumption as a function of VSP.

2.2.1 Data Collection and Quality Assurance

Two drivers collected seven days of data in November 2008. For six of the test days, the vehicle initially operated in CD mode. A total of 121,908 seconds of data were collected over the eight routes. Of these data, 6.4 percent were excluded because of data quality issues, particularly with respect to large discrepancies in simultaneous exhaust gas concentrations when comparing the parallel gas analyzers in situations in which the engine is turning on or off.

2.2.2 Energy Use for Gasoline and Grid Electricity

The amount of grid electricity and gasoline used during vehicle operation on each of the eight routes is given in Table 2. Total battery discharge, averaging 3.8 kWh per day, occurred among multiple route segments in which CD mode is observed. For example, on Test Day 1, 1.3 kWh was used during the 11.6 mile outbound leg of Route C and 2.5 kWh was used over 20.1 miles of the outbound leg and 7.0 miles of the inbound leg of Route 2. An average of 33 miles per day was driven in CD mode.

On average, the daily fuel use reported by the ECU agreed with the actual amount of gasoline needed to refill the tank to within 3 percent. For all routes, the fuel economy based on consumption of gasoline is 28 to 95 percent higher during CD mode than CS mode. Gasoline fuel economies were, on average, approximately 33 percent higher for routes that contained less interstate driving and more engine starts per mile, such as Routes A and B. The gasoline and grid equivalent fuel economy is lower than the gasoline fuel economy for CD mode by an average of 42 percent, and similar to the gasoline fuel economy for CS mode.

According to the U.S. Environmental Protection Agency (EPA), the 2005 Toyota Prius HEV has a combined fuel economy of 46 mpg (EPA, 2010a). CD mode fuel economy was found to be 7 and 9 mpg higher than NREL's dynamometer testing and INL's fleet testing of PHEVs, respectively (Gonder and Brooker, 2009; INL, 2010). CS mode fuel economy was the same as both dynamometer and fleet testing at 43 mpg, while overall equivalent fuel economy, 42 mpg, was worse than the fuel economy reported in both dynamometer and fleet testing at 49 and 48 mpg, respectively (Gonder and Brooker, 2009; INL, 2010). The observed CS mode fuel economy for the PHEV may be worse by 4 mpg than the combined fuel economy of the Prius in part because of the additional 85 kg weight of the plug-in battery (A123 Systems, 2010).

2.2.3 Direct and Indirect Emissions

The average emission factors for each route are shown in Table 3. These emission factors consist of direct emissions from the tailpipe for all routes under both CD and CS modes and the indirect emissions from electricity generation for CD mode. Emissions associated with electricity usage are estimated based on the mix of sources used to generate electricity in the Southeast Electricity Reliability Corporation, or SERC, region, which includes North Carolina. CO_2, and NO_x emission rates from electricity generation, in units of mass per kWh, are calculated based on EPA data (E.H. Pechan, 2008). Grid-based CO and HC emission rates for each fossil fuel were calculated based on EPA National Emissions Inventory data and U.S. Energy Information Administration (EIA) Annual Energy Outlook data (EPA, 2010a; EIA, 2007) to account for regional variability in emission rates, not national averages given by EPA data.

The PEMS does not measure SO_2 emissions. However, using the maximum allowable gasoline sulfur concentration of 30 parts per million (ppm) per gallon (EPA, 2000), an upper bound of the direct emission rate of SO_2 is 9.6 mg per gallon, which is approximately 12,000 times lower than the SO_2 emission rate from power plants.

In certification tests, the 2005 Toyota Prius had emission rates of 0.01 g NO_X/mile, 0.009 g HC/mile, and 0.1 g CO/mile (EPA, 2010c). The EPA Tier 2 Bin 3 emission standard, which this Prius must meet, is 0.03 g NO_X/mile, 0.055 g HC/mile and 2.1 g CO/mile (EPA, 2000). Average measured tailpipe emission rates for HC and CO were higher on most routes than the certification data, but below the EPA emission standard. Average measured tailpipe NO_x emission rates were higher than the emission standard on all routes except for Route E.

Tailpipe emission rates of CO_2 were 21 to 48 percent lower during CD mode than CS mode for all routes because of decreased fuel use. However, total CO_2 emission rates during CD mode were higher than tailpipe emission rates during CS mode for all routes except Routes A and 2. Grid emission rates of CO_2 were 27 to 47 percent of total CO_2 emission rates in CD mode on all routes.

CD mode tailpipe NO_X emission rates were lower by 16 to 73 percent compared to CS mode. Total NO_X emission rates during CD mode are higher than tailpipe emission rates during CS mode for all routes. Emission rates of NO_X from electricity use were nearly 2 to 45 times higher than CD mode tailpipe emission rates on all routes.

Tailpipe CO emission rates were 2 to 11 times higher in CD mode for Routes A through D than in CS mode. Tailpipe HC emission rates were lower in CD mode than in CS mode on the same routes, except for Route D. On these routes, lower speed driving with an increased number of signalized intersections lead to a 43 percent increase in the number of instances in which the engine turns on and off per mile than the other tested routes. Even though the relative difference in emission rates of CO and HC are large, the absolute differences are small because of very low emission rates.

Grid-related emission rates vary depending on electricity generation resource mix. For example, the Northeast Power Coordinating Council (NPCC) region, which has the lowest average emissions for electricity generation, has 36 and 55 percent lower CO_2 and NO_X power production emissions per unit of electricity generated, respectively, compared to SERC (EPA, 2007b). If the PHEV was operated in the Northeast, total CO_2 emission rates during CD mode would be similar to or lower than tailpipe emission rates during CS mode for four routes (A, 1, and 2). Total NO_X emission rates during CD mode would be higher than tailpipe emission rates during CS mode for all routes. SO_2 emission rates from the grid are substantially higher in all regions than from gasoline combustion because the sulfur concentration of gasoline is very low.

The highest grid-related CO_2 emissions are found in the Midwest Reliability Organization (MRO) region, which are 33 percent higher than in SERC. NO_x emissions are also 86 percent higher in MRO compared to SERC, while SO_2 emissions are 6 percent lower. Total CO2 emission rates in CD mode would be 18 to 100 percent higher than tailpipe emission rates in CS mode, while total NOx emission rates in CD mode would be 4 to 36 times greater than tailpipe emission rates in CS mode.

Besides NPCC, the lowest emissions of CO_2 and NO_x are found in the Western Electricity Coordinating Council (WECC) region, where emissions are 24 and 21 percent lower than SERC, respectively. SO_2 emissions are also 83 percent lower in WECC compared to SERC; the lowest in the nation.

In the SERC region, grid CO emission rates were lower than tailpipe emission rates for local driving on Routes A through E, and grid HC emission rates were lower than or similar to tailpipe emission rates on all routes except for Route 2.

2.2.4 Energy Use and Emissions versus Vehicle Specific Power

For positive VSP, the rate of fuel use increases monotonically as shown in Figure 3, but not linearly, as is the case for CVs. Fuel use is sensitive to VSP for negative values of VSP, which includes deceleration and vehicle travel at constant speed on a negative road grade (such as down a hill). During CD mode, the rate of gasoline consumption for VSP greater than -10 kW/ton is typically 0.2 to 0.4 g/s less than during CS mode. This is expected, since power from the plug-in battery is used during CD mode to provide motor power. This partially offsets the amount of engine power and, therefore, fuel needed to meet the total demand for power.

Figures 4(a) and 4(b) show the electricity consumption of the plug-in battery versus VSP for CD mode for engine off and on, respectively. The battery discharges for both negative and positive VSP, since the battery can only be recharged from the grid. As VSP increases, the discharge rate increases. For higher values of VSP, between 8 and 20 kW/ton, the discharge rate levels off, signifying saturation at a maximum rate. When the ICE is off, average battery discharge is approximately 0 to 0.7 Wh/s higher than when the ICE is on for

VSP greater than 5 kW/ton. However, for negative values of VSP, the plug-in battery discharge rate is higher when the engine is on. This is due to a lower traction battery discharge rate when the engine is on.

The electricity consumption of the traction battery versus VSP for CD and CS modes and for engine on and off is given in Figures 5(a) through 5(d). In all cases, the traction battery, on average, recharges during episodes of negative VSP and discharges during episodes of positive VSP. For both CD and CS modes, recharge and discharge of the traction battery is greater when the engine is off. When the engine is off, recharge and discharge rates are similar for CS and CD modes. Traction battery discharge rates level off for high values of VSP at approximately 2 Wh/s, signifying saturation at a maximum rate. When the engine is on, discharge rates for CD and CS modes are very small and similar for positive values of VSP.

NO_x emission rates are plotted versus VSP for CS mode in Figure 6. NO_X emission rates are approximately constant for negative VSP values, and increase as positive VSP values increase. This suggests that locations that experience high vehicle speeds and acceleration, such as major arterials and interstates, would be subject to higher NO_x emissions. This is consistent with Table 4, with high tailpipe NO_x emission factors observed on Routes 1, 2, and 3.

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TABLE 1 Characteristics of Test Routes and Field Study Results

Route Characteristics					Field Study Results			
Route Segment[a]	**Route Distance (mi)**	**Route Speed Limits (mph)**	**# Signalized Intersections**	**# of Runs**	**Total Travel Time (sec)**	**Total Travel Distance (mi)**	**Average Vehicle Speed (mph)**	**Range of Driven Speeds (mph)**
A out	10	15 – 45	41	6	8,524	60	26	0 – 62
A in	10	15 – 45	41	6	7,950	58	26	0 – 62
B out	11	15 – 60	32	6	8,579	67	28	0 – 72
B in	11	15 – 60	32	6	9,215	65	25	0 – 72
C out	11	15 – 60	29	6	8,190	66	29	0 – 80
C in	11	15 – 60	29	6	7,667	65	30	0 – 80
D	10	15 – 65	18	6	6,050	59	35	0 – 75
E	2	15 – 45	0	6	2,482	14	20	0 – 53
1 out	16	25 – 65	8	6	7,488	97	46	0 – 81
1 in	16	25 – 65	8	6	7,385	96	47	0 – 81
2 out	20	25 – 65	17	6	9,894	119	43	0 – 81
2 in	21	25 – 65	17	6	10,406	123	43	0 – 81
3 out	17	25 – 50	23	6	10,414	101	35	0 – 68
3 in	17	25 – 50	23	6	11,340	103	33	0 – 68

[a] Outbound or inbound leg of a route

TABLE 2 Route Average Equivalent Fuel Use and Fuel Economy Based on Fuel Use for Engine and Grid Electricity Use for Plug-In Hybrid System

				Fuel Use			Fuel Economy		
Route	**Mode**	**Total Dist[a] (mi)**	**Net Grid Electricity[b] (kWh)**	**Gasoline (gal)**	**Grid (gal_{eq})**	**Gasoline & Grid (gal_{eq})**	**Gasoline (mpg)**	**Gasoline & Grid (mpg)**	**Engine Starts per mile**
A	CD	49	6.7	0.58	0.60	1.18	84	42	2.1
	CS	74	---	1.71	---	1.71	43	---	4.5
B	CD	37	5.4	0.46	0.48	0.94	82	40	2.1
	CS	109	---	2.44	---	2.44	45	---	3.3
C	CD	15	2.0	0.23	0.18	0.40	66	37	3.6
	CS	131	---	2.97	---	2.97	44	---	2.4
D	CD	12	1.4	0.23	0.12	0.36	50	32	0.3
	CS	50	---	1.26	---	1.26	39	---	2.0
E	CD	3	0.4	0.05	0.03	0.08	59	34	4.5
	CS	12	---	0.31	---	0.31	39	---	5.4
1	CD	22	2.4	0.37	0.21	0.58	59	37	0.5
	CS	175	---	4.38	---	4.38	40	---	0.7
2	CD	27	2.5	0.43	0.22	0.65	64	42	1.7
	CS	221	---	5.18	---	5.18	43	---	1.1
3	CD	27	2.3	0.46	0.20	0.67	58	40	1.0
	CS	183	---	4.26	---	4.26	43	---	1.7

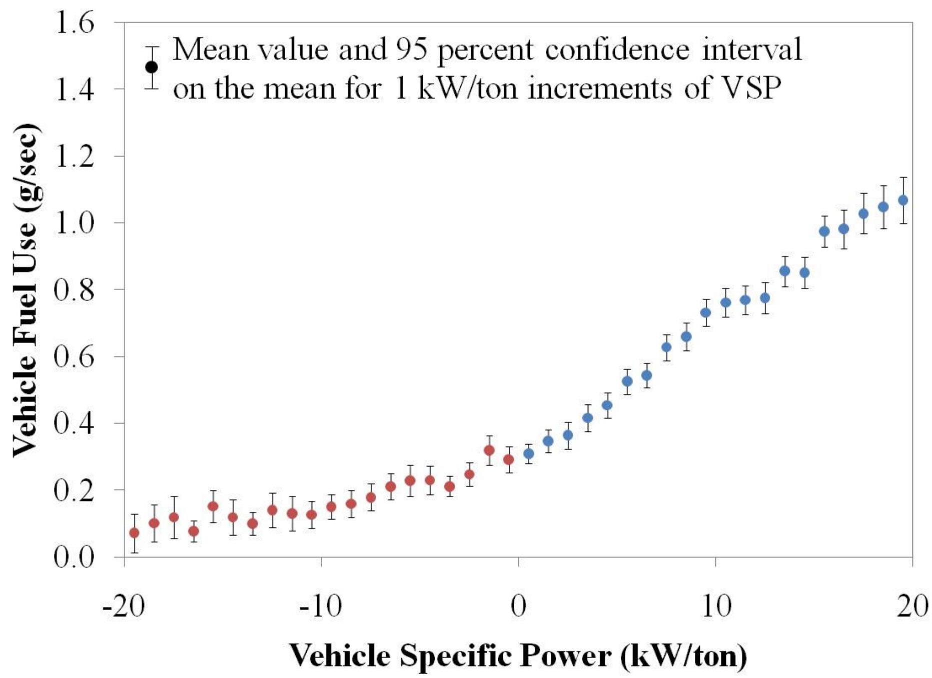
[a] There are 6 repeated roundtrip runs on each route
[b] These results include data for more than one day in the case of Routes A, B, and C.

TABLE 3 Measured Tailpipe and Estimated Southeast Reliability Corporation (SERC) Region Grid-Based Emission Factors [a, b]

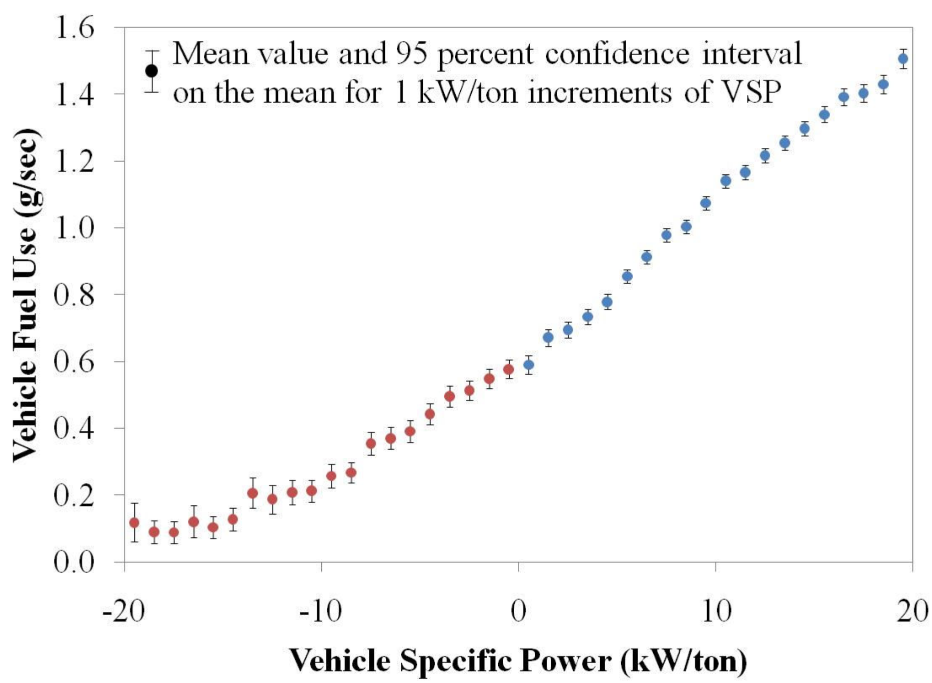
Route	Mode	Emissions Source	CO_2 (g/mi)	CO (mg/mi)	HC (mg/mi)	NO_X (mg/mi)	SO_2 (mg/mi)
A	CD	Tailpipe	105	150	17	16	< 1
		Grid	91	14	1	135	411
		Total	196	164	18	151	411
	CS	Tailpipe	202	48	68	56	< 1
B	CD	Tailpipe	107	168	25	15	< 1
		Grid	95	15	1	135	435
		Total	202	183	26	150	435
	CS	Tailpipe	197	86	44	38	< 1
C	CD	Tailpipe	133	254	18	26	< 1
		Grid	87	14	1	123	395
		Total	220	268	19	149	395
	CS	Tailpipe	200	48	71	31	< 1
D	CD	Tailpipe	176	497	60	11	< 1
		Grid	77	12	1	109	353
		Total	253	509	61	120	353
	CS	Tailpipe	224	46	15	40	< 1
E	CD	Tailpipe	148	47	< 1	3	< 1
		Grid	96	14	1	135	435
		Total	244	61	1	138	435
	CS	Tailpipe	227	96	178	9	< 1
1	CD	Tailpipe	150	< 1	1	20	< 1
		Grid	73	11	1	102	329
		Total	223	11	2	122	329
	CS	Tailpipe	220	27	25	71	< 1
2	CD	Tailpipe	138	15	10	31	< 1
		Grid	60	10	1	85	275
		Total	198	25	11	116	275
	CS	Tailpipe	206	57	29	52	< 1
3	CD	Tailpipe	152	< 1	4	45	< 1
		Grid	56	9	1	80	257
		Total	208	9	5	125	257
	CS	Tailpipe	204	46	55	56	< 1

[a] Emissions for electricity generation in SERC are calculated based on 2007 EPA eGRID data for CO_2, NO_X, and SO_2, and 2005 NEI data for CO and hydrocarbons (HC), and account for a 7% transmission loss between the power plant and vehicle recharging station. The average electric utility emission factors are 664 g CO_2/kWh, 935 mg NO_X/kWh, 3.03 g SO_2/kWh, 152 mg CO/kWh, and 11 mg HC/kWh. Tailpipe SO_2 emissions are based on ≤ 30 ppm sulfur in gasoline.

[b] SERC electricity generation mix is 57.1% coal, 24.2% nuclear, 11.7% gas, and 7.0% other sources.

