ABSTRACT

ZHENG, XIAOHUI. Measuring, Evaluating, and Modeling Energy Use and Emission Rates for a Plug-In Hybrid Electric Vehicle Based on Real-World Measurement. (Under the direction of Dr. H. Christopher Frey.)

Plug-in Hybrid Electric Vehicles (PHEVs) have recently entered the commercial market in the United States. PHEVs typically have initial purchase costs higher than comparably sized conventional vehicles, but may offer benefits of improved energy economy, reduced emissions, and flexibility to use electricity as an energy source. However, little has been done to quantify these benefits in terms of energy use and emissions. To demonstrate a method for quantifying the real-world activity, energy use, and emissions of PHEVs, taking into account two PHEV operation modes (charge depleting (CD) and charge sustaining (CS) modes) based on different electricity generation resource mix, variations in power demand, energy on and off activity, and cold start and hot stabilized running operation, a 2013 Toyota Prius Plug-In was measured in the real world. The total energy use and emissions includes direct gasoline consumption and tailpipe emissions, upstream energy use and emissions for gasoline production (including crude oil recovery and transportation, and gasoline refining, transportation and distribution), and indirect energy use and emissions related to power generation for grid-based electricity consumed by the PHEV (including feedstock recovery/production and transportation, and electricity generation and transmission). Energy
use and emission rates are compared between CD and CS modes. The effect of different electricity generation resource mix on energy use and emission rates in CD mode is quantified. Vehicle specific power (VSP) based modal average energy use and emission rates are inferred to assess trends in energy use and emissions with respect to engine load and for comparisons of engine on versus engine off, and cold start versus hot stabilized running. The results show that for CD versus CS mode, when PHEV using electricity from the North Carolina energy mix, the total energy use, and CO, NO\textsubscript{x}, SO\textsubscript{x}, PM\textsubscript{2.5}, and PM\textsubscript{10} emission rates are higher, the CO\textsubscript{2} emission rate is similar, the HC emission rate is lower. For both CD and CS modes, the total energy use and CO\textsubscript{2} emission rates for engine on and off approximately increase with increasing VSP modes. During cold start compared to hot stabilized running, the direct tailpipe CO and HC emissions are higher by 4 to 6 times. A model is developed to predict whether engine is on or off, based on externally observable variables, such as vehicle speed, road grade, vehicle acceleration and VSP, and to calculate cycle average energy use and emissions and to estimate instantaneous emissions of PHEVs, with respect to two different operating modes, based on the in-use measurement. The method demonstrated is applicable to estimate energy use and emissions of PHEVs during real-world driving.
Measuring, Evaluating, and Modeling Energy Use and Emission Rates for a Plug-In Hybrid Electric Vehicle Based on Real-World Measurement

by

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BIOGRAPHY

Xiaohui Zheng comes from a lovely small village with a beautiful mountain view. She received her Bachelor of Science in Environmental Engineering and Science, from the most famous university in China – Tsinghua University– in July 2009. She joined the Department of Civil, Construction, and Environmental Engineering at North Carolina State University in August 2013 to pursue a Master of Science degree. Her research focuses on analyzing and modeling energy use and emissions in the transportation sector. This thesis completes the requirements for that degree.
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CHAPTER 1  INTRODUCTION

The introduction chapter includes the overview, objectives and organization of this thesis.

1.1 Overview

Plug-in hybrid electric vehicles (PHEVs) have the potential to lower carbon dioxide (CO$_2$) and criteria pollutant emissions, and to improve energy efficiency, sustainability and security for the transportation sector.$^{1,2,3,4}$ A growing number of PHEV models are available in the U.S. and other markets. These PHEVs include the Chevrolet Volt, Ford C-Max Energi Plug-in Hybrid, Ford Fusion Energi Plug-in Hybrid, Toyota Prius Plug-in Hybrid, and other models from BMW, Cadillac, Honda, McLaren Automotive, Mercedes-Benz, and Porsche. In 2014, 55,357 PHEVs were sold in the US, which is a 13% increase from the previous year, and part of an increasing trend.$^5$ The increasing market share of PHEVs could affect energy use and emissions for the transportation sector. However, little has been done to quantify the energy use and emissions of PHEVs. The purpose of this paper is to demonstrate a method for quantifying the real-world activity, energy use and emissions of PHEVs based on in-use measurements.

A PHEV is a hybrid electric vehicle (HEV) with a grid-based rechargeable traction battery (TB). The TB can be charged from the electric grid, regenerative braking or excess energy
from the internal combustion engine (ICE).\textsuperscript{6,7} PHEVs operate in either charge depleting (CD) or charge sustaining (CS) mode.\textsuperscript{6,8,9} When the TB state of charge (SOC) is sufficient, a PHEV operates in CD mode. In CD mode, the PHEV performs like an electric vehicle (EV), whose electric motor provides propulsion for the vehicle. The TB SOC is generally decreasing during CD mode until the SOC reaches a lower operation limit, at which point the PHEV switches to CS mode. In CS mode, the PHEV performs like an HEV; the ICE provides propulsion in combination with or instead of the electric motor. In CS mode, the TB SOC is maintained within a narrow range.

The energy use and emissions related to PHEVs operation come from both grid electricity and gasoline. Grid electricity is only consumed in CD mode. When electricity is the only energy source for propulsion, tailpipe emissions will be zero. Most emissions related to PHEVs operating in CD mode will be shifted from densely populated urban areas to sites of power plants, which are usually located at a considerable distance from large populations.\textsuperscript{10,11} Furthermore, emissions during CD mode also depend on the electricity generation resource mix of the region where PHEVs operate.\textsuperscript{4,12,13} Gasoline can be used in both CD and CS modes. When gasoline is used, tailpipe emissions will be produced.
The effect of PHEV technology on vehicle energy use in CD and CS modes has been evaluated in recent studies, with little discussion of emissions. Moreover, much of the reported data collection has focused on HEVs retrofitted to be PHEVs, rather than on production PHEVs. For example, Idaho National Laboratory (INL) evaluated gasoline fuel economy and electricity consumption for CD and CS modes for 228 retrofitted Toyota Prius vehicles.\textsuperscript{14} The gasoline fuel economy for CD mode was found to be 44% higher compared to the CS mode average gasoline fuel economy of 43 mpg. More recently, INL has been measuring fuel economy and electricity consumption for four production Toyota Prius PHEVs.\textsuperscript{15} During CD mode operation with engine off, electricity consumption is 356 Wh/mile. During CS mode, the gasoline fuel economy is 51 mpg, which is 19% higher than that of the retrofitted Toyota Prius vehicles previously measured by INL. Graver et al. measured on-road energy use, direct tailpipe emissions, and indirect emissions from electricity generation for CD and CS modes for a retrofitted Prius converted to a PHEV.\textsuperscript{16}

Gasoline fuel use in CD mode was found to be 38% lower, relative to CS mode. However, the overall gasoline and grid equivalent energy economy for CD mode was found to be 7% lower than that for CS mode. Differences in electricity generation mix among U.S. states were found to affect the total emissions rates for CD mode. However, upstream energy use and emissions for gasoline production were not accounted for when compared total energy
use and emissions between CD and CS modes. A more fair comparison of total energy use and emissions between CD and CS modes can be achieved if fuel cycles for both gasoline and electricity are taken into consideration. Therefore, there is a need for a method to estimate energy use and emissions with respect to these two operating modes of PHEVs taking into account fuel cycles for both gasoline and electricity, and to evaluate the effect of electricity generation mix on PHEVs energy use and emissions in CD mode.

The PHEV ICE has the ability to turn on and off during operation, depending on power demand, the TB SOC, and the ability of the electric motor to provide demanded power.\textsuperscript{8, 17, 18} During CD mode, engine is mainly off. For some PHEVs, the ICE can turn on during CD mode to assist propulsion when the electric motor cannot solely meet high power demand.\textsuperscript{8} During CS mode, the engine is mainly on. The ICE is off typically under situations of low power demand that can be met solely with the electric motor, or no power demand when driving downhill, decelerating, or braking.\textsuperscript{18} Therefore, energy and emission sources for PHEVs depend not only on CD and CS modes, but also on engine on and off activity.

To accurately develop a method to estimate energy use and emissions for PHEVs, engine on and off activity should be taken into account. Power demand in terms of vehicle specific power (VSP) is proven to correlate strongly to fuel use and tailpipe emissions for
conventional gasoline and diesel vehicles. However, few studies have quantified energy use and emissions for PHEVs by applying a VSP-based modal model. There is a need to model energy use and emission rates for PHEVs to represent a variety of power demand scenarios, taking into account engine on and off operation, and CD and CS modes.