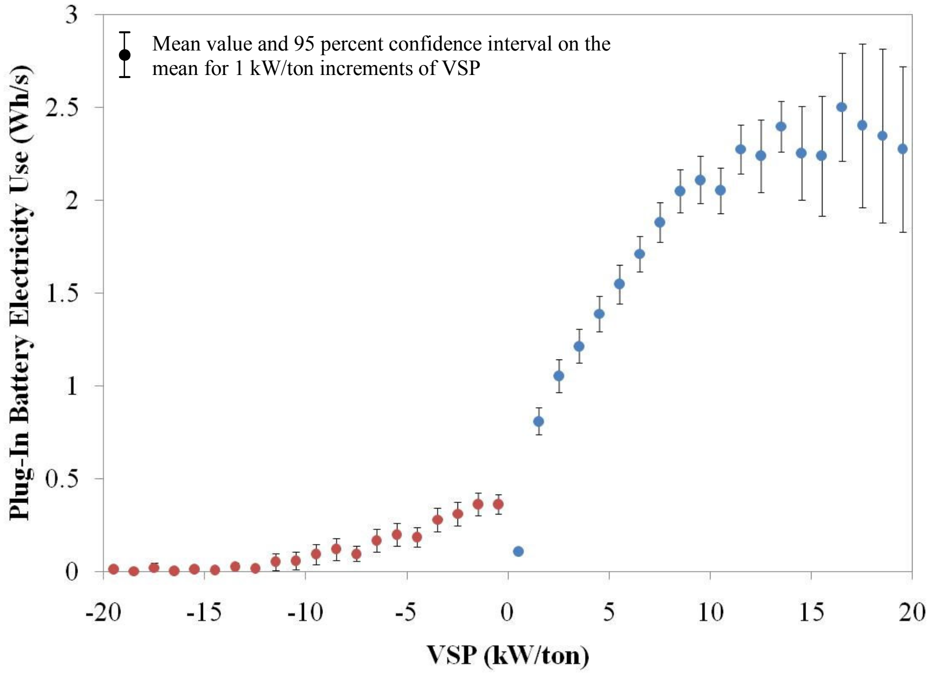


(a) Vehicle fuel use for charge depleting mode

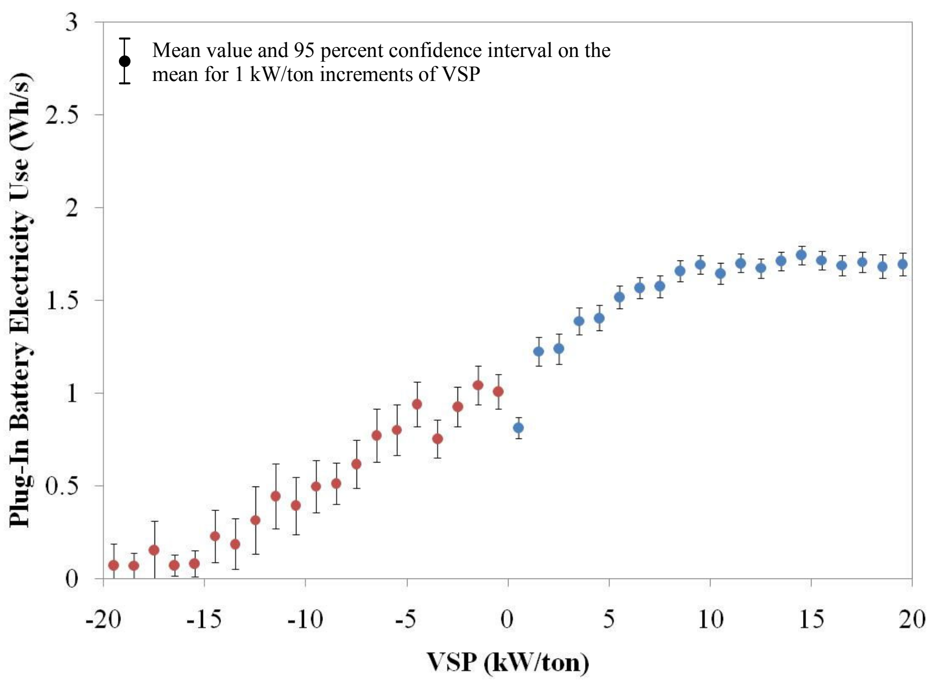


(b) Vehicle fuel use for charge sustaining mode

FIGURE 3 Vehicle fuel use versus vehicle specific power.

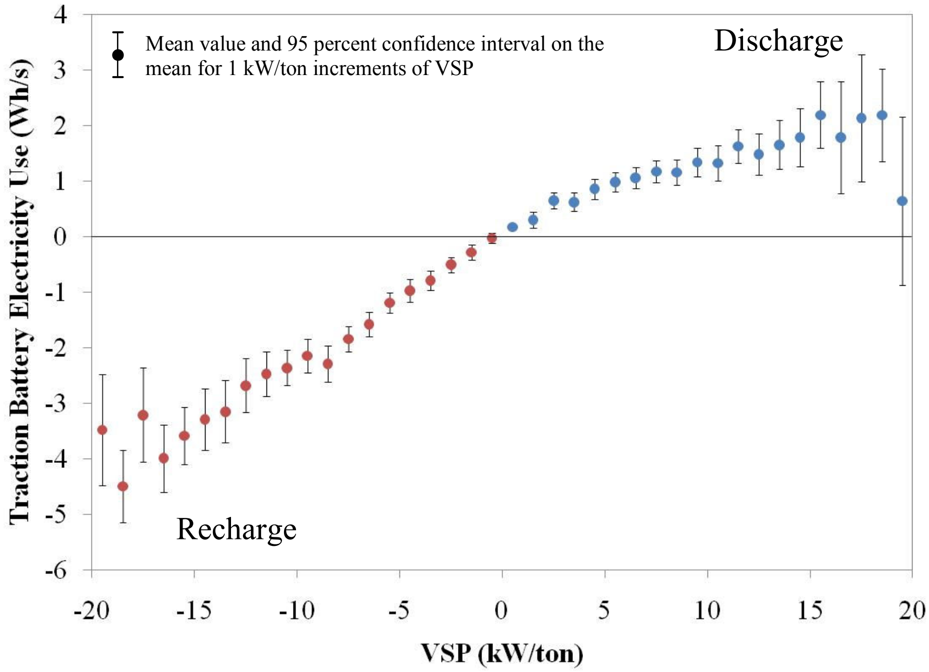


(a) Engine off

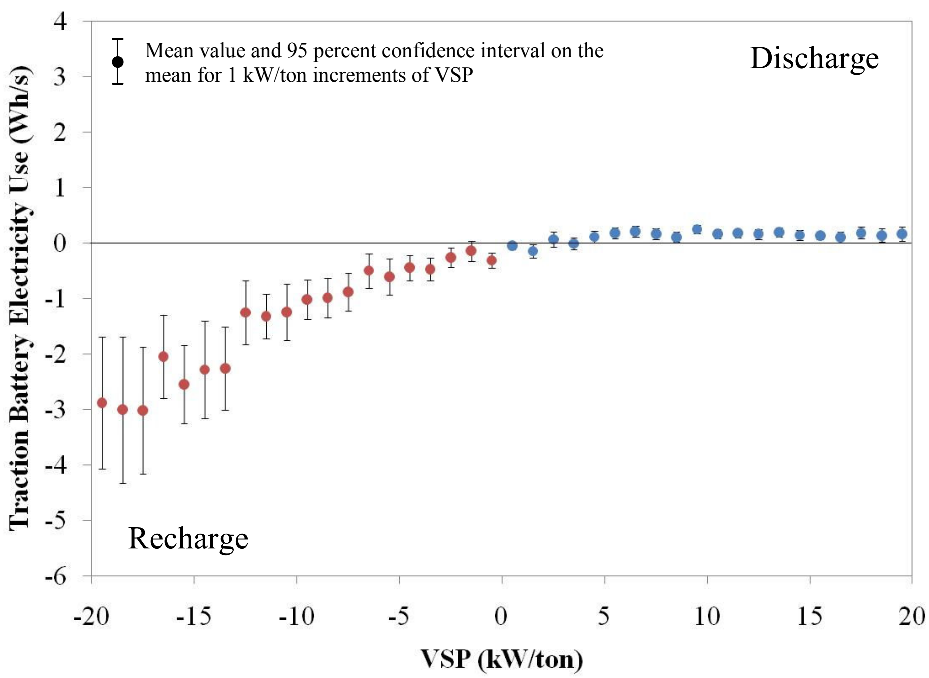


(b) Engine on

FIGURE 4 Plug-in battery electricity use versus vehicle specific power during charge depleting mode.

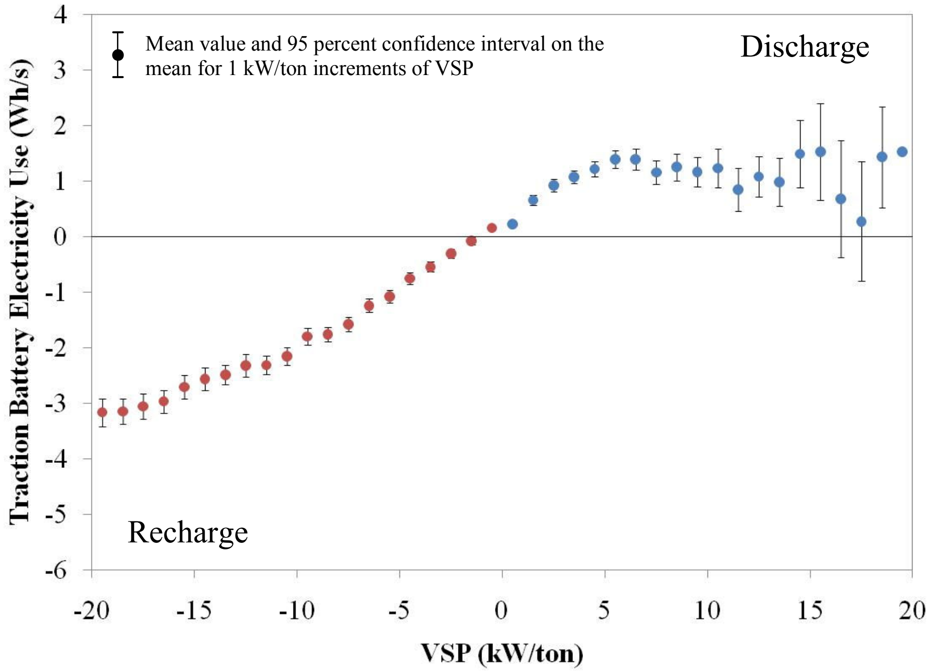


(a) Charge Depleting Mode, Engine Off

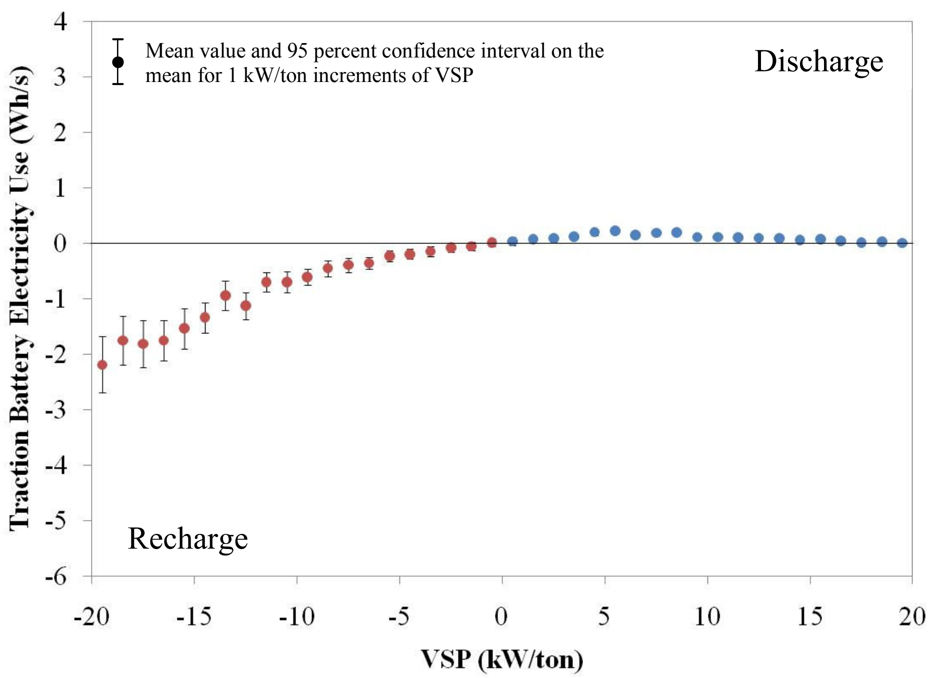


(b) Charge Depleting Mode, Engine On

FIGURE 5 Traction battery electricity use versus vehicle specific power.



(c) Charge Sustaining Mode, Engine Off



(d) Charge Sustaining Mode, Engine On

FIGURE 5 (Continued).

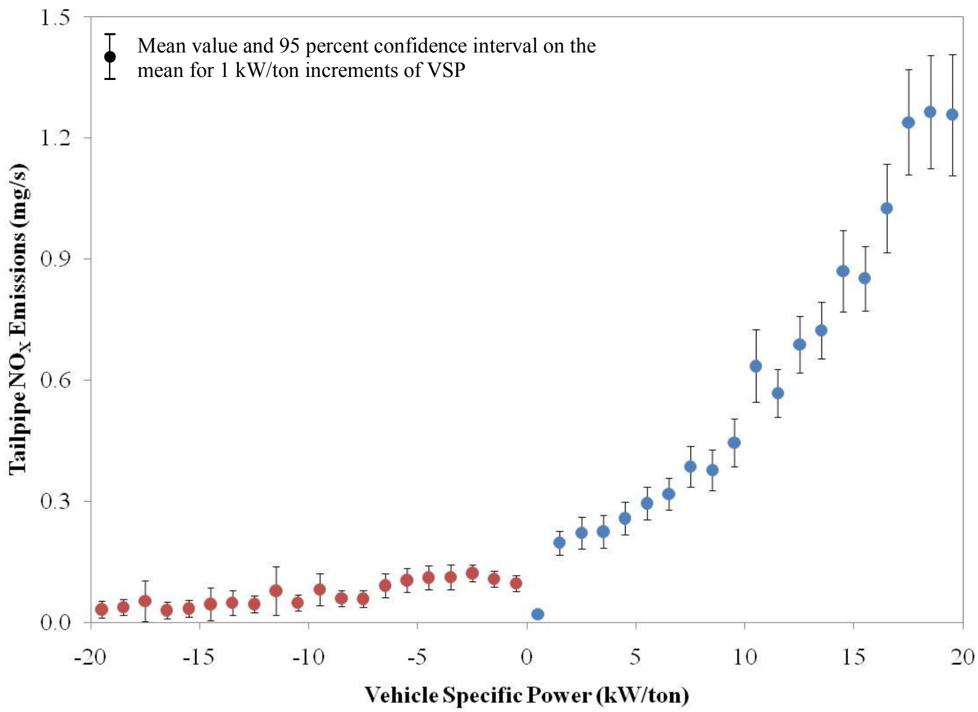


FIGURE 6 Tailpipe NO_x emissions versus vehicle specific power for Charge Sustaining mode and engine on.

PART III

MODELING OF PLUG-IN HYBRID ELECTRIC VEHICLE ENERGY USE AND EMISSIONS BASED ON IN-USE MEASUREMENT

3.0 Overview

Plug-in hybrid electric vehicles (PHEVs) obtain a portion of their energy input from electricity taken from the grid to charge a plug-in battery on-board the vehicle. The energy obtained from the grid supplements that available via an internal combustion engine (ICE) to provide power for vehicle propulsion. Depending on the configuration of the hybrid electric propulsion system, the engine may restart and shutdown periodically during vehicle operation, leading to episodic variations in fuel use and emissions. These episodes are distributed on the road network, leading to spatial and temporal variation in fuel use and emissions. The purpose of this work is to develop an empirically-based model of energy use and emissions of an example PHEV. Engine starts and shutdowns are predicted as a function of second-by-second vehicle specific power (VSP). VSP is a function of vehicle speed and acceleration, and road grade. Consumption of power from the grid is predicted based on initial plug-in battery state of charge and the duration of charge depleting mode with respect to distance travelled until the battery reaches a minimum state-of-charge set-point. For situations in which the engine is on, fuel use and emissions are predicted based on an empirically calibrated model of average fuel use and emissions rates of CO_2, CO, hydrocarbons, and NO with respect to modal ranges of VSP. The model is calibrated for a 2005 Toyota Prius that was retrofitted with a Hymotion A123 plug in retrofit kit. Second-by-second data for the retrofitted Prius were measured for eight selected routes in the Raleigh, NC area using a portable emissions measurement system, electronic control unit data logger, and geographic positioning system with barometric altimeter. The data were stratified into calibration and validation datasets. The model was developed based on the calibration data and used to make predictions for the validation data.

There have been many proposed models for determining engine operation in both hybrid and plug-in hybrid vehicles. However, these models are mainly designed for simulation (Chan, 2007). Engine on and off rules have been implemented into the Advanced Vehicle Simulator, ADVISOR, for a hybrid vehicle based on SOC of the traction battery and electric launch speed, or the vehicle speed in which the vehicle attempts to operate only with the traction battery (Markel and Wipke, 2001). Similarly, engine operation has been characterized by traction battery SOC and vehicle power demand (Chan, 2007; Markel and Wipke, 2001; Cheng *et al*., 2009).

3.1 Methods

The methodology of this research consists of developing: (1) plug-in battery on/off operation modes; (2) ICE on/off operation rules; and (3) a vehicle specific power (VSP)-based modal emissions model based on real-world test data. The operation rules and fuel use and emissions models were implemented to predict EU&E for test data not used in the models' calibration.

3.1.1 Field Study Design

Two drivers collected seven days of data in November 2008 on a 2005 Toyota Prius retrofitted with an A123 Hymotion plug-in battery system. The data were collected on selected routes in the Research Triangle Park, NC area used in previous PEMS data collection with conventional light duty gasoline vehicles (Frey *et al.*, 2008). For six of the test days, the vehicle initially operated in CD mode. The data was separated, as shown in Table 4 for calibration and verification of a predictive model.

3.1.2 Instruments

Real-world PHEV data was used to develop the plug-in battery and ICE on/off operation rules and emissions models. A portable emissions measurement system (PEMS) was used to quantify activity, energy use, and emissions of a PHEV on a second-by-second basis during actual duty cycles. An electronic control unit (ECU) data logger was used to record vehicle road speed, voltage and current associated with electricity flow to or from the plug-in battery, state-of-charge of the plug-in battery, engine RPM, and fuel flow rate. A handheld global positioning system (GPS) with barometric altimeter was used to estimate road grade based on differences in elevation over a distance.