Because the first PHEV engine start can occur after a trip has started, the distribution of cold starts may differ from that of a light duty gasoline conventional vehicle (CV). Cold start is defined as an engine start that occurs after a long uninterrupted engine shut-down period. Thus, the engine, fuel system, and catalytic converter are at ambient temperature. During a cold start, to ensure the presence of sufficient fuel vapor for combustion, the engine is typically commanded to run fuel rich, which can increase products of incomplete combustion including carbon monoxide (CO) and hydrocarbons (HC). Until the catalytic converter warms to its “light-off temperature,” it will be ineffective at controlling emissions of CO, HC and oxides of nitrogen (NOx).

For CVs, cold starts occur at the point of origin of a trip. However, for a PHEV in CD mode, the first engine start could occur some distance from the trip origin, thus altering the real-world location of cold starts. Furthermore, PHEVs may have extended periods of engine off activity, during which engine coolant temperature ($T_{EC}$) and catalyst temperature ($T_{cat}$) may
Thus, a subsequent engine start may have a cold start effect. These characteristics could lead to multiple cold start events per trip for a PHEV, which potentially could effect tailpipe emissions during CD mode and the first few minutes of CS mode.

Strategies to reduce PHEV cold start emissions have been evaluated, such as engine on and off control, gear selection, and hybrid energy management strategies; however, the effect of adoption of such strategies is not clear. Measurements of PHEV cold start effect are not reported; however, the effect of cold starts on tailpipe emissions for HEVs has been evaluated to some extent. For example, chassis dynamometer measurements were conducted on five in-use HEVs to examine the cold start extra emissions (CSEEs) and effect on fuel consumption. Compared to the average CSEEs for a sample of Euro-4 CVs, the measured HEVs had lower CSEEs for CO, HC and NO\textsubscript{x} emissions, similar or higher CSEEs for CO\textsubscript{2} emissions, and similar or higher fuel consumption. The effect of different periods of continuous engine off time on CO and NO\textsubscript{x} emissions was studied for a Toyota Prius HEV based on on-road driving data. After longer engine shut-down periods, CO and NO\textsubscript{x} emissions during an engine start tended to increase.

The Advanced Vehicle Simulator (ADVISOR) has been used to simulate and analyze the performance, emissions and fuel economy of PHEVs. Engine on and off rules programmed
into ADVISOR for the Prius Plug-In Hybrid were based on the Traction Battery SOC, power demand, vehicle speed, and $T_{EC}$. The ADVISOR simulation results for PHEVs emissions only account for the direct tailpipe CO, HC, NO$_x$, and PM emissions. An external observer would not have access to data on SOC or $T_{EC}$. The externally observable variables, such as vehicle speed, acceleration, and road grade, are easier to obtain.

Depending on the PHEV operating mode, CD or CS mode, the conditions under which engine turns on differs. The approach of using externally observable variables to determine whether the PHEV engine is on or off has not been reported yet. Externally observable variables-based models have practical value for traffic management or simulation applications. Thus, it is important to derive rules for both CD and CS modes of determining whether engine is on or off using externally observable variables (such as vehicle speed, acceleration, and road grade).

To more accurately assess the emissions, emission estimates are needed at various spatial and temporal scales. A mesoscale emission rate model can be incorporated with existing traffic demand models, which produce mesoscale vehicle speeds for road links. A microscale emission rate model can be used to quantify the local effect of traffic control measures and other factors that contribute to variability in vehicle speed and acceleration. Since the main
energy sources for the two operating modes of PHEVs differ, i.e. grid electricity for CD mode and gasoline for CS mode, the location where emissions take place differs between these two operating modes. Power plant emissions are associated with CD mode and on road tailpipe emissions are associated with CS mode. It is important to develop a model that takes into account these two operating modes. The PHEV engine may turn on and off periodically during vehicle operation, which leads to the episodic fuel use and tailpipe emissions over the transportation network. It is important to develop a model that can identify the locations where emissions occur, which would in turn help improve traffic control measures and air quality management. Thus, it is important to develop a mesoscale predictive model to determine the duration and travel distance of CD mode, and to estimate the cycle average energy use and emissions for PHEVs with respect to two different operating modes, based on the in-use measurement., and to develop a microscale predictive model to estimate the second-by-second emissions over the space and time of a road network with respect to the two different operating modes, based on the in-use measurement.