3.1.3 Vehicle Specific Power

VSP has typically been used to estimate the fuel consumption of conventional light duty gasoline vehicles (LDGVs). VSP is an estimate of the power output required of the drivetrain in order to move the vehicle. VSP accounts for the kinetic energy of vehicle movement, acceleration due to gravity, rolling resistance, and aerodynamic drag. Based on typical values of rolling resistance and aerodynamic drag, VSP is estimated as (Jimenez-Palacios, 1999):

$$\mathrm{VSP} = 0.278v\,[0.305a + 9.81r + 0.132] + 0.0000065v^3 \tag{1}$$

Where VSP = vehicle specific power (kW/ton); v = vehicle speed (km/h); a = vehicle acceleration (km/h per sec); and r = road grade (%).

Here, VSP is used to account for the energy demand of a PHEV, rather than the fuel demand of an LDGV (Choi and Frey, 2010). For a conventional LDGV, vehicle fuel use is typically constant for negative values of VSP, and increases linearly with positive VSP (Frey *et al.*, 2008). For a PHEV, the battery-motor system will sometimes augment the power output of the engine during plug-in and/or traction battery discharge, and at other times consume some of the engine output for recharging the traction battery.

VSP was calculated for all data based on vehicle speed reported by the ECU data logger and road grade derived from GPS measurements.

3.1.4 Deriving Plug-In Battery Operation Rules

The second-by-second electrical power extracted from the PIB, in Watt-hours, was estimated based on the ECU-reported voltage and current. The electrical power extracted from the PIB was plotted versus VSP for engine on and off conditions, and used to create modal average PIB electrical discharge rates in kW/s. Previous analysis of this PHEV reported an average PIB discharge of 3.8 kWh during CD mode. When the PIB is fully charged from the grid, its initial SOC is 100 percent. Discharge rates with respect to second-by-second VSP and engine status predictions are summed until a total PIB discharge of 3.8 kWh is reached.

3.1.5 Deriving Engine Operation Rules

The PHEV has the potential to operate using only electrical power from the vehicle batteries, in which case there is no fuel use and zero tailpipe emissions. Therefore, it is important to identify when the ICE is on or off.

Using the collected data, fuel consumption versus engine speed was compared to identify the minimum engine speed at which the engine is on and consuming fuel. Engine speed is an indicator of engine operation. Engine speed versus vehicle speed was compared to identify that above a threshold vehicle speed, the engine is always on. A classification and regression tree (CART) analysis was completed on the calibration data to see if any engine operation rules could be derived. Vehicle speed, acceleration, road grade, and traction battery SOC were variables in the CART analysis.

3.1.6 Estimation of Modal Average Fuel Use and Emission Rates

The driving patterns for the PHEV were modeled based on the joint distribution of time spent in each VSP bin of 1 kW/ton and ICE status. Modal average fuel use and emission rates were estimated previously from all data collected.

For positive VSP, the rate of fuel use increases monotonically, but not linearly, as is the case for conventional LDGVs. Fuel use is sensitive to VSP for negative values of VSP, which includes deceleration and vehicle travel at constant speed on a negative road grade (such as down a hill). NO_x emission rates are approximately constant for negative VSP values, and increase as positive VSP values increase.

3.2 Results

Plug-in battery and engine on/off operation rules for a PHEV were identified and validated. Based on the developed operation rules, fuel use and emissions were estimated based on average modal fuel use and emission rates.

3.2.1 Characterization of Vehicle Activity

The 120,000 seconds of PHEV data were separated into two databases. Approximately 75 percent of the data were used as a calibration database for model creation.

The remaining data were used as a validation database for model verification. Similar proportions of data from each of the eight test routes were included in both the calibration and validation databases for both CD and CS modes. This is shown in Table 4.

Modal average plug-in battery electrical discharge rates, shown in Figure 1 was used in order to determine the amount of time and distance in which the vehicle traveled in CD mode. With SOC equaling 100% once the plug-in battery is no longer connected the grid, electricity discharge is summed, based on VSP and engine status, until a total discharge of 3.8 kWh is achieved. At this point the model predicts that the PHEV enters CS mode, and the plug-in battery is no longer used.

The plug-in battery operation rule is:

$$\sum_{E=0}^{1} \sum_{VSP=1}^{N} t_{e,VSP} \times D_{e,VSP} = 3.8 \text{ kWh} \quad (2)$$

Where t = time in VSP mode for engine status e (sec), D = plug-in battery discharge rate (kW/s), e = engine status (on/off), and VSP = vehicle specific power bin (kW/ton).

PHEV fuel use reported by the data logger was plotted versus engine RPM, also reported by the data logger, as shown in Figure 2. If the ICE is not on, then there would be no fuel flow. Therefore, an RPM of 900 is the critical indicator of engine status. In the calibration and validation databases, engine status was converted into binary variables, with "0" denoting engine off and "1" denoting engine on.

The result of the CART analysis, shown in Figures 3 and 4, demonstrates that for both CD and CS modes, there was a strong correlation of speeds ≥ 40 mph and the engine being on. There was a strong correlation between the engine being off and VSP being 8 and 1 kW/ton for CD and CS modes, respectively. There was no correlation between energy use and traction battery SOC, unlike hypothesized by the literature, which concludes that below a low SOC set point the engine is always on, assisting in recharging the traction battery, and above a high SOC set point the engine is always off (Chan, 2007; Cheng et al., 2009; Markel and Wipke, 2001). The collected data, shown in Figure 5, concludes that these set points, 57.5 and 72.5 percent, are rarely reached. Therefore, the affects of traction battery SOC are negligent in this model.

Vehicle speed is plotted versus engine RPM, as shown in Figure 6. A majority of the data reported at speeds ≥ 40 mph occur at or above the critical 900 RPM engine speed, confirming the preliminary CART analysis. Therefore, the PHEV engine can be classified as on whenever the vehicle is traveling at least 40 mph. The calibration and validation databases were stratified into two speed categories: (1) < 40 mph; and (2) ≥ 40 mph.

For speeds ≥ 40 mph, there is certainty that the engine is on. Therefore, engine operation rules are only needed for speeds < 40 mph. Based on the CART analysis, the engine is off when VSP is ≤ 8 kW/ton for CD mode and ≤ 1 kW/ton for CS mode. Both the calibration and validation data were stratified into VSP bins of 1 kW/ton.

The engine operation rule is:

For CD mode: If VSS ≥ 40, the engine is on

If VSS < 40 and VSP > 8, the engine is on

Otherwise, the engine is off

For CS mode: If VSS ≥ 40, the engine is on

If VSS < 40 and VSP > 1, the engine is on

Otherwise, the engine is off

Where VSS = vehicle speed (mph) and VSP = vehicle specific power (kw/ton).

The plug-in battery and engine operation rules were used to predict the distance in which the plug-in battery was on for one test day. The predicted distance driven during CD mode for the selected test day was 34.9 miles, which is 1.75 percent higher than the actual distance driven.

3.2.2 Energy Use and Emissions Predictions

Empirically estimated modal average fuel use and emission rates were coupled with the plug-in battery and engine operation models to estimate total fuel consumption and emissions for both the calibration and verification databases. Comparisons between actual and predicted fuel use and emissions are described in Table 2.

Another analysis was conducted by increasing the amount of data in which the engine was off during CS mode by changing the engine operation rule to include data with speeds < 40 mph and VSP of ≤ 4 kW/ton for CS mode. This is suggested by a branch split in the CART tree shown in Figure 4. Comparisons between actual and predicted fuel use and emissions are described in Table 3. The predicted fuel use and emission rates from the engine operation model for the validation data are more accurate when a VSP of ≤ 4 kW/ton for CS mode is used rather than ≤ 1 kW/ton, reducing by 5 percent the difference between predicted and actual fuel use and CO_2 emissions, by 4 percent for NO_x and HC emissions, and by 6 percent for CO emissions.

The engine operation model overpredicted fuel use and all emissions in the validation database. However, all deviations from the actually measured fuel use and emissions were less than 4 percent, with the exception of HC emissions which deviated by 40 percent.

However, the actual emissions of HC were less than 1 gram for the 30,251 seconds of data. Emissions of NO_x, HC, and CO were better estimated in CS mode than CD mode, while fuel use and CO_2 emissions were better estimated in CD mode than CS mode. One source of prediction error is the use of rate averages. There is variability in measured fuel use and emissions for each VSP bin.

The plug-in battery and engine operation models were used to predict the time and distance in which the plug-in battery was on, and the fuel use and emissions during CD and CS modes for Test Day 5. The predicted distance driven during CD mode was 34.9 miles, which is 1.75 percent higher than the actual distance driven. Table 4 compares actual and predicted fuel use and emissions after using the plug-in battery and engine operation models for Test Day 5. Total fuel use and CO emissions were within 2.6 and 55.6 percent, respectively. Total NO_x, HC, and CO_2 emissions were within 17.4, 8.4, and 0.9 percent, respectively. The amount of time the engine was on was predicted within 0.075 percent.

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TABLE 4 Real-World Plug-In Hybrid Electric Vehicle Data Separated into Calibration and Verification Databases[a]

Route Segment	Test Day 1	Test Day 2	Test Day 3	Test Day 4	Test Day 5	Test Day 6	Test Day 7
Aout	Calibrate CS	---	Calibrate CD	Validate CS	Calibrate CD	Calibrate CS	Calibrate CD
Ain	Calibrate CS	---	Validate CS	Calibrate CS	Validate CD	Validate CS	Calibrate CD
Bout	Calibrate CS	Validate CS	Calibrate CS	Calibrate CD	---	Calibrate CD	Validate CD Calibrate CS
Bin	Validate CS	Calibrate CS	Calibrate CS	Calibrate CS	---	Calibrate CD	Calibrate CS
Cout	Calibrate CD	Validate CS	Calibrate CS	---	Calibrate CS	Validate CD Validate CS	Calibrate CS
Cin	Validate CS	Calibrate CS	Calibrate CS	---	Calibrate CS	Calibrate CS	Calibrate CS
D	Calibrate CD	Validate CS	---	Calibrate CS	Calibrate CD	Calibrate CS	Calibrate CS
E	Calibrate CD	Calibrate CS	---	Validate CS	Validate CD	Validate CS	Calibrate CS
1out	Calibrate CD	Calibrate CS	Validate CD	Calibrate CS	Calibrate CS	---	Validate CS
1in	Validate CS	Calibrate CS	Validate CS Calibrate CD	Calibrate CS	Calibrate CS	---	Calibrate CS
2out	Calibrate CD	Calibrate CS	Calibrate CS	Calibrate CS	Validate CS	Calibrate CS	---
2in	Validate CD Calibrate CS	Calibrate CS	Calibrate CS	Calibrate CS	Calibrate CS	Validate CS	---
3out	---	Calibrate CS	Validate CS	Calibrate CD	Validate CS	Calibrate CS	Calibrate CS
3in	---	Calibrate CS	Calibrate CS	Validate CD	Calibrate CS	Calibrate CS	Validate CS

[a] 2005 Toyota Prius retrofitted with A123 Hymotion plug-in battery system

TABLE 5 Comparisons of Fuel Use and Emissions between Actual and Engine Operation Model Predicted Values when Engine is Off for Vehicle Speeds Less than 40 mph and Vehicle Specific Power Less than or Equal to 1 kW/ton for Charge Sustaining Mode

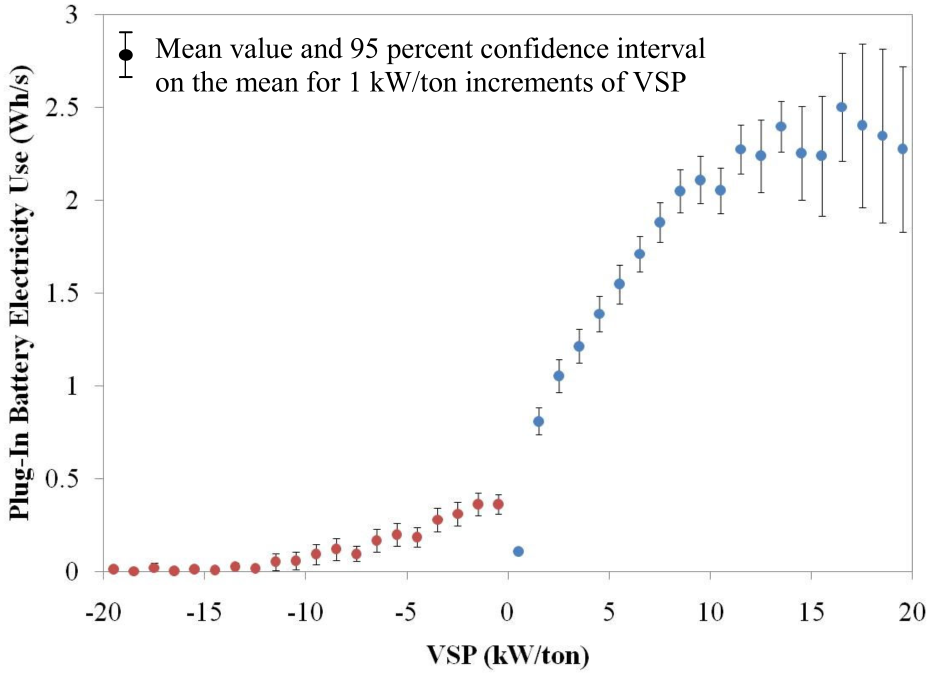
		Fuel (gal)	NO_x (g)	HC (g)	CO (g)	CO_2 (kg)
CD Calibration n = 17,566	Actual	2.10	2.89	1.95	15.7	14.7
	Predicted	2.05	2.87	1.50	12.5	14.3
	Difference (%)	-2.32	-0.80	-23.0	-20.8	-2.80
CD Validation n = 5,776	Actual	0.70	0.95	0.11	1.91	4.93
	Predicted	0.71	1.01	0.51	4.17	4.98
	Difference (%)	1.63	5.91	386	119	1.10
CS Calibration n = 70,929	Actual	16.5	31.2	2.16	24.7	107
	Predicted	17.7	32.7	2.35	28.7	114
	Difference (%)	7.27	4.89	8.67	16.1	6.46
CS Validation n = 24,475	Actual	5.43	9.82	0.80	10.7	34.4
	Predicted	5.89	10.6	0.79	9.62	37.7
	Difference (%)	8.47	7.67	-0.64	-10.1	9.70
All Calibration n = 88,495	Actual	18.6	34.1	4.11	40.5	122
	Predicted	19.8	35.6	3.85	41.2	128
	Difference (%)	6.45	4.40	-6.33	1.73	4.92
All Validation n = 30,251	Actual	6.14	10.8	0.90	12.6	39.3
	Predicted	6.60	11.6	1.30	13.8	42.7
	Difference (%)	7.49	6.90	44.4	9.52	8.65

TABLE 6. Comparisons of Fuel Use and Emissions between Actual and Engine Operation Model Predicted Values when Engine is Off for Vehicle Speeds Less than 40 mph and Vehicle Specific Power Less than or Equal to 4 kW/ton for Charge Sustaining Mode

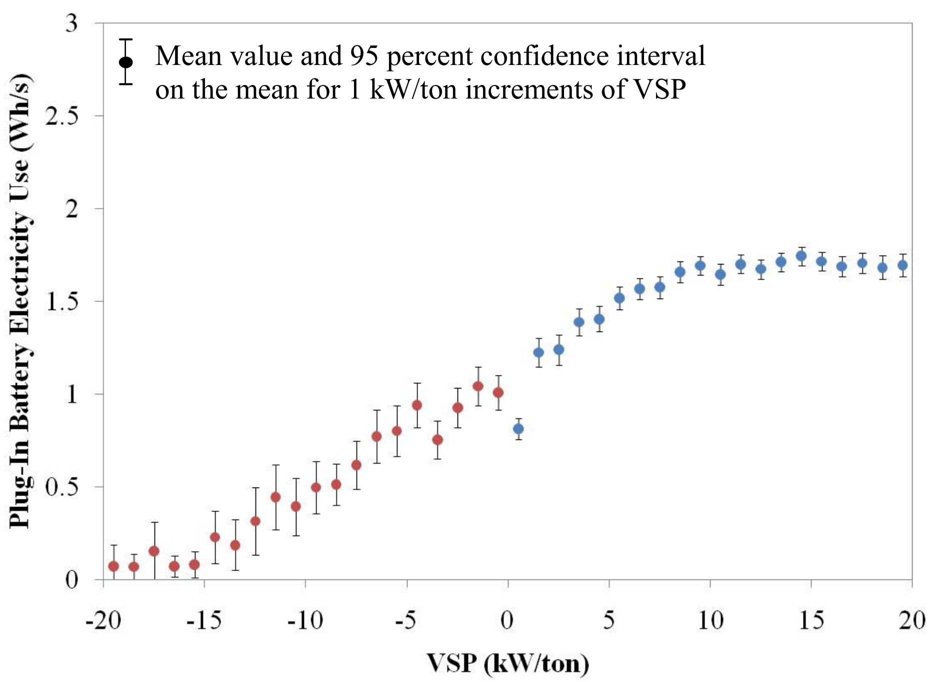
		Fuel (gal)	NO_x (g)	HC (g)	CO (g)	CO_2 (kg)	Engine On (sec)
CD Calibration n = 17,566	Actual	2.10	2.89	1.95	15.7	14.7	9,167
	Predicted	2.05	2.87	1.50	12.5	14.3	8,183
	Difference (%)	-2.32	-0.80	-23.0	-20.8	-2.80	-10.7
CD Validation n = 5,776	Actual	0.70	0.95	0.11	1.91	4.93	2,902
	Predicted	0.71	1.01	0.51	4.17	4.98	2,802
	Difference (%)	1.63	5.91	386	119	1.10	-3.45
CS Calibration n = 70,929	Actual	16.5	31.2	2.16	24.7	107	44,709
	Predicted	16.9	31.6	2.24	26.9	109	48,489
	Difference (%)	2.50	1.29	3.54	8.80	1.65	8.45
CS Validation n = 24,475	Actual	5.43	9.82	0.80	10.7	34.4	14,815
	Predicted	5.56	10.1	0.75	8.86	35.6	16,372
	Difference (%)	2.35	2.86	-6.51	-17.2	3.38	10.5
All Calibration n = 88,495	Actual	18.6	34.1	4.11	40.5	122	53,876
	Predicted	19.0	34.4	3.74	39.4	123	56,672
	Difference (%)	2.15	0.88	-9.00	-2.72	0.82	5.19
All Validation n = 30,251	Actual	6.14	10.8	0.90	12.6	39.3	17,717
	Predicted	6.28	11.1	1.26	13.0	40.6	19,174
	Difference (%)	2.28	2.78	40.0	3.17	3.31	8.22

TABLE 7. Comparisons of Fuel Use and Emissions between Actual and Predicted Values for Test Day 5

		Fuel (gal)	NO_x (g)	HC (g)	CO (g)	CO_2 (kg)	Engine On (sec)	Engine Starts
Charge Depleting	Actual	0.49	0.48	0.59	4.67	3.40	2,290	52
	Predicted	0.50	0.66	0.39	3.29	3.45	2,107	206
	Difference (%)	1.36	37.8	-35.0	-29.6	1.44	-7.99	296
Charge Sustaining	Actual	3.12	7.48	0.29	0.70	20.8	8,434	427
	Predicted	3.21	5.91	0.43	5.06	20.6	8,625	154
	Difference (%)	2.75	-20.9	45.3	626	-1.23	2.26	177
All Data	Actual	3.61	7.96	0.89	5.36	24.2	10,724	206
	Predicted	3.70	6.57	0.81	8.35	24.0	10,732	633
	Difference (%)	2.56	-17.4	-8.36	55.6	-0.85	0.07	207



(a) Engine off



(b) Engine on

FIGURE 7 Plug-in battery electricity use versus vehicle specific power during Charge Depleting mode.