Currently, there is still a lack of on road measurement energy economy and emissions data for production PHEVs, which can be the basis for further studies. For example, the estimated energy use and emission rates can be used to develop a model unique to the engine operational characteristics of PHEVs to support energy use and emissions estimation in CD mode.
and CS modes and, thus, emission inventories. The energy economy data can be used to estimate the impact of PHEVs operation on electric grid. The emissions data can be used to study the PHEV cold start effect.

1.2 Objectives

The first objective is to demonstrate a method for quantifying the real-world activity, energy use, and emissions of PHEVs, taking into account CD and CS operation modes for different electricity generation resource mix, variations in power demand, engine on and off activity, and cold start and hot stabilized running operation. The method is based on in-use measurement of a production PHEV during actual on-road operation. The total energy use and emissions include direct gasoline consumption and tailpipe emissions, upstream energy use and emissions for gasoline production, and indirect energy use and emissions related to power generation for grid-based electricity consumed by the PHEV.

The second objective is to determine the engine on and off rules for both CD and CS modes, and to develop a mesoscale predictive model to calculate the cycle average energy use and emissions of PHEVs and a microscale predictive model to estimate the second-by-second emissions, with respect to two different operating modes, based on the in-use measurement.
1.3 References


CHAPTER 2 METHODS

A 2013 Toyota Prius Plug-In Hybrid was measured on pre-selected study routes in January 2013. Figure 1 shows the 2013 Toyota Prius Plug-In Hybrid. Instruments used for real-world driving data collection included a portable emissions measurement system (PEMS), an on-board diagnostic (OBD) scan tool, multiple global positioning system (GPS) receivers with barometric altimeters, and a watt-hour meter. Upstream energy use and emissions for gasoline production, and indirect energy use and emissions for electricity production were estimated. Quality assurance was performed to check for possible errors before data analysis. Comparison of energy use and emissions between CD and CS modes was made, taking into account differences in electricity generation resource mix among U.S. states. A vehicle specific power (VSP) based modal modeling approach was used to analyze the average energy use and emission rates of the PHEV with respect to different engine loads, for comparisons of engine on versus engine off in CD and CS modes, and for cold start versus hot stabilized running. Estimates of energy use and emissions take into account upstream energy use and emissions for gasoline production, indirect energy use and emissions for electricity production, and direct gasoline use and tailpipe emissions from vehicle operation. A model is developed to predict engine status, based on externally observable variables, and to predict energy use and emission rates of PHEV.
2.1 Field Study Design

A 2013 Toyota Prius Plug-In Hybrid was measured on eight previously specified study routes in Raleigh, North Carolina (NC) and Research Triangle Park (RTP), NC area from January 18, 2013 to January 25, 2013. Figure 2 shows these routes. Routes A, B, C are between NC state and North Raleigh. Route D is between NC State and Southeast Raleigh.
Route E is within NC State. Routes 1, 2, and 3 are between North Raleigh and RTP. Route A is mostly comprised of minor and major arterials, with 18% of travel distance on a limited access road. Routes B, C and D are mostly comprised of major arterials and freeways, with 50%, 44%, and 48% of travel distance on freeways, respectively. Route E is mainly comprised of minor arterials. Routes 1 and 2 are mainly comprised of freeway driving. Route 3 is comprised of minor and major arterials. Route 3 has signalized major arterials with speed limits as high as 55 mph. Table 1 shows the travel distance and percentage of travel distance on freeways for each study route.

Figure 2 Map of Study Routes for Routes A, B, and C between NC State University and North Raleigh, Route D between NC State and Southeast Raleigh, Route E within NC State, and Routes 1, 2 and 3 between North Raleigh and Research Triangle Park (RTP)
Table 1 The Travel Distance and Percentage of Travel Distance on Freeways for Each Study Route

<table>
<thead>
<tr>
<th>Routes</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>One Way Travel Distance (mile)</td>
<td>10.6</td>
<td>12.1</td>
<td>11.5</td>
<td>12.2</td>
<td>2.8</td>
<td>16.3</td>
<td>20.2</td>
<td>17.6</td>
</tr>
<tr>
<td>Percentage of Travel Distance on Freeways (%)</td>
<td>17.9</td>
<td>50.4</td>
<td>44.3</td>
<td>47.5</td>
<td>0</td>
<td>79.8</td>
<td>77.2</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 2 shows the 2013 Toyota Prius Plug-In Hybrid measurement schedule. Prior to each day of measurement, the fuel tank was topped off, and the TB was fully charged. The sum of the amount of gasoline used to refill the tank and grid electricity used to recharge the TB was the direct energy use for the prior day of measurement.
Table 2 The 2013 Toyota Prius Plug-In Hybrid Measurement Schedule