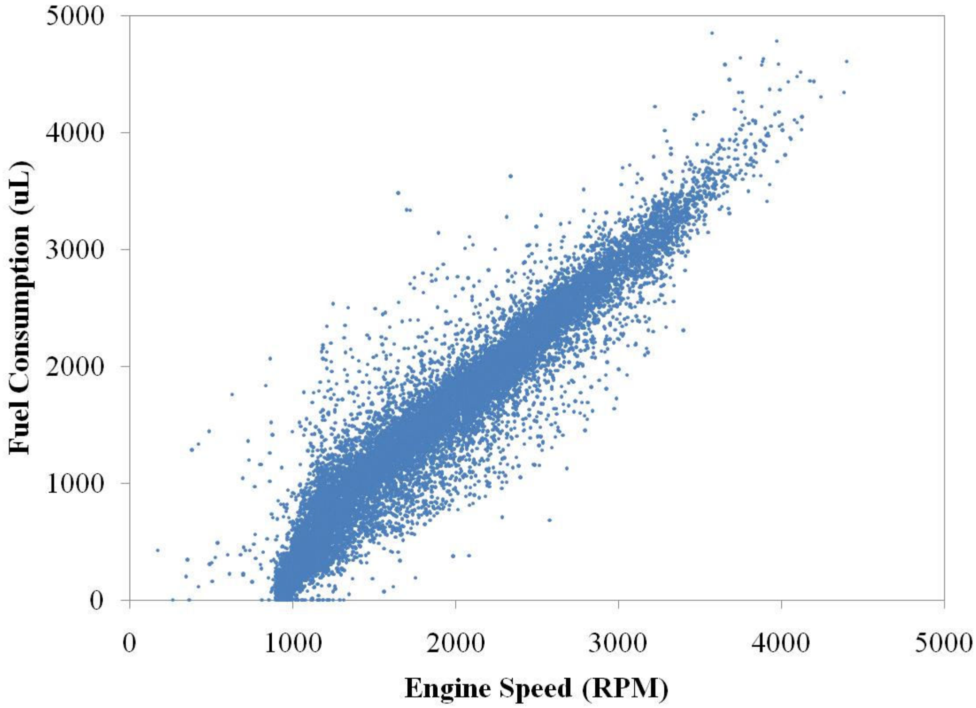


FIGURE 8 Fuel consumption versus engine speed.

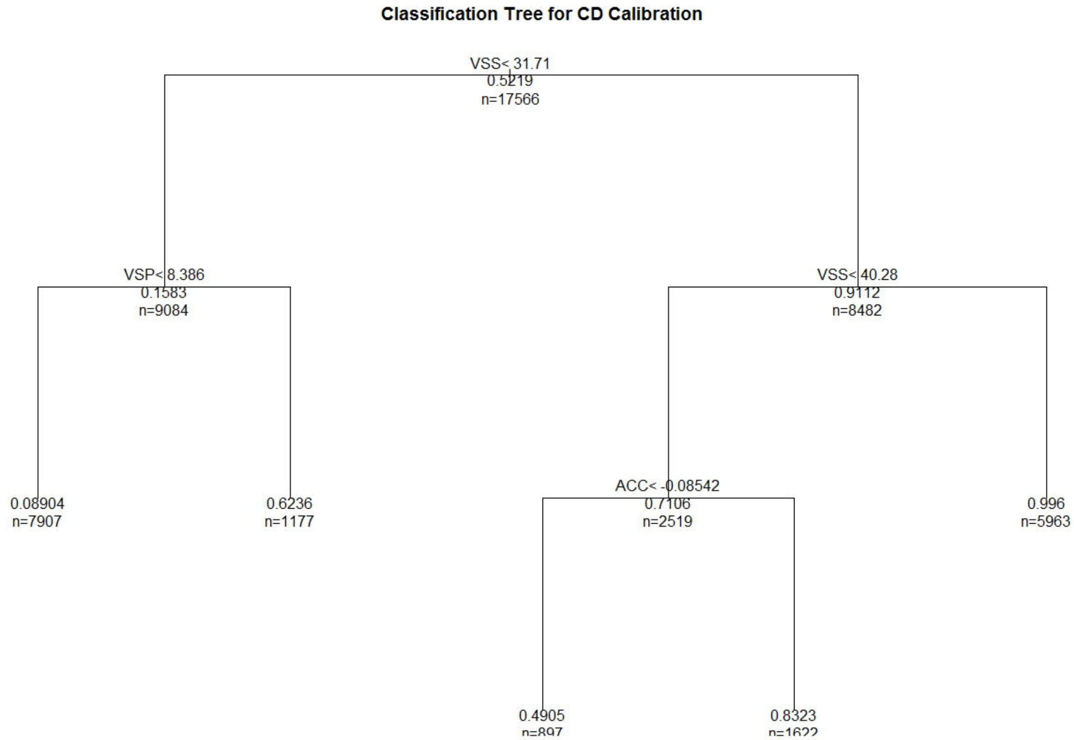


FIGURE 9 Characterization and regression tree for determining when the internal combustion engine is on during Charge Depleting mode.

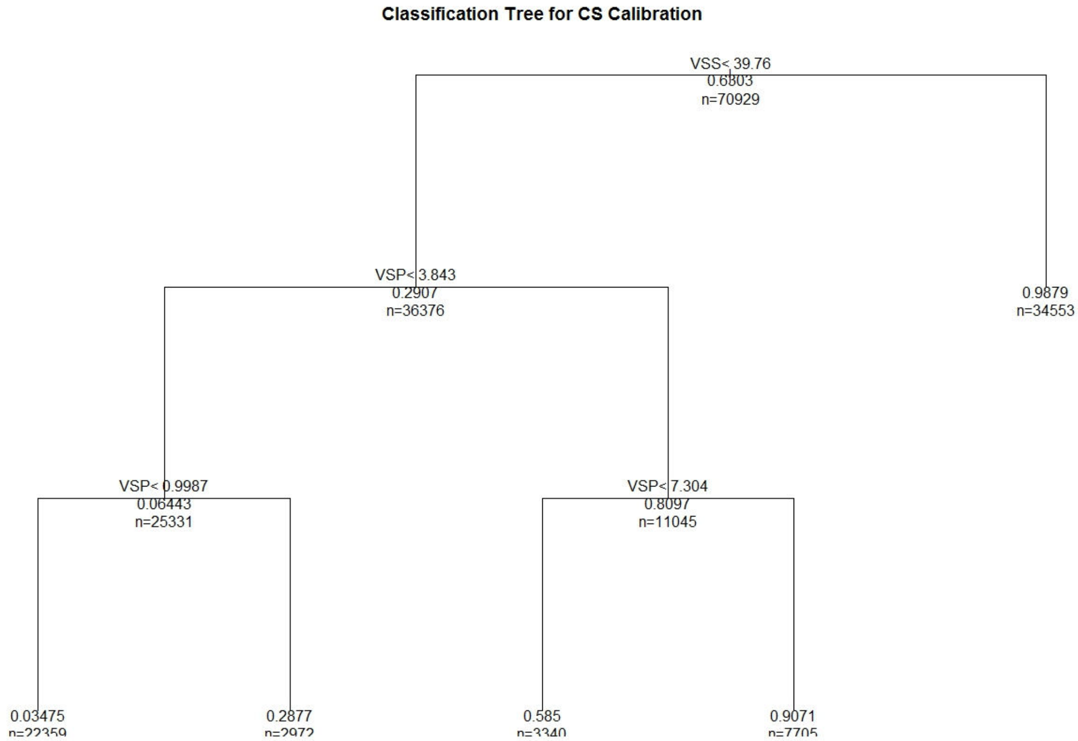


FIGURE 10 Characterization and regression tree for determining when the internal combustion engine is on during Charge Sustaining mode.

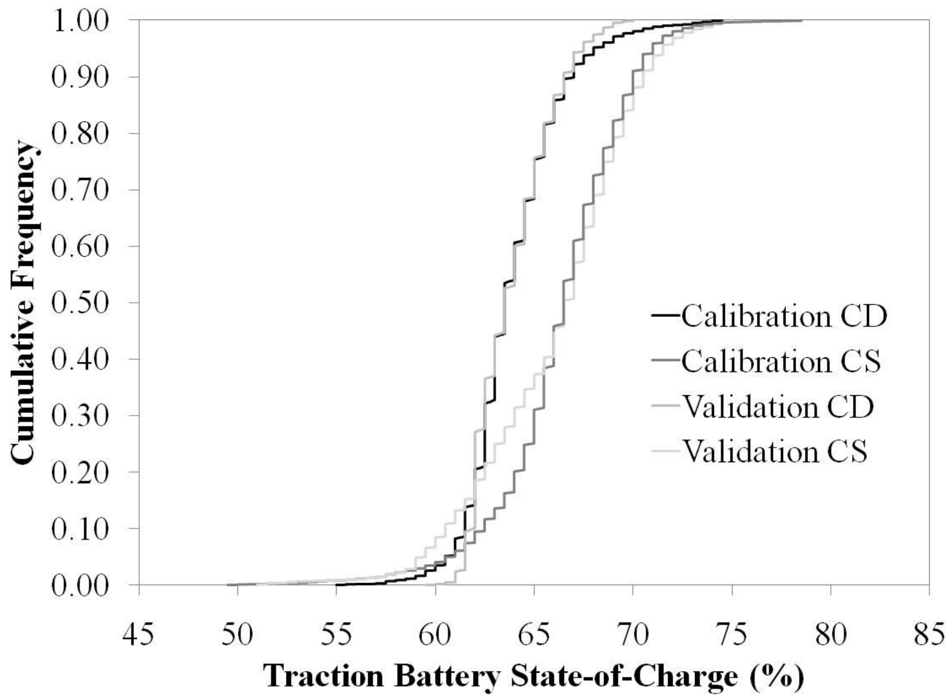


FIGURE 11 Cumulative distribution functions of traction battery state-of-charge.

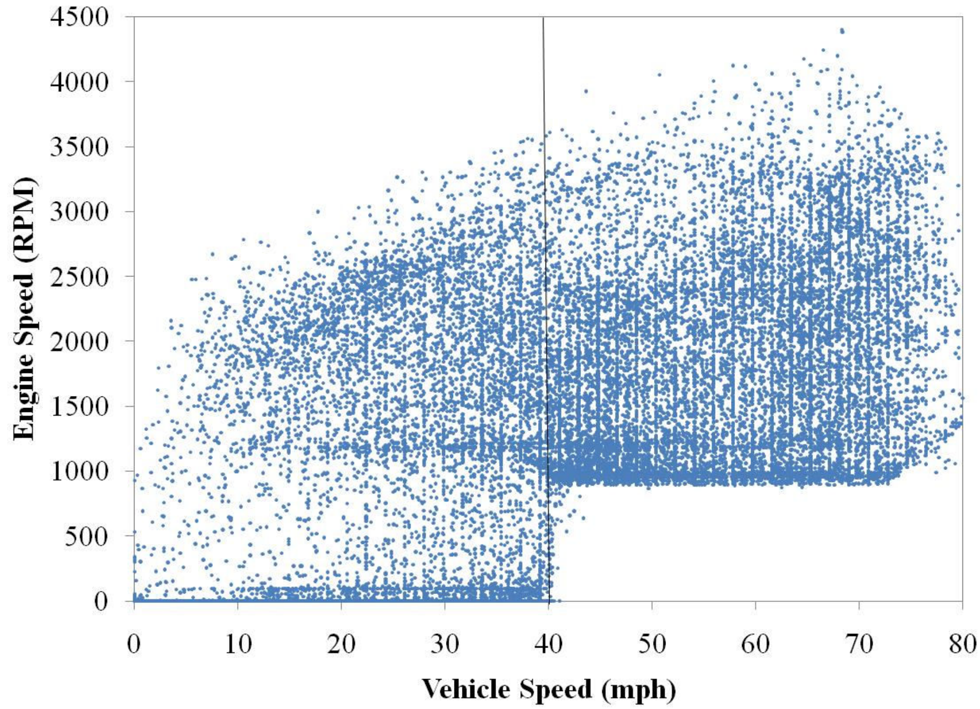


FIGURE 12 Engine speed versus vehicle speed.

PART IV
CONCLUSIONS AND RECOMMENDATIONS

4.0 Overview

This chapter provides an overview of this thesis including introduction, objectives, major research tasks, and organization.

4.1 Conclusions

Energy use differs depending on whether the ICE is on or off and whether the PHEV is in CD or CS mode. Fuel use is approximately 30 percent lower for positive VSP during CD versus CS mode due to shift of some vehicle power from the ICE to the PIB. The traction battery recharges and discharges at greater rates when the engine is off. On average, 0.12 kWh of grid energy was used per mile driven during CD mode, comparable to the 0.13 kWh observed during the Vehicles Technology Program (INL, 2010).

Tailpipe emission rates vary depending on whether the PHEV is in CD or CS mode. Tailpipe emission rates of CO_2 and NO_X are, on average, 25 and 60 percent lower, respectively, for CD versus CS mode.

Comparisons of total emission rates during CD mode are sensitive to generation mix. The current energy mixes in the selected NERC regions lead to tailpipe and grid emission rates for CO_2 and NO_x during CD mode to be higher than tailpipe emission rates in CS mode for all routes, with a few exceptions. Therefore, the percentage of electricity generated from non-carbon sources need to increase from current levels in order for total emissions in CD mode to be lower than in CS mode. Both more efficient powertrains and the development of battery charging stations powered by alternative energy could also make PHEVs a viable option for reducing CO_2, NO_X, and SO_2 emissions from transport.

On average, the observed CD range of 33 miles is two-thirds of typical average daily driving. It could be possible to make an entire daily commute without consuming any gasoline if the PHEV was recharged at work.

The frequency and duration of engine use is sensitive to vehicle operations. Thus, PHEV emissions will not occur uniformly over the transportation network. The episodic nature of these emissions motivates the need for a microscale model that enables prediction of locations at which PHEV emissions will tend to occur, as well as location or conditions under which such tailpipe emissions may be low or zero. For example, locations for microscale variability in tailpipe CO and HC emissions include signalized intersections and stop signs where the ICE turns on and off due to acceleration and deceleration, which is evident during CD mode where the need for the ICE is more sporadic. When the engine turns on, emissions peak at approximately 90 mg CO/sec and 12 mg HC/sec and then decrease to approximately 15 mg CO/sec and 2 mg HC/sec after two seconds. Higher NO_X emissions are observable on routes with average high speeds and acceleration, especially during CS mode.

The development of the plug-in battery and ICE status prediction models has highlighted the correlation between EU&E and PHEV activity. When the ICE is characterized as off, it is implied that there is no fuel consumption and no emissions formed. During CS mode, where a majority of driving occurs, the ICE rarely turns on for negative values of VSP and is almost exclusively high for high positive values of VSP.

4.2 Recommendations

The use of two sources of energy for a vehicle must be addressed in characterizing fuel economy. "Energy economy" should be estimated, taking into account the gasoline equivalent of the energy required to generate the electricity consumed by the vehicle. On this basis, the energy economy for CS modes was, on average, 10 percent higher than for CD mode, even though the gasoline fuel economy during CD mode were at least 25 percent higher than during CS mode.

This work is based on measurements on only one PHEV. More testing should be completed on additional retrofitted PHEVs, as well as production PHEVs. PHEVs with different powertrain configurations and different plug-in retrofits may result in different fuel use and emission rates.

The proposed plug-in battery and engine status and emissions models are recommended for further application and adjustment as more data becomes available. All activity, energy use, and emissions measurements were completed on only one PHEV over seven days. More testing campaigns on this PHEV, as well as additional retrofitted HEVs or new production PHEVs, will help to develop a more sophisticated model with decreased variability.

4.3 References

INL. *North American PHEV Demonstration Fleet Summary Report: Hymotion Prius (V2Green data logger)*. U.S. Deparment of Energy, Idaho National Laboratory http://avt.inl.gov/pdf/phev/HymotionPriusV2GreenApr08-Oct10.pdf (accessed December 1, 2010).

APPENDICES

APPENDIX A
ROUTE MAP AND DIRECTIONS

Eight routes were tested with the PHEV in the Raleigh, NC area. Six of these routes (Routes A, B, C, 1, 2, and 3) were used in previous PEMS data collection with conventional light duty gasoline vehicles (Frey *et al.*, 2008), and shown in Figure SI-1. Routes A, B, and C represent local commuting within Raleigh. Route D represents a local commute from Southeast Raleigh to NCSU's Centennial Campus. Route E represents driving within Centennial Campus. Routes 1, 2, and 3 represent commuting from a residential district to the Research Triangle Park business district. Road types vary from minor arterials to freeways.

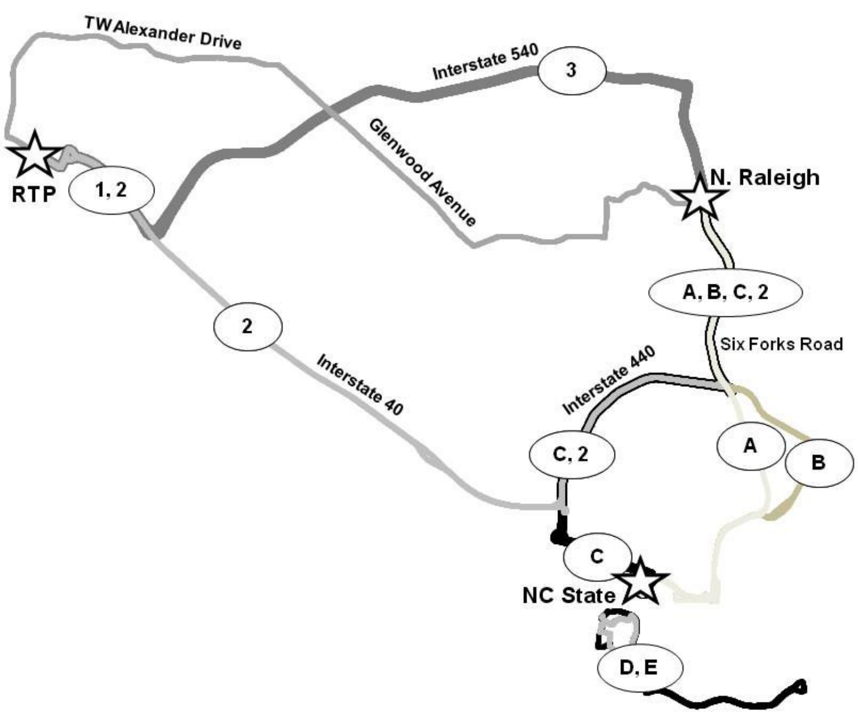


FIGURE A-1 Map of Tested Routes.

<u>Route A out</u>: NC State to North Raleigh via Downtown, Wake Forest

(1) Starting at Coliseum Parking Deck, continue on **Cates Ave**
(2) Turn **left** onto **Pullen Rd**
(3) Turn **right** onto **Hillsborough St**
(4) Continue onto **W Morgan St**
(5) Turn **left** onto **S McDowell St / US 401**
(6) Take ramp on **right** to **Wake Forest Rd North**
(7) Turn **left** onto **E Six Forks Rd**
(8) Turn **right** onto **Mourning Dove Rd**
(9) End at Peachtree Market parking lot

<u>Route A in</u>: North Raleigh to NC State via Wake Forest, Downtown

(1) Starting at Peachtree Market / Mourning Dove Rd, turn **left** onto **Six Forks Rd**
(2) Turn **right** onto **Wake Forest Rd**
(3) Take ramp on **right** to **Capital Blvd**
(4) Turn **right** onto **W Edenton St**
(5) Continue onto **Hillsborough St**
(6) Turn **left** onto **Pullen Rd**
(7) Turn **right** onto **E Dunn Ave**
(8) Turn **left** onto **Jeter Dr**
(9) Turn **left** onto **Cates Ave**
(10) End at Coliseum Parking Deck

<u>Route B out</u>: NC State to North Raleigh via Downtown, I-440

(1) Starting at Coliseum Parking Deck, continue on **Cates Ave**
(2) Turn **left** onto **Pullen Rd**
(3) Turn **right** onto **Hillsborough St**
(4) Continue onto **W Morgan St**
(5) Turn **left** onto **S McDowell St / US 401**
(6) Take ramp on **right** to **I-440 West**
(7) Take **Exit 8B** on right to **Six Forks Rd North**
(8) Turn **right** onto **Mourning Dove Rd**
(9) End at Peachtree Market parking lot

<u>Route B in</u>: North Raleigh to NC State via I440, Downtown

(1) Starting at Peachtree Market / Mourning Dove Rd, turn **left** onto **Six Forks Rd**
(2) Take ramp on **left** to **I-440 East**
(3) Take **Exit 11A** on **right** to **Capital Blvd South**
(4) Turn **right** onto **W Edenton St**
(5) Continue onto **Hillsborough St**
(6) Turn **left** onto **Pullen Rd**
(7) Turn **right** onto **E Dunn Ave**
(8) Turn **left** onto **Jeter Dr**
(9) Turn **left** onto **Cates Ave**
(10) End at Coliseum Parking Deck

<u>Route C out</u>: NC State to North Raleigh via Hillsborough, I-440

(1) Starting at Coliseum Parking Deck, continue on **Cates Ave**
(2) Turn **left** onto **Pullen Rd**
(3) Turn **left** onto **Hillsborough St**
(4) Take ramp on **right** to **I-440 East**
(5) Take **Exit 8B** on right to **Six Forks Rd North**
(6) Turn **right** onto **Mourning Dove Rd**
(7) End at Peachtree Market parking lot

<u>Route C in</u>: North Raleigh to NC State via I-440, Hillsborough

(1) Starting at Peachtree Market / Mourning Dove Rd, turn **left** onto **Six Forks Rd**
(2) Take ramp on **right** to **I-440 West**
(3) Take **Exit 3** on **right** to **Hillsborough St**
(4) Turn **right** onto **Pullen Rd**
(5) Turn **right** onto **E Dunn Ave**
(6) Turn **left** onto **Jeter Dr**
(7) Turn **left** onto **Cates Ave**
(8) End at Coliseum Parking Deck

<u>Route D</u>: NCSU Centennial Campus to Southeast Raleigh via I-440

(1) Starting from Research Building IV, turn **right** onto **Capability Dr**
(2) Turn **left** onto **Varsity Dr**
(3) Turn **right** onto **Avent Ferry Rd**
(4) Turn **right** onto **Centennial Pkwy**
(5) Turn **right** onto **Lake Wheeler Rd**
(6) Take ramp on **left** to **I-440 East**
(7) Take **Exit 300A** on right to **Rock Quarry Rd North**
(8) Turn **left** onto **Rock Quarry Rd**
(9) Take ramp on **left** to **I-440 West**
(10) Take **Exit 297** on right to **Lake Wheeler Rd**
(11) Turn **right** onto **Lake Wheeler Rd**
(12) Turn **left** onto **Centennial Pkwy**
(13) Turn **left** onto **Avent Ferry Rd**
(14) Turn **left** onto **Varsity Dr**
(15) Turn **right** onto **Capability Drive**
(16) End at Research Building IV

<u>Route E</u>: NCSU Centennial Campus

(1) Starting from Research Building IV, turn **right** onto **Capability Dr**
(2) Turn **right** onto **Varsity Dr**
(3) Turn **left** onto **Main Campus Dr**
(4) Turn **right** onto **Centennial Pkwy**
(5) Turn **right** onto **Crump Rd**
(6) Turn **right** onto **Main Campus Dr**
(7) Turn **left** onto **Research Dr**
(8) Turn **right** onto **Capability Drive**
(9) End at Research Building IV

<u>Route 1 out</u>: North Raleigh to RTP via I-540

(1) Starting at Peachtree Market / Mourning Dove Rd, turn **right** onto **Six Forks Rd**
(2) Take ramp on **left** to **I-540 West**
(3) Take **Exit 1B** on **right** to **I-40 West**
(4) Take **Exit 280** on **right** to **Davis Dr**
(5) Turn **left** onto **Davis Dr**
(6) Turn **right** onto **NC-54**
(7) Turn **right** onto **Park Office Dr**
(8) End at Park Office Dr parking lot

<u>Route 1 in</u>: RTP to North Raleigh via I-540

(1) Starting at Park Office Dr, turn **left** onto **NC-54**
(2) Turn **left** onto **Davis Dr**
(3) Take ramp on **right** to **I-40 East**
(4) Take **Exit 283** on **right** to **I-540 East**
(5) Take **Exit 11** on **right** to **Six Forks Road South**
(6) Turn **left** onto **Mourning Dove Rd**
(7) End at Peachtree Market parking lot

<u>Route 2 out</u>: North Raleigh to RTP via I-440, I-40

(1) Starting at Peachtree Market / Mourning Dove Rd, turn **left** onto **Six Forks Rd**
(2) Take ramp on **right** to **I-440 West**
(3) Take **Exit 4B** on **right** to **I-40 West**
(4) Take **Exit 280** on **right** to **Davis Dr**
(5) Turn **left** onto **Davis Dr**
(6) Turn **right** onto **NC-54**
(7) Turn **right** onto **Park Office Dr**
(8) End at Park Office Dr parking lot

<u>Route 2 in</u>: RTP to North Raleigh via I-40, I-440

(1) Starting at Park Office Dr, turn **left** onto **NC-54**
(2) Turn **left** onto **Davis Dr**
(3) Take ramp on **right** to **I-40 East**
(4) Take **Exit 289** on **right** to **I-440 East**
(5) Take **Exit 8B** on right to **Six Forks Rd North**
(6) Turn **right** onto **Mourning Dove Rd**
(7) End at Peachtree Market parking lot

<u>Route 3 out</u>: North Raleigh to RTP via Glenwood, T W Alexander

(1) Starting at Peachtree Market / Mourning Dove Rd, continue onto **Sawmill Rd**
(2) Turn **left** onto **Creedmoor Rd**
(3) Turn **right** onto **Lynn Rd**
(4) Turn **right** onto **Glenwood Ave**
(5) Turn **left** onto **T W Alexander Dr**
(6) Turn **left** onto **NC-54**
(7) Turn **left** onto **Park Office Dr**
(8) End at Park Office Dr parking lot

<u>Route 3 in</u>: RTP to North Raleigh via T W Alexander, Glenwood

(1) Starting at Park Office Dr, turn **right** onto **NC-54**
(2) Turn **right** onto **T W Alexander Dr**
(3) Turn **right** onto **Glenwood Ave**
(4) Turn **left** onto **Lynn Rd**
(5) Turn **left** onto **Creedmoor Rd**
(6) Turn **right** onto **Sawmill Rd**
(7) Continue onto **Mourning Dove Rd**
(8) End at Peachtree Market parking lot

References

Frey, H.C.; Zhang, K.; Rouphail, N.M. Fuel Use and Emissions Comparisons for Alternative Routes, Time of Day, Road Grade, and Vehicles Based on In-Use Measurements. *Environ. Sci. Technol.* 2008, *42* (7), 2483-2489; DOI 10.1021/es702493v

APPENDIX B
PEMS PRECISION, ACCURACY, AND CALIBRATION

The PEMS used here is the OEM-2100 Montana system, manufactured by Clean Air Technologies International, Inc. The Montana system is comprised of two parallel five-gas analyzers, a particulate matter (PM) measurement system, and engine sensor array, a global positioning system (GPS), and an on-board computer (CATI, 2003).

The two parallel gas analyzers simultaneously measure the volume percentage of carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons (HC), nitric oxide (NO), and oxygen (O_2) in the vehicle exhaust. HC, CO, and CO_2 are measured using non-dispersive infrared (NDIR). The accuracy for CO and CO_2 are excellent. The accuracy of the HC measurement depends on the type of fuel used (Vojtisek-Lom and Allsop, 2001; Andros, 2007). NO is measured using an electrochemical cell. Nitrogen oxides (NO_X) is typically comprised of approximately 95 volume percent NO; therefore, NO emissions converted to an equivalent NO_2 mass basis (using the molecular weight of NO_2) are a good indicator of total NO_X emissions. NO_X emissions are typically reported as equivalent NO_2. The performance of the Montana system has been verified in comparison to that of a laboratory grade chassis dynamometer measurement system (Battelle, 2003). The PEMS is calibrated in the laboratory using a cylinder gas. In the field, the PEMS periodically recalibrates to ambient air to prevent instrument measurement drift.

The PEMS reports the mass emission rates estimated using concentration and engine data as detailed elsewhere (Vojtisek-Lom and Allsop, 2001). The precision of this PEMS is ±25ppm, ±4 ppm, ±0.02%, and ±0.3% for NO, HC, CO and CO2, respectively (Zhang, 2006). Comparison of the PEMS with a dynamometer laboratory shows that the Montana system has good precision and accuracy (Battelle, 2003; Vojtisek-Lom and Allsop, 2001). For example, the Montana system has been evaluated in the Environmental Technology Verification (ETV) program of the U.S. EPA. In an independent study by Battelle (2003), emissions of several vehicles were measured simultaneously on a laboratory grade dynamometer facility and with the PEMS. The coefficients of determination (R^2) for the comparison for exceeded 0.86 for all pollutants, indicating good precision. The slopes of the parity plots for CO, CO2 and NO ranged from 0.92 to 1.05, indicating good accuracy. NDIR is well known to respond only partially to the total loading of hydrocarbon species in the exhaust, because it responds well to alkanes but is less responsive for other types of S-3 compounds, such as aromatics (Singer *et al.*, 1998; Stephens *et al.*, 1996a; Stephens *et al.*, 1996b). HC measurements are estimated to be low by a factor of two compared to the actual pollutant loading because of the NDIR detection method (Frey *et al.*, 2004).

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APPENDIX C
TEST SCHEDULE

Seven days of data collection were conducted in November 2008. For six of the test days, the vehicle initially operated in CD mode. Each test day, seven of the eight routes were driven to ensure that each route was tested six times and included both CD and CS modes.

Driver A operated the PHEV on Test Days 1, 2, 4, and 6. Driver B operated the PHEV on Test Days 3, 5, and 7.

TABLE A-1 PHEV Test Schedule

Test Day	Route Segment[a]											
	1	2	3	4	5	6	7	8	9	10	11	12
1	C out	2 out	2 in	C in	B out	B in	A out	1 out	1 in	A in	D	E
2[b]	C out	C in	D	E	B out	3 out	3 in	2 out	2 in	1 out	1 in	B in
3	A out	1 out	1 in	3 out	3 in	A in	B out	2 out	2 in	B in	C out	C in
4	B out	3 out	3 in	2 out	2 in	B in	A out	1 out	1 in	A in	D	E
5	D	E	A out	A in	C out	2 out	2 in	1 out	1 in	3 out	3 in	C in
6	B out	B in	C out	C in	A out	3 out	3 in	2 out	2 in	A in	D	E
7	A out	A in	B out	B in	C out	1 out	1 in	3 out	3 in	C in	D	E

[a] Outbound or inbound leg of a route
[b] No charge depleting data observed

APPENDIX D
ENERGY USE VALIDATION

Fuel use by the internal combustion engine is reported by the ECU in microliters of fuel during each reporting period, approximately a 0.7 second interval. These data were integrated over time and used to estimate fuel consumption on a second-by-second basis. For validation, reported fuel use over the entire test day was compared to the amount of gasoline used to refill the fuel tank after testing. The fuel use recorded on the gas receipt should be larger than the fuel use reported by the OBD due to additional miles traveled to move the PHEV into place to start a test and the distance traveled at the end of the test day to refuel.

There is a large discrepancy between the gas receipt recorded fuel use and the OBD recorded fuel use for Test Day 3. The reason for this is unknown. However, the amount of fuel needed to refill the tank is very low and thus is more suspect from the OBD recorded fuel use. Removing this data, the average absolute difference between the two recorded fuel use values is 3 percent. On five of the test days, the gas receipt and OBD estimates of fuel use agreed to within 0.4 gallons.

Plug-in battery discharge was estimated by multiplying second-by-second battery current and voltage and summing from the start of the test day to the time when the SOC reached a set point (typically between 3 and 5 percent of total capacity). For validation, reported electricity use over the entire test day was compared to the amount of electricity used to recharge the plug-in battery after testing. The electricity use reported by the Watt-hour meter should be larger than the electricity use reported by the OBD due to additional miles traveled to move the PHEV into place to start a test and the battery recharge efficiency.

For the 6 test days where the plug-in battery was used, the amount of electricity needed to recharge the plug-in battery are within 0.33 kWh, and are all larger than the plug-in battery electricity use recorded by the OBD. The OBD recorded electricity use for the six test days where the plug-in battery was used is within 0.6 kWh.

During CD mode, the plug-in battery supplies 30 to 50 percent of the energy needed for vehicle propulsion not met by the traction battery.

TABLE A-2 PHEV Fuel Use Validation Data

Test Day	Travel Distance Between Refueling (mi)	Gas Receipt Recorded Fuel Use (gal)	Travel Distance During Testing (mi)	OBD Recorded Fuel Use (gal)	Refueling Fuel Economy (mpg)	OBD Fuel Economy (mpg)
1	159	4.374	155	3.464	36	45
2	175	3.994	159	3.934	44	40
3	195	2.377	192	4.076	82	47
4	172	3.997	168	3.711	43	45
5	170	3.316	164	3.547	51	46
6	161	3.001	158	3.367	54	47
7	155	3.289	149	3.220	47	46

TABLE A-3 PHEV Electricity Use Validation Data

Test Date	Travel Distance in CD Mode (mi)	Watt-Hour Meter Recorded Electricity Use [a] (kWh)	OBD Recorded Electricity Use [b] (kWh)
1	38.4	5.45	3.82
2	0.0	0.00	0.00
3	32.0	5.20	3.78
4	38.7	5.34	3.86
5	32.2	5.29	4.02
6	27.1	5.42	3.94
7	22.6	5.12	3.42

[a] Electricity needed to recharge the plug-in battery from minimum setpoint to 100 percent
[b] Electricity used in CD mode

APPENDIX E
ELECTRICITY GENERATION EMISSION FACTORS

Grid-related emission rates vary depending on electricity generation resource mix. As the percentage of fossil fuels in the generation resource mix increases, the emission rates of CO_2, NO_X, and SO_2 increase. Below are average emission rates per North American Electricity Reliability Corporation (NERC) region. The percentages of electricity generated from fossil fuels are also summarized. The NERC region with the lowest percentage of electricity generation coming from non-renewable resources (NPCC), all have the lowest emission rates for CO_2 and NO_x from electricity generation.

TABLE A-4 Electricity Generation Emission Factors, by NERC Region

NERC Region	CO_2 (g/kWh)	NO_X (mg/kWh)	SO_2 (mg/kWh)	Generation Resource Mix Coal (%)	Oil (%)	Gas (%)
ASCC Alaska Systems Coordinating Council	529	1610	0.52	9.5	11.6	56.6
FRCC Florida Reliability Coordinating Council	640	1006	1.73	26.2	17.9	39.0
HICC Hawaiian Islands Coordinating Council	840	1883	2.02	14.2	78.8	0.0
MRO Midwest Reliability Organization	885	1736	2.85	72.7	0.8	5.2
NPCC Northeast Power Coordinating Council	425	425	1.17	14.4	13.2	29.2
RFC ReliabilityFirst Corporation	692	1111	4.37	64.4	1.4	5.8
SERC Southeast Reliability Corporation	664	935	3.03	57.1	1.5	11.7
SPP Southwest Power Pool, Inc.	850	1371	2.16	62.6	0.7	27.7
TRE Texas Regional Entity	643	425	1.55	37.1	0.5	47.5
WECC Western Electricity Coordinating Council	502	737	0.52	33.4	0.5	26.3

Emission factors include 7% transmission loss.

Source: EPA. "eGrid2007 version 1.1"; http://www.epa.gov/cleanenergy/energy -resources/ egrid/index.html. accessed September 2009.