<table>
<thead>
<tr>
<th>Measurement Date</th>
<th>Study Routes</th>
</tr>
</thead>
<tbody>
<tr>
<td>18-Jan-2013</td>
<td>C out  C in  D  E  A out  3 out  3 in  1 out  1 in  A in  C out  C in</td>
</tr>
<tr>
<td>19-Jan-2013</td>
<td>A out  1 out  1 in  A in  C out  3 out  3 in  C in  B out  B in  -  -</td>
</tr>
<tr>
<td>20-Jan-2013</td>
<td>A out  A in  E  D  C out  1 out  1 in  3 out  3 in  C in  -  -</td>
</tr>
<tr>
<td>21-Jan-2013</td>
<td>B out  1 out  1 in  B in  A out  A in  C out  3 out  3 in  C in  -  -</td>
</tr>
<tr>
<td>22-Jan-2013</td>
<td>B out  B in  A out  1 out  1 in  A in  C out  3 out  3 in  C in  -  -</td>
</tr>
<tr>
<td>23-Jan-2013</td>
<td>D  E  A out  1 out  1 in  A in  C out  3 out  3 in  C in  -  -</td>
</tr>
<tr>
<td>24-Jan-2013</td>
<td>C out  1 out  1 in  C in  A out  2 out  2 in  3 out  3 in  A in  -  -</td>
</tr>
<tr>
<td>25-Jan-2013</td>
<td>C out  1 out  1 in  2 out  2 in  -  -  -  -  -  -  -  -</td>
</tr>
</tbody>
</table>

*Note: Route sequence shown is order in which routes were measured. Routes A, B, C, 1, 2, and 3 have outbound and inbound legs.*

### 2.2 Instruments

Instruments used for vehicle real-world driving data collection included a GlobalMRV Axion PEMS, an OBD scan tool, multiple GPS receivers with barometric altimeters, and a watt-hour meter.
2.2.1 Portable Emissions Measurement System (PEMS)

A GlobalMRV Axion PEMS was used to measure second-by-second direct tailpipe exhaust gas concentrations. Figure 3 shows the GlobalMRV Axion PEMS. The PEMS uses non-dispersive infrared (NDIR) to measure CO$_2$, CO and HC concentrations, and electrochemical sensors to measure NO$_x$, and O$_2$ concentrations. The PEMS has two parallel five-gas analyzers, which were calibrated before measurement using a cylinder gas of known composition, and during measurement using ambient air periodically to prevent drift. The process of self-calibration during measurement is referred to as “zeroing.” This type of PEMS was validated in comparison to a reference method dynamometer laboratory as part of the U.S. Environmental Protection Agency (EPA) Environmental Technology Verification (ETV) program, and results show close agreement.
Figure 3 The GlobalMRV Axion Portable Emissions Measurement System (PEMS)
2.2.2 On-Board Diagnostic Scan Tool

An OBD scan tool was used to record real-world vehicle activity data. Figure 4 shows the OBD scan tool. The OBD scan tool logged data at a frequency of more than 1 Hz, including vehicle speed (VSS), engine speed (RPM), manifold absolute pressure (MAP), intake air temperature (IAT), mass air flow (MAF), mass fuel flow (MFF), engine coolant temperature ($T_{EC}$), catalyst temperature ($T_{cat}$), and traction battery (TB) state of charge (SOC).

Figure 4 The On-Board Diagnostic (OBD) Scan Tool
2.2.3 Global Positioning System (GPS) Receivers with Barometric Altimeters

Multiple GPS receivers with barometric altimeters were used to record the second-by-second vehicle position in terms of longitude, latitude, and altitude. Figure 5 shows the GPS receivers with barometric altimeters. Data from multiple GPS receivers were combined into one dataset to calculate 0.1-mile segment average road grade for all such segments along each route.\(^5\)

Figure 5 The Global Positioning System (GPS) Receivers with Barometric Altimeters
2.2.4 Watt-Hour Meter

A watt-hour meter was used to measure the grid electricity consumed to recharge the TB to full capacity after measurement. Figure 6 shows the watt-hour meter.