Calculation of Selected North American Electricity Reliability Corporation (NERC) Region Carbon Monoxide (CO) and Hydrocarbon (HC) Emission Factors

From the U.S. Environmental Protection Agency (EPA) 2005 National Emissions Inventory (NEI) Source Classification Code (SCC) Summary and U.S. Energy Information Administration (EIA) Annual Energy Outlook 2007 with Projections to 2030:

Coal

Electricity generation (2005):	1993 x 10^9 kWh
Total CO Emissions (2005):	293,715 tons
Total HC Emissions (2005):	28,560 tons
CO Emission Factor:	134 mg/kWh
HC Emission Factor:	13 mg/kWh

Oil

Electricity generation (2005):	116×10^9 kWh
Total CO Emissions (2005):	59,518 tons
Total HC Emissions (2005):	4,519 tons
CO Emission Factor:	465 mg/kWh
HC Emission Factor:	35 mg/kWh

Natural Gas

Electricity generation (2005):	675×10^9 kWh
Total CO Emissions (2005):	81,295 tons
Total HC Emissions (2005):	9,058 tons
CO Emission Factor:	109 mg/kWh
HC Emission Factor:	12 mg/kWh

NERC Region Emission Factors (including 7% transmission loss):

$$EF_{i,j} = \frac{1}{\left(\frac{n}{100}\right)} \sum_{i=1}^{N} EF_{i,k} \left(\frac{E_{j,k}}{100}\right)$$

Where, $EF_{i,j}$ = emission factor for pollutant i from NERC region j (mg/kWh), n = transmission loss (%), $EF_{i,k}$ = emission factor for pollutant i from fuel source k (mg/kWh), and $E_{j,k}$ = electricity generation mix in NERC region j of fuel source k (%)

MRO Region: 72.7% coal, 0.8% oil, 5.2% gas
CO: 1.075[134(0.727) + 465(0.008) + 109(0.052)] = 115 mg/kWh
HC: 1.075[13(0.727) + 35(0.008) + 12(0.052)] = 11 mg/kWh

NPCC Region: 14.4% coal, 13.2% oil, 29.2% gas
CO: 1.075[134(0.144) + 465(0.132) + 109(0.292)] = 121 mg/kWh
HC: 1.075[13(0.144) + 35(0.132) + 12(0.292)] = 10 mg/kWh

SERC Region: 57.1% coal, 1.5% oil, 11.7% gas
CO: 1.075[134(0.571) + 465(0.015) + 109(0.117)] = 103 mg/kWh
HC: 1.075[13(0.571) + 35(0.015) + 12(0.117)] = 10 mg/kWh

WECC Region: 33.4% coal, 0.5% oil, 26.3% gas
CO: 1.075[134(0.334) + 465(0.005) + 109(0.263)] = 81 mg/kWh
HC: 1.075[13(0.334) + 35(0.005) + 12(0.263)] = 8 mg/kWh

APPENDIX F
VEHICLE EMISSION RATES FOR SELECTED NERC REGIONS

Grid-related emission rates vary depending on electricity generation resource mix. There are significant differences in the comparison of total CD versus tailpipe CS emissions based on differences in electricity generation mix. It is possible for total CD emissions to be lower than tailpipe CS emissions for all routes if a generation mix with a lower percentage of fossil fuel is used in power production.

Below are comparisons of CO_2, NO_X, and SO_2 emission rates based on average electricity generation mixes in the Midwest Reliability Organization (MRO), Northeast Power Coordinating Council (NPCC) and Western Electricity Coordinating Council (WECC) regions. These results are used to inform summaries given in the section “Direct and Indirect Emissions” of the main paper.

TABLE A-5 Measured Tailpipe and Estimated Midwest Reliability Organization (MRO) Region Grid-Based Emission Factors

Route	Mode	Emissions Source	CO_2 (g/mi)	CO (mg/mi)	HC (mg/mi)	NO_X (mg/mi)	SO_2 (mg/mi)
A	CD	Tailpipe	105	150	17	16	< 1
		Grid	121	16	2	251	387
		Total	226	166	19	267	387
	CS	Tailpipe	202	160	68	56	< 1
B	CD	Tailpipe	107	168	25	15	< 1
		Grid	127	17	2	251	409
		Total	234	185	27	266	409
	CS	Tailpipe	197	86	44	38	< 1
C	CD	Tailpipe	133	254	18	26	< 1
		Grid	116	15	1	228	372
		Total	249	269	19	254	372
	CS	Tailpipe	200	48	71	31	< 1
D	CD	Tailpipe	176	497	60	11	< 1
		Grid	103	13	1	202	332
		Total	279	410	61	213	332
	CS	Tailpipe	224	46	15	40	< 1
E	CD	Tailpipe	148	47	< 1	3	< 1
		Grid	128	15	1	251	409
		Total	276	62	1	254	409
	CS	Tailpipe	227	96	178	9	< 1
1	CD	Tailpipe	150	< 1	1	20	< 1
		Grid	97	13	1	189	310
		Total	247	13	2	209	310
	CS	Tailpipe	220	27	25	71	< 1
2	CD	Tailpipe	138	15	10	31	< 1
		Grid	80	11	1	158	259
		Total	218	26	11	189	259
	CS	Tailpipe	206	57	29	52	< 1
3	CD	Tailpipe	152	< 1	4	45	< 1
		Grid	75	10	1	149	242
		Total	228	10	5	194	242
	CS	Tailpipe	204	46	55	56	< 1

[a] Emissions for electricity generation in MRO are based on 2007 EPA eGRID data for CO_2, NO_X, and SO_2, and 2005 NEI data for CO and HC, and account for a 7% transmission loss between the power plant and vehicle charging station. The average electric utility emission factors are 889 g CO_2/kWh, 1744 mg NO_X/kWh, 2.86 g SO_2/kWh, 115 mg CO/kWh, and 11 mg HC/kWh. Tailpipe SO_2 emissions are based on ≤ 30 ppm sulfur in gasoline.

[b] MRO electricity generation mix is 72.7% coal, 0.8% oil, 5.2% gas, and 21.3% other sources.

TABLE A-6 Measured Tailpipe and Estimated Northeast Power Coordinating Council (NPCC) Region Grid-Based Emission Factors

	Mode	Emissions Source	CO_2 (g/mi)	CO (mg/mi)	HC (mg/mi)	NO_X (mg/mi)	SO_2 (mg/mi)
A	CD	Tailpipe	105	150	17	16	< 1
		Grid	58	17	1	61	159
		Total	163	167	18	77	159
	CS	Tailpipe	202	160	68	56	< 1
B	CD	Tailpipe	107	168	25	15	< 1
		Grid	61	18	1	61	168
		Total	168	186	26	76	168
	CS	Tailpipe	197	86	44	38	< 1
C	CD	Tailpipe	133	254	18	26	< 1
		Grid	56	16	1	56	152
		Total	189	270	19	82	152
	CS	Tailpipe	200	48	71	31	< 1
D	CD	Tailpipe	176	497	60	11	< 1
		Grid	49	14	1	50	136
		Total	225	511	61	61	136
	CS	Tailpipe	224	46	15	40	< 1
E	CD	Tailpipe	148	47	< 1	3	< 1
		Grid	90	16	1	61	168
		Total	238	63	1	64	168
	CS	Tailpipe	227	96	178	9	< 1
1	CD	Tailpipe	150	< 1	1	20	< 1
		Grid	47	13	1	46	127
		Total	197	13	2	66	127
	CS	Tailpipe	220	27	25	71	< 1
2	CD	Tailpipe	138	15	10	31	< 1
		Grid	38	11	1	39	106
		Total	176	26	11	70	106
	CS	Tailpipe	206	57	29	52	< 1
3	CD	Tailpipe	152	< 1	4	45	< 1
		Grid	36	10	1	36	99
		Total	188	10	5	81	99
	CS	Tailpipe	204	46	55	56	< 1

[a] Emissions for electricity generation in NPCC are based on 2007 EPA eGRID data for CO_2, NO_X, and SO_2, and 2005 NEI data for CO and HC, and account for a 7% transmission loss between the power plant and vehicle charging station. The average electric utility emission factors are 425 g CO_2/kWh, 425 mg NO_X/kWh, 1.17 g SO_2/kWh, 121 mg CO/kWh, and 11 mg HC/kWh. Tailpipe SO_2 emissions are based on ≤ 30 ppm sulfur in gasoline.

[b] NPCC electricity generation mix is 14.4% coal, 13.2% oil, 29.2% gas, and 43.2% other sources.

TABLE A-7 Measured Tailpipe and Estimated Western Electricity Coordinating Council (WECC) Region Grid-Based Emission Factors

Route	Mode	Emissions Source	CO_2 (g/mi)	CO (mg/mi)	HC (mg/mi)	NO_X (mg/mi)	SO_2 (mg/mi)
A	CD	Tailpipe	105	150	17	16	< 1
		Grid	69	14	1	106	71
		Total	174	164	18	122	71
	CS	Tailpipe	202	160	68	56	< 1
B	CD	Tailpipe	107	168	25	15	< 1
		Grid	72	15	1	106	75
		Total	179	183	26	121	75
	CS	Tailpipe	197	86	44	38	< 1
C	CD	Tailpipe	133	254	18	26	< 1
		Grid	66	14	1	97	68
		Total	199	268	19	123	68
	CS	Tailpipe	200	48	71	31	< 1
D	CD	Tailpipe	176	497	60	11	< 1
		Grid	58	12	1	86	61
		Total	234	509	61	97	61
	CS	Tailpipe	224	46	15	40	< 1
E	CD	Tailpipe	148	47	< 1	3	< 1
		Grid	73	14	1	106	75
		Total	221	61	1	109	75
	CS	Tailpipe	227	96	178	9	< 1
1	CD	Tailpipe	150	< 1	1	20	< 1
		Grid	55	11	1	80	57
		Total	205	11	2	100	57
	CS	Tailpipe	220	27	25	71	< 1
2	CD	Tailpipe	138	15	10	31	< 1
		Grid	45	10	1	67	47
		Total	183	25	11	98	47
	CS	Tailpipe	206	57	29	52	< 1
3	CD	Tailpipe	152	< 1	4	45	< 1
		Grid	42	9	1	63	44
		Total	194	9	5	108	44
	CS	Tailpipe	204	46	55	56	< 1

[a] Emissions for electricity generation in WECC are based on 2007 EPA eGRID data for CO_2, NO_X, and SO_2, and 2005 NEI data for CO and HC, and account for a 7% transmission loss between the power plant and vehicle charging station. The average electric utility emission factors are 504 g CO_2/kWh, 741 mg NO_X/kWh, 0.53 g SO_2/kWh, 104 mg CO/kWh, and 10 mg HC/kWh. Tailpipe SO_2 emissions are based on ≤ 30 ppm sulfur in gasoline.

[b] WECC electricity generation mix is 33.4% coal, 0.5% oil, 26.3% gas, and 39.8% other sources.

APPENDIX G

TAILPIPE EMISSION RATES VERSUS VSP (kW/TON)

An advantage of collecting real-world data for PHEVs using PEMS is the capability to quantify the effect of events during vehicle operation, such as short periods of high speed, acceleration, or road grade, on emissions. The below graphs explore the relationship between tailpipe emissions and vehicle specific power. Mean emission rates and 95% confidence intervals on the mean are shown for each range of 1.0 kW/ton of VSP.

The key findings are:

- Emissions of NO_x are fairly constant at negative VSP, and increase for positive values of VSP. Emissions of NO_x are higher during CS mode than during CD mode.

- Emissions of HC and CO are sporadic during CD mode, with no trend in emission rate versus VSP visible, compared to during CS mode. Emissions of HC and CO are, on average, higher during CD mode than during CS mode.

- Emissions of CO_2 are fairly constant at negative VSP, especially during CD mode, and increase for positive values of VSP. Emissions of CO_2 are higher during CS mode than during CD mode.

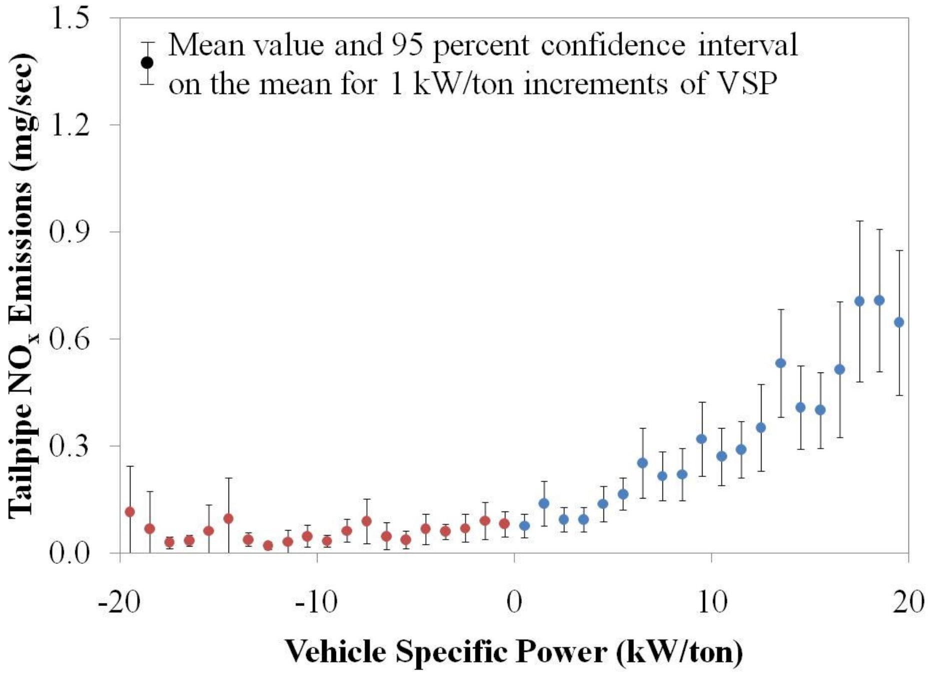

FIGURE A-2 Tailpipe NO_x emissions versus vehicle specific power for Charge Depleting mode and engine on.

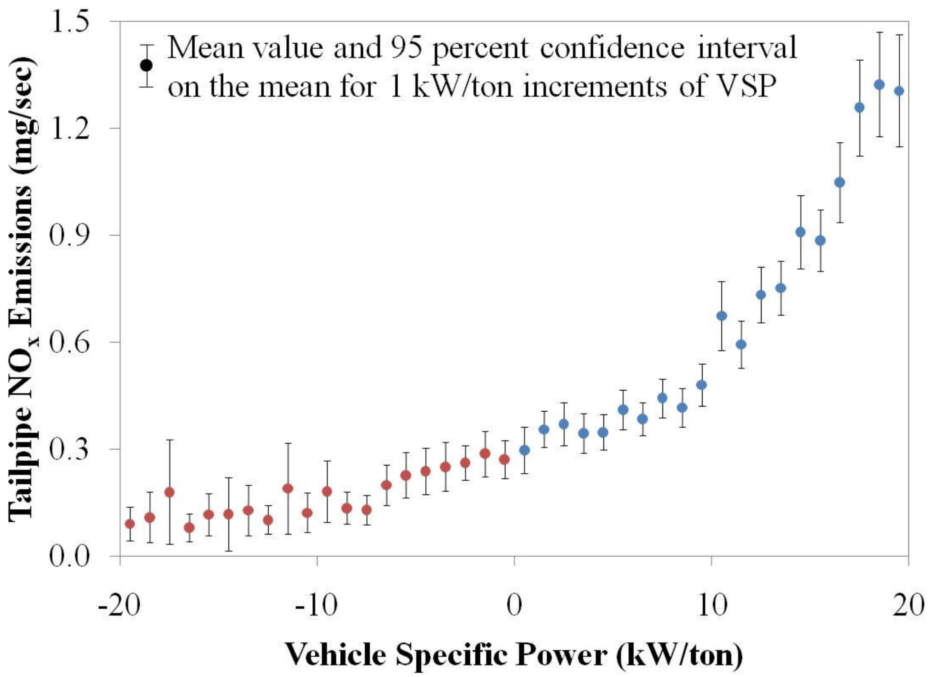

FIGURE A-3 Tailpipe NO_x emissions versus vehicle specific power for Charge Sustaining mode and engine on.

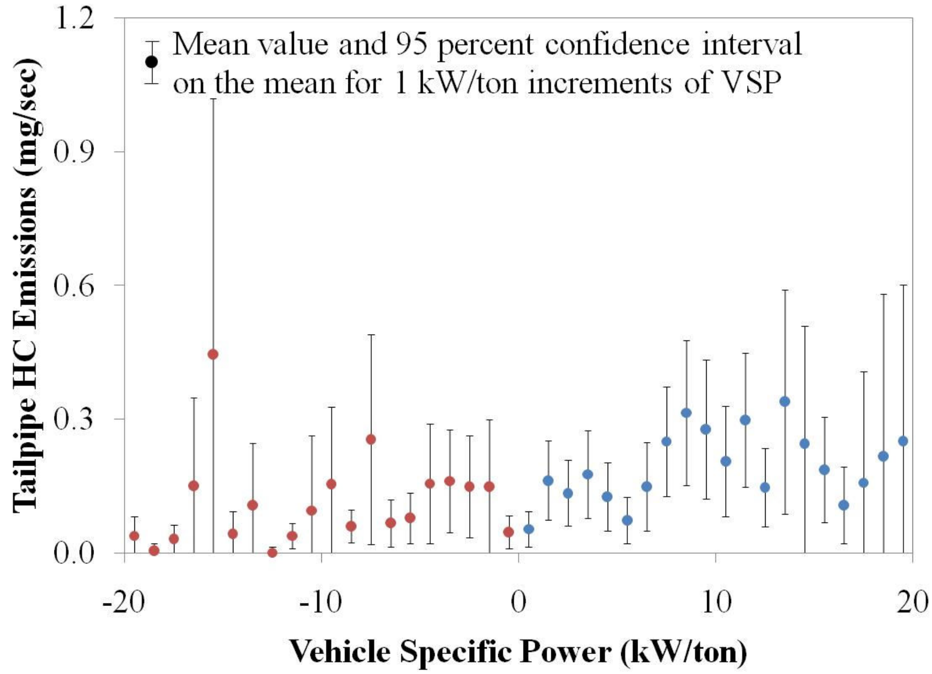

FIGURE A-4 Tailpipe HC emissions versus vehicle specific power for Charge Depleting mode and engine on.

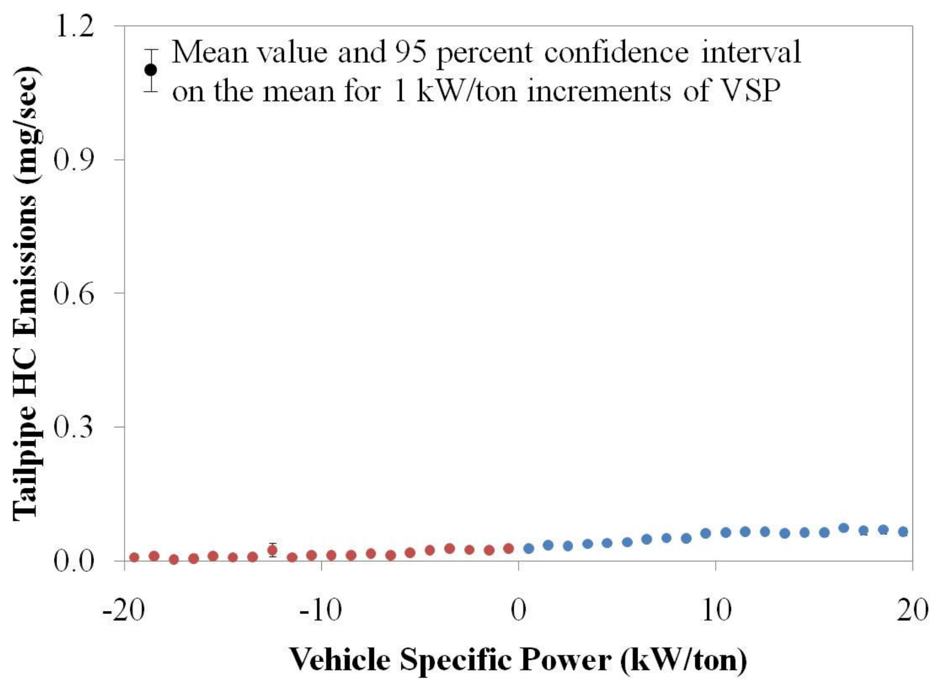

FIGURE A-5 Tailpipe HC emissions versus vehicle specific power for Charge Sustaining mode and engine on.

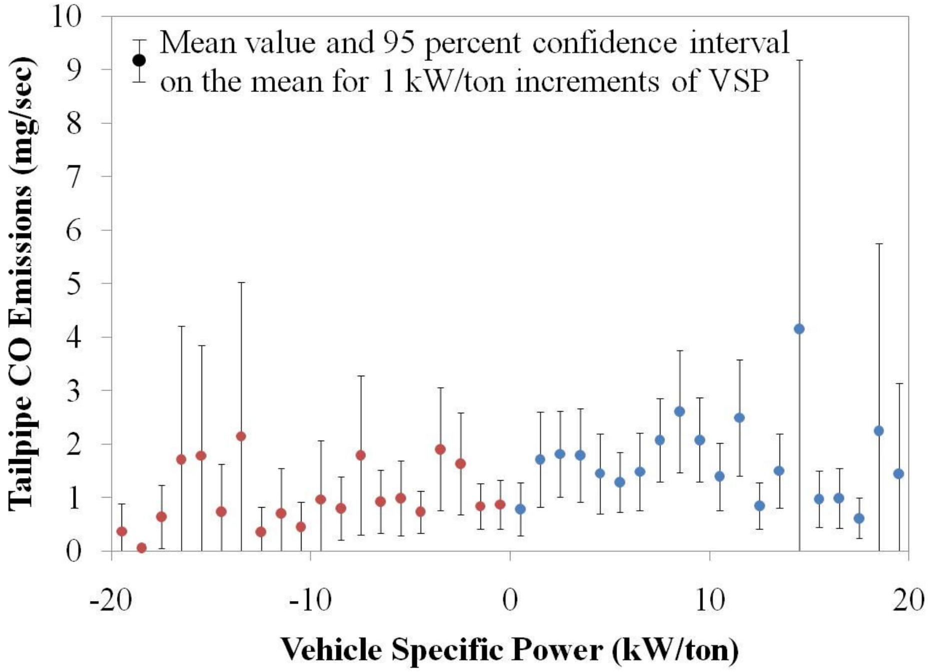

FIGURE A-6 Tailpipe CO emissions versus vehicle specific power for Charge Depleting mode and engine on.

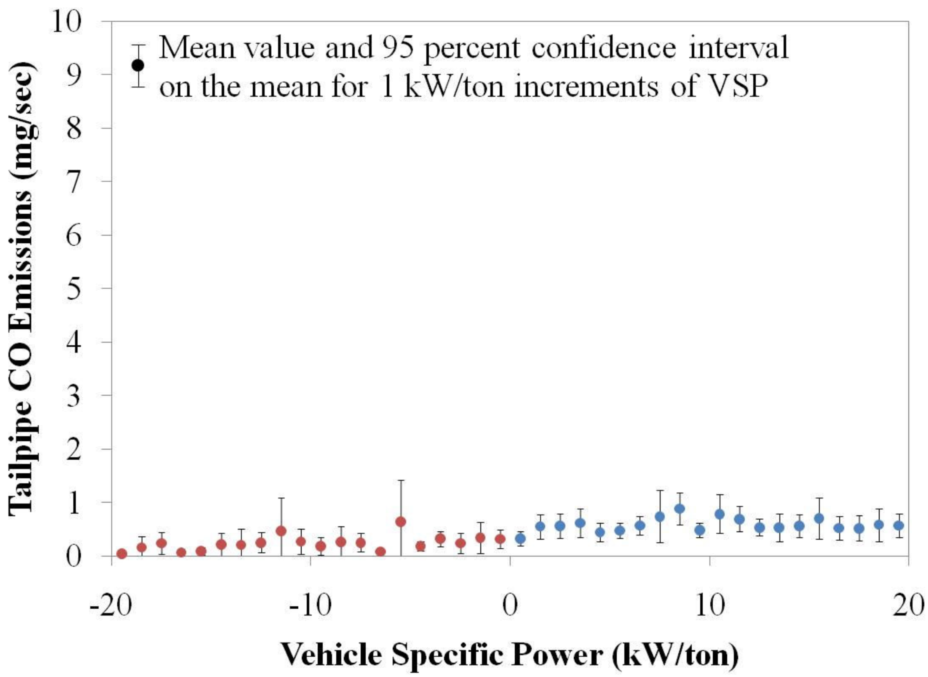

FIGURE A-7 Tailpipe CO emissions versus vehicle specific power for Charge Sustaining mode and engine on.

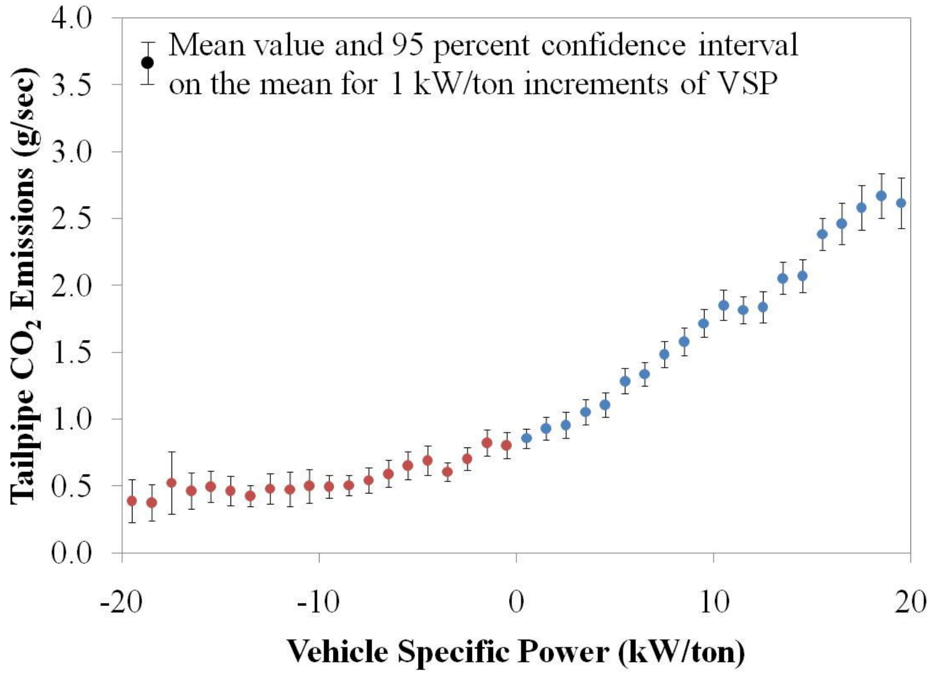

FIGURE A-8 Tailpipe CO_2 emissions versus vehicle specific power for Charge Depleting mode and engine on.

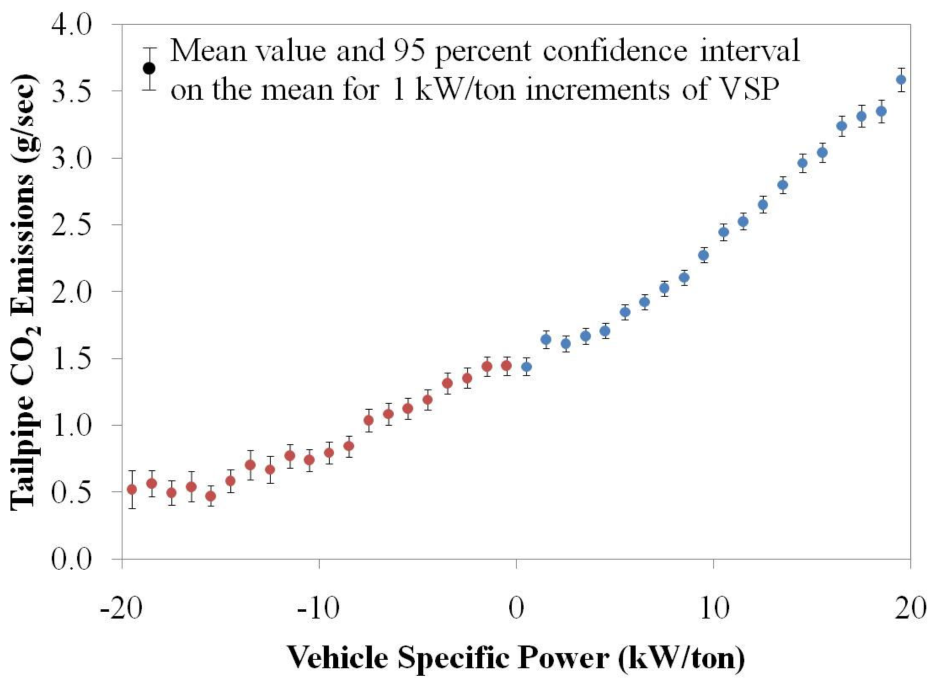

FIGURE A-9 Tailpipe CO_2 emissions versus vehicle specific power for Charge Sustaining mode and engine on.

APPENDIX H
EMISSIONS FOR PHEV OPERATING MODES

While there is not a standardized definition of operating modes for a PHEV, they can be classified based on whether the vehicle is: (a) at zero versus non-zero speed, and (b) decelerating, cruising, or accelerating. Furthermore, operating modes can be stratified taking into account conditions under which the engine is on versus off, and whether the traction battery is discharging or recharging. Transient engine status is characterized as times when the engine does not consume fuel, but there is an RPM reading. The engine RPM remains around 1000, where it could be easily ramped up if more power is needed or ramped down if battery power can be utilized for an extended time. One example of a transient state occurring is when the driver "tricks" the engine to turn off, while still maintaining speeds where the engine would typically still remain on.

Tables A-10 through A-12 contain measured tailpipe emission factors for each PHEV operating mode. They are separated into CD, CS, and a combination of CD and CS modes. The internal combustion engine is off for Modes A through E. During Modes F through L, the ICE is in a transient state—the engine's RPM is over 900, yet there is no fuel use. The internal combustion engine is on for Modes M through Q.

TABLE A-8 PHEV Operating Modes and Emissions for Charge Depleting Mode

Mode	Engine Status	Vehicle Speed	Traction Battery Status	Vehicle Acceleration	Time in Mode (sec)	Average VSP (kW/ton)	CO_2 (g/mile)	NO_X (mg/mile)	CO (mg/mile)	HC (mg/mile)
A	Off	v = 0	Discharge	---	3,789	0	0	0	0	0
B	Off	v > 0	Recharge	Deceleration	1,389	- 10.0	0	0	0	0
C	Off	v > 0	Recharge	Cruise and Acceleration	1,758	0.8	0	0	0	0
D	Off	v > 0	Discharge	Deceleration	740	- 1.8	0	0	0	0
E	Off	v > 0	Discharge	Cruise and Acceleration	2,919	4.3	0	0	0	0
F	Transient	v > 0	Recharge	Deceleration	174	- 17.0	0	0	0	0
G	Transient	v > 0	Recharge	Cruise	847	0.3	0	0	0	0
H	Transient	v > 0	Recharge	Acceleration	14	9.5	0	0	0	0
J	Transient	v > 0	Discharge	Deceleration	31	- 3.7	0	0	0	0
K	Transient	v > 0	Discharge	Cruise	570	3.0	0	0	0	0
L	Transient	v > 0	Discharge	Acceleration	48	10.7	0	0	0	0
M	On	v > 0	Recharge	Cruise and Deceleration	3,066	6.5	118	23	137	13
N	On	v > 0	Recharge	Acceleration	688	15.5	297	93	292	44
P	On	v > 0	Discharge	Cruise and Deceleration	4,393	9.0	126	19	45	7
Q	On	v > 0	Discharge	Acceleration	986	15.9	292	81	140	21

TABLE A-9 PHEV Operating Modes and Emissions for Charge Sustaining Mode

Mode	Engine Status	Vehicle Speed	Traction Battery Status	Vehicle Acceleration	Time in Mode (sec)	Average VSP (kW/ton)	CO_2 (g/mile)	NO_X (mg/mile)	CO (mg/mile)	HC (mg/mile)
A	Off	v = 0	Discharge	---	12,391	0	0	0	0	0
B	Off	v > 0	Recharge	Deceleration	5,428	- 11.1	0	0	0	0
C	Off	v > 0	Recharge	Cruise and Acceleration	4,442	- 0.2	0	0	0	0
D	Off	v > 0	Discharge	Deceleration	2,841	- 3.0	0	0	0	0
E	Off	v > 0	Discharge	Cruise and Acceleration	6,637	1.9	0	0	0	0
F	Transient	v > 0	Recharge	Deceleration	711	- 16.7	0	0	0	0
G	Transient	v > 0	Recharge	Cruise	2,601	- 1.3	0	0	0	0
H	Transient	v > 0	Recharge	Acceleration	123	9.6	0	0	0	0
J	Transient	v > 0	Discharge	Deceleration	140	- 8.0	0	0	0	0
K	Transient	v > 0	Discharge	Cruise	1,103	2.2	0	0	0	0
L	Transient	v > 0	Discharge	Acceleration	192	7.0	0	0	0	0
M	On	v > 0	Recharge	Cruise and Deceleration	18,877	9.5	183	59	37	4
N	On	v > 0	Recharge	Acceleration	3,334	15.7	327	96	74	14
P	On	v > 0	Discharge	Cruise and Deceleration	21,326	8.4	162	39	36	3
Q	On	v > 0	Discharge	Acceleration	5,529	14.5	324	97	53	14

TABLE A-10 PHEV Operating Modes and Emissions for Charge Depleting and Sustaining Modes

Mode	Engine Status	Vehicle Speed	Traction Battery Status	Vehicle Acceleration	Time in Mode (sec)	Average VSP (kW/ton)	CO_2 (g/mile)	NO_X (mg/mile)	CO (mg/mile)	HC (mg/mile)
A	Off	v = 0	Discharge	---	16,180	0	0	0	0	0
B	Off	v > 0	Recharge	Deceleration	6,817	- 10.9	0	0	0	0
C	Off	v > 0	Recharge	Cruise and Acceleration	6,200	0.1	0	0	0	0
D	Off	v > 0	Discharge	Deceleration	3,581	- 2.8	0	0	0	0
E	Off	v > 0	Discharge	Cruise and Acceleration	9,556	2.6	0	0	0	0
F	Transient	v > 0	Recharge	Deceleration	885	- 16.8	0	0	0	0
G	Transient	v > 0	Recharge	Cruise	3,448	- 0.9	0	0	0	0
H	Transient	v > 0	Recharge	Acceleration	137	9.6	0	0	0	0
J	Transient	v > 0	Discharge	Deceleration	171	- 7.2	0	0	0	0
K	Transient	v > 0	Discharge	Cruise	1,673	2.4	0	0	0	0
L	Transient	v > 0	Discharge	Acceleration	240	7.7	0	0	0	0
M	On	v > 0	Recharge	Cruise and Deceleration	21,943	9.0	175	54	50	5
N	On	v > 0	Recharge	Acceleration	4,022	15.7	322	95	109	19
P	On	v > 0	Discharge	Cruise and Deceleration	25,719	8.5	157	36	37	4
Q	On	v > 0	Discharge	Acceleration	6,515	14.7	319	94	67	15

APPENDIX I
PHEV OPERATING MODES TRANSITION MATRIX

The transition matrix, depicting both CD and CS modes, helps to describe the change in vehicle operation modes and the average duration in each mode. A majority of the time, the vehicle stays within an operation mode, or changes to another operation mode within the same engine status (off, transient, or on).

TABLE A-11 PHEV Operating Modes Transition Matrix for Charge Depleting and Charge Sustaining Modes

STARTING MODE	ENDING MODE																	Transitions				Avg. Mode
	A	B	C	D	E	F	G	H	J	K	L	M	N	P	Q	+	%	Stay in Mode		Out of Mode		Duration (sec)
A	18971	0	4	28	571	0	0	0	0	8	22	0	0	0	23	19627	16.9%	18971	*96.7%*	656	*3.3%*	28.9
B	1	5752	312	1172	86	18	3	1	12	3	0	22	0	1	0	7383	6.4%	5752	*77.9%*	1631	*22.1%*	3.5
C	10	1073	4393	116	1020	2	25	7	0	15	1	49	10	16	10	6747	5.8%	4393	*65.1%*	2354	*34.9%*	1.9
D	143	207	40	2223	1012	4	4	0	55	55	11	23	3	150	19	3949	3.4%	2223	*56.3%*	1726	*43.7%*	1.3
E	502	31	1039	357	6952	1	36	3	6	217	168	129	55	357	355	10208	8.8%	6952	*68.1%*	3256	*31.9%*	2.1
F	0	104	5	8	0	474	113	0	18	5	0	148	0	59	0	934	0.8%	474	*50.7%*	460	*49.3%*	1.0
G	0	31	172	3	74	192	2410	11	12	228	2	254	4	210	0	3603	3.1%	2410	*66.9%*	1193	*33.1%*	2.0
H	0	0	90	1	26	0	11	12	0	0	0	2	8	1	0	151	0.1%	12	*7.9%*	139	*92.1%*	0.1
J	0	2	1	4	1	10	7	0	34	19	1	18	2	74	9	182	0.2%	34	*18.7%*	148	*81.3%*	0.2
K	0	2	21	8	61	4	215	0	19	873	5	106	24	326	45	1709	1.5%	873	*51.1%*	836	*48.9%*	1.0
L	0	0	10	0	34	0	4	1	0	5	8	4	55	6	138	265	0.2%	8	*3.0%*	257	*97.0%*	0.0
M	0	161	336	17	124	220	616	8	12	88	0	13549	340	7285	185	22941	19.8%	13549	*59.1%*	9392	*40.9%*	1.4
N	0	1	189	0	52	0	15	63	0	4	13	523	2084	290	1182	4416	3.8%	2084	*47.2%*	2332	*52.8%*	0.9
P	2	5	70	13	106	6	126	7	14	177	3	7881	275	17457	631	26773	23.1%	17457	*65.2%*	9316	*34.8%*	1.9
Q	0	0	44	1	95	0	9	37	0	15	32	273	1574	519	4644	7243	6.2%	4644	*64.1%*	2599	*35.9%*	1.8
+	19629	7369	6726	3951	10214	931	3594	150	182	1712	266	22981	4434	26751	7241	116131						

	Off	Trans	On
Off	46015	677	1222
Trans	658	4693	1493
On	1216	1465	58895

Off modes: A - E
Transient modes: F - L
On modes: M - Q

The number of transitions into a mode may not equal the number of transitions out of the same mode due to the following reasons:

(1) Data is discontinuous from the loss of data due to the QA process,
(2) Vehicle is initially in a mode without a prior transition at start of test,
(3) Vehicle is in a mode when the vehicle is shut off at the end of test,
(4) Vehicle may transition into an undefined operation mode

APPENDIX J
VEHICLE ACTIVITY AND EMISSIONS TIME TRACES

To illustrate the type of data that was collected, time traces of vehicle activity and correlating emissions were created for the outbound trip on Route 3 on Test Day 4. Figure SI-8 shows second-by-second speed versus elapsed trip time. Instantaneous speed ranged from zero to approximately 62 mph. Figures SI-9 and SI-10 depict VSP and engine RPM versus elapsed trip time.