Figure 6 The Watt-Hour Meter
2.3 Upstream Energy Use and Emissions for Gasoline Production

The upstream energy use and emissions related to the amount of gasoline consumed by the PHEV are taken into account. The upstream energy use and emissions for gasoline production are from crude oil recovery and transportation, and gasoline refining, transportation and distribution. Emissions related to gasoline refining are from feed inputs, combustion, and non-combustion, such as, crude cracking (both thermal and catalytic), hydrocarbon reforming, catalyst regeneration, sulfur recovery, and blowdown systems. The feed inputs are used of residual oil, natural gas, butane, electricity, and hydrogen, and inputs of feedstocks other than crude oil. The upstream energy use and emission factors for producing 1 gallon of gasoline are estimated based on the Argonne National Laboratory’s Greenhouse Gas, Regulated Emissions, and Energy Use in Transportation (GREET) 1 2014 model.6

2.4 Indirect Energy Use and Emissions for Electricity Production

The U.S. EPA rated fuel economy for PHEVs unrealistically assumes 100% electricity generation efficiency and no transmission loss, which leads to a gasoline equivalent fuel use of 0.03 gallons per kWh of grid electricity.7
Electricity generation efficiency and transmission loss are taken into account in estimating indirect gasoline equivalent energy use and emissions associated with grid electricity consumed by the PHEV. Indirect energy use and emission factors are based on a national average electricity transmission loss of 6%.\textsuperscript{8} Indirect energy use and emissions for electricity production take into account feedstock recovery, production and transportation, and electricity generation and transmission.\textsuperscript{9}

Grid-related indirect energy use and emissions vary with electricity generation resource mix. Based on the most recently available data, for each state in the U.S., the percentage of each energy resource for electricity generation was estimated from the net electricity generation data from each major energy resource reported by the U.S. Energy Information Administration (EIA).\textsuperscript{10} The major energy resources include coal, petroleum, gas, nuclear, water, wind, and biomass. The percentage of each energy resource for electricity generation for each state was used as input to the GREET 1 2014 model to estimate the energy use and emissions related to feedstock recovery, production and transportation for electricity generation.\textsuperscript{6}

For 2011, energy use for electricity generation at power plants for each state in the U.S. is reported by the EIA.\textsuperscript{11} Electricity generation emission factors were estimated from emission
inventory data for electricity generation from each major energy resource for each state in the U.S. reported by the EPA,\textsuperscript{12,13} and net electricity generation data for each state in the U.S. reported by the EIA.\textsuperscript{10}

2.5 Quality Assurance

The OBD data were converted to a second-by-second basis using linear interpolation to match with the time step of the PEMS and GPS data. Data from the PEMS, OBD and GPS were time aligned and combined into one dataset. The combined dataset was screened for possible errors, which were corrected if they could be, or removed if not. A number of most common encountered errors have been previously identified. Further details of the data synchronization process and quality assurance are detailed elsewhere.\textsuperscript{3,14}

2.6 Charge Depleting (CD) and Charge Sustaining (CS) Modes

Since the TB was fully charged before each day of measurement, the PHEV operated first in CD mode and switched to CS mode. When CD mode ended, the engine turned on. The TB SOC generally decreased during CD mode and fluctuated within a narrow range in CS mode.\textsuperscript{6,8,9} Thus, the trends of TB SOC and engine speed data were used to infer rules for identifying CD or CS mode.
To quantify the sensitivity of energy use and emissions of PHEVs to CD and CS modes, and different electricity generation resource mix, the total energy use and pollutant mass emission rates for CD or CS mode are calculated as:

$$\text{TER}_{i,j} = \frac{\sum_{i=1}^{T_j} \text{EF}_{\text{Indirect, Elec}, i} \times E_j + \sum_{i=1}^{T_j} \text{EF}_{\text{Upstream, Gas}, i} \times \text{ER}^*_{\text{Direct Gas, energy}, j} / \rho_{\text{Gas}} + \sum_{i=1}^{T_j} \text{ER}^*_{\text{Direct Gas, i, j}}}{S_j}$$

(1)

Where,

\(i\) = Specie, such as, energy, CO\(_2\), CO, HC, NO\(_x\), SO\(_x\), PM\(_{2.5}\), or PM\(_{10}\)

\(j\) = PHEV operating mode: CD or CS mode

\(\text{TER}_{i,j}\) = Total energy use or emission rate for specie \(i\) in PHEV operating mode \(j\) (g/mile for energy and CO\(_2\), otherwise mg/mile.)

\(\text{EF}_{\text{Indirect, Elec}, i}\) = Indirect energy use or emission factor from the electric grid for specie \(i\) (g/kWh for energy and CO\(_2\), otherwise mg/kWh. Section “Indirect