Emission traces for the measured pollutants are shown in Figures SI-11 through SI-14 for NO_X, CO_2, CO, and HC, respectively. For NO_X, CO, and HC, the highest emission rates, on a mass per time basis, occur during small episodes. The largest peaks for NO_X emissions occur when the vehicle quickly accelerates from zero to approximately 50 mph. CO and HC emissions peak every time the engine turns on, and are comparatively low otherwise.

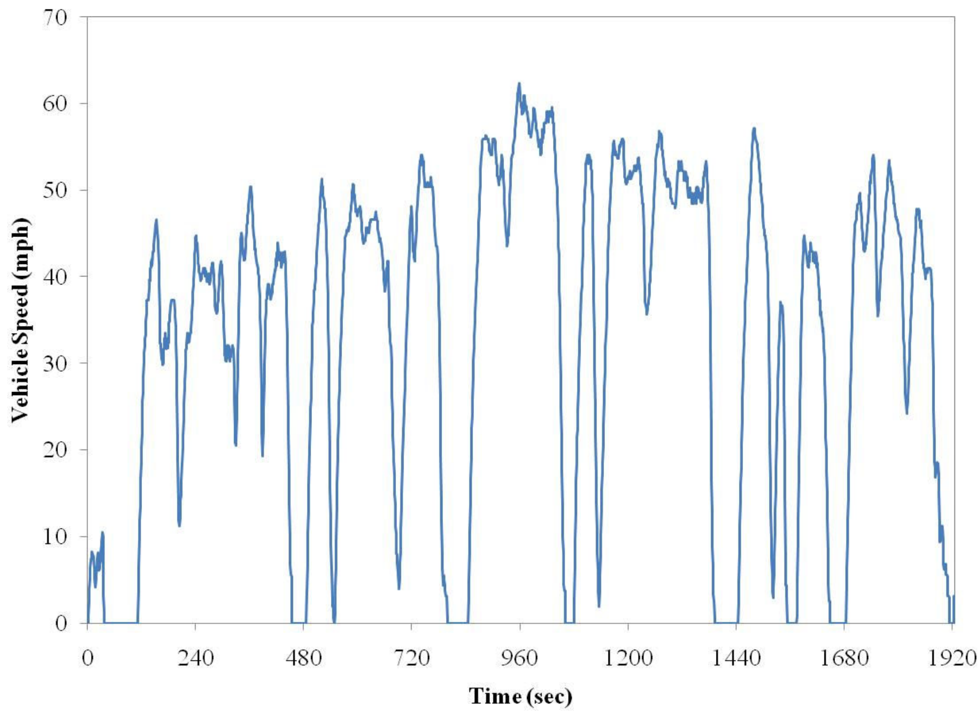

FIGURE A-10 Time plot of vehicle speed during Charge Sustaining mode for Route 3 Outbound on Test Day 4.

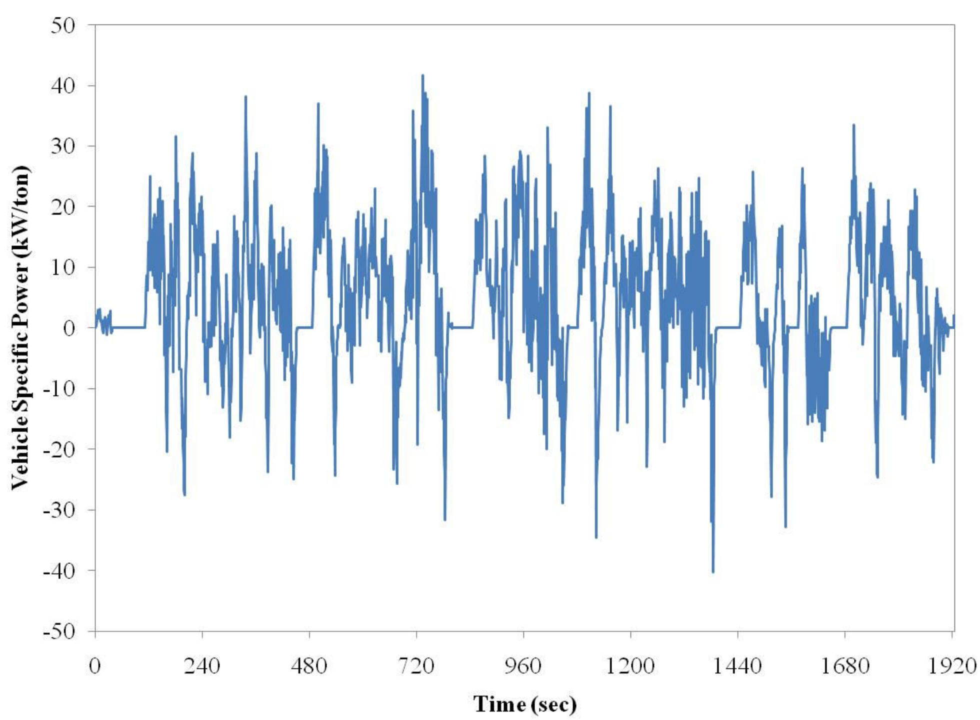

FIGURE A-11 Time plot of vehicle specific power during Charge Sustaining mode for Route 3 Outbound on Test Day 4.

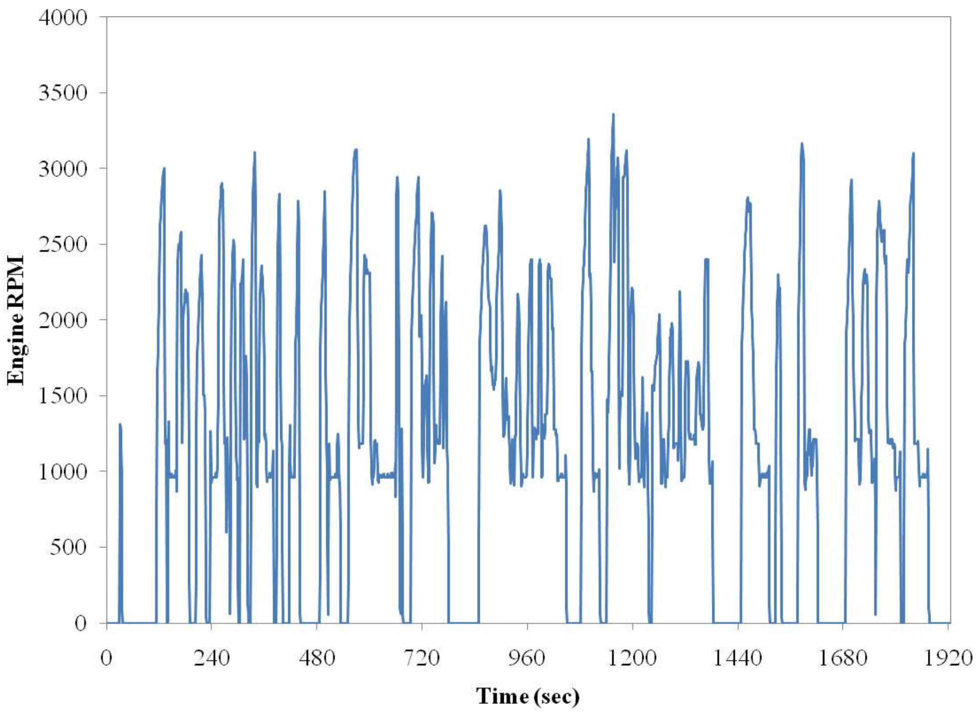

FIGURE A-12 Time plot of engine speed during Charge Sustaining mode for Route 3 Outbound on Test Day 4.

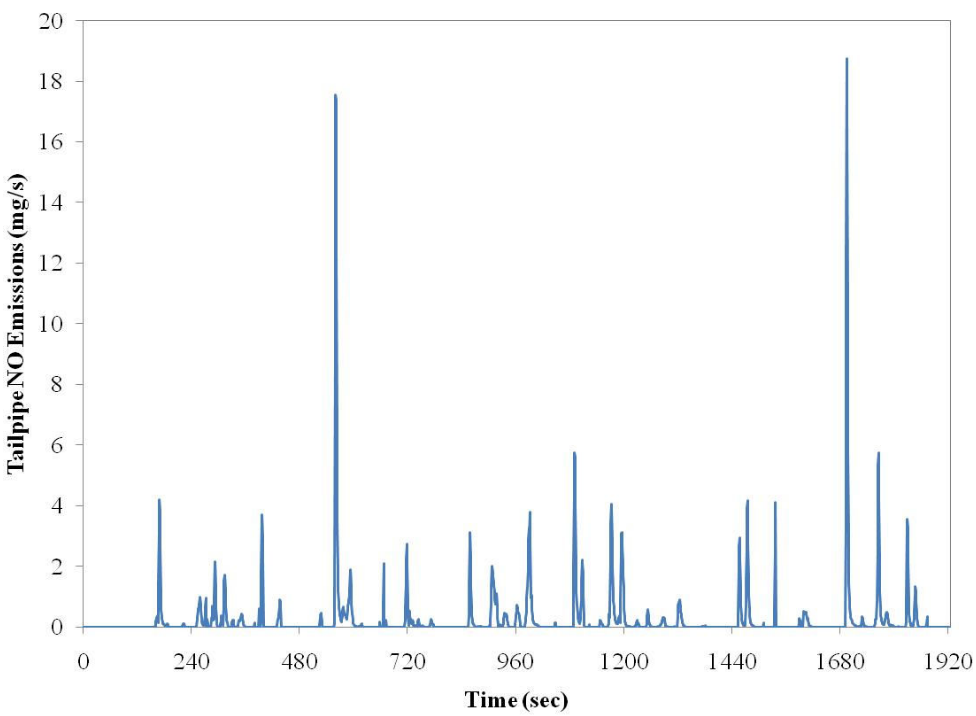

FIGURE A-13 Time plot of tailpipe NO_x emission rate during Charge Sustaining mode for Route 3 Outbound on Test Day 4.

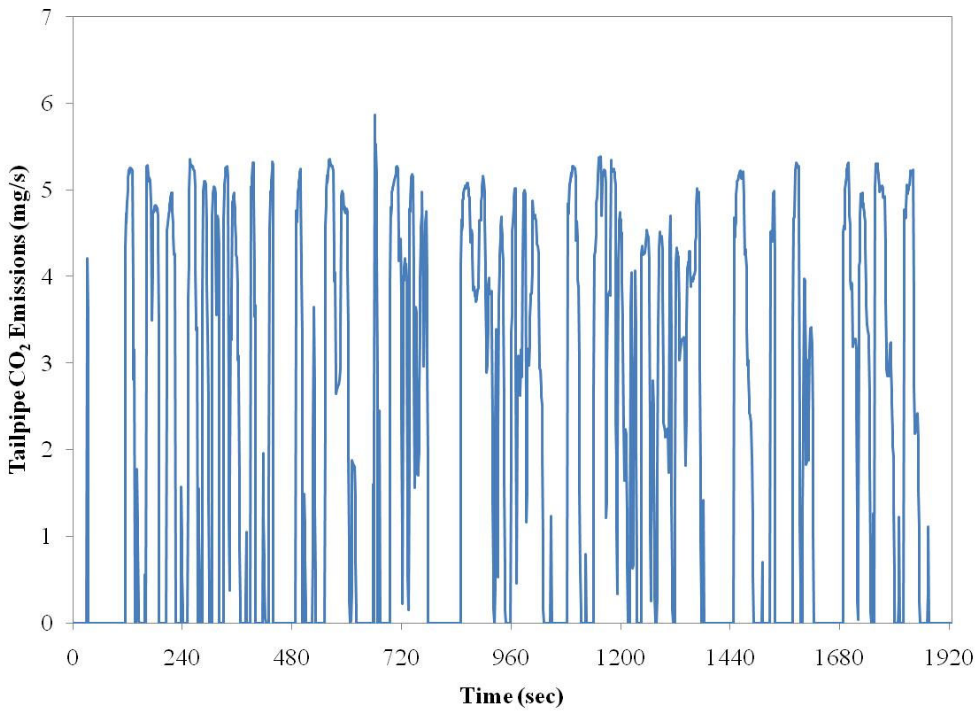

FIGURE A-14 Time plot of tailpipe CO_2 emission rate during Charge Sustaining mode for Route 3 Outbound on Test Day 4.

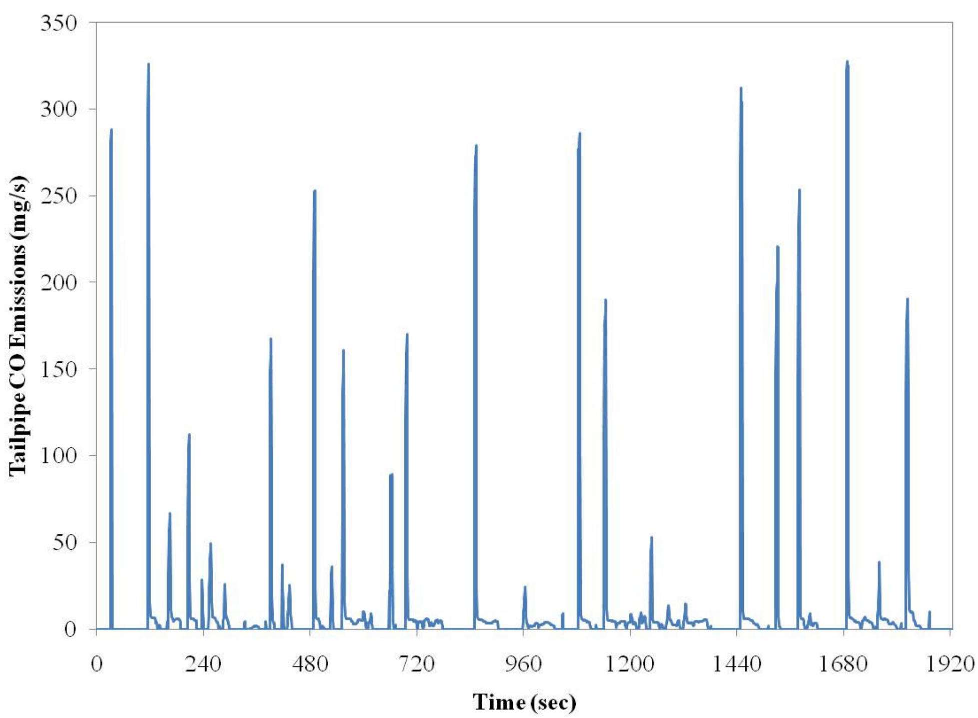

FIGURE A-15 Time plot of tailpipe CO emission rate during Charge Sustaining mode for Route 3 Outbound on Test Day 4.

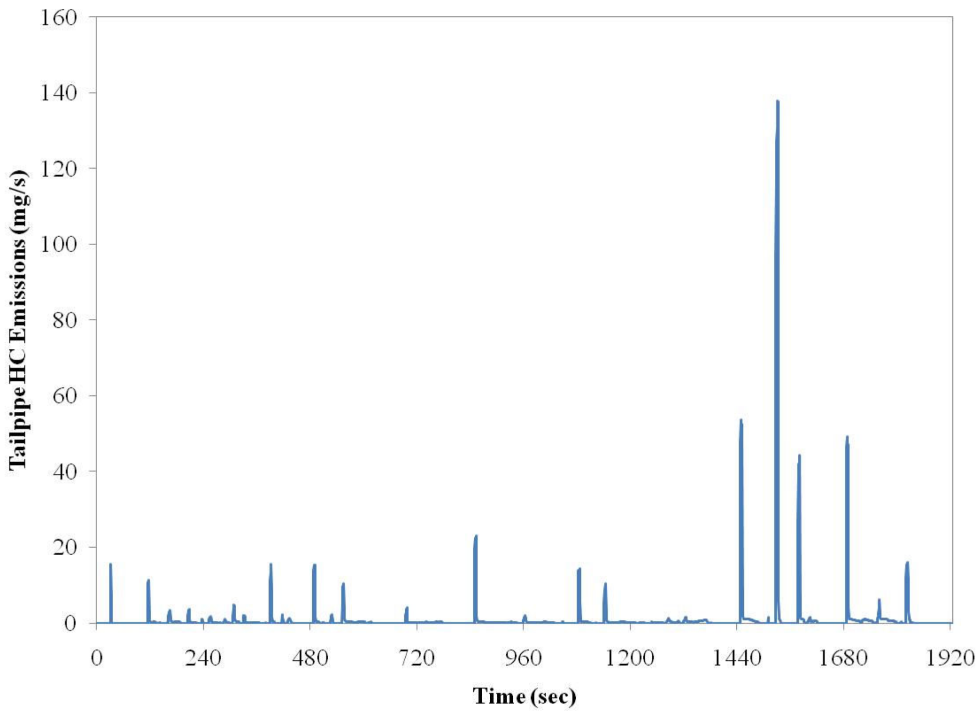

FIGURE A-16 Time plot of tailpipe HC emission rate during Charge Sustaining mode for Route 3 Outbound on Test Day 4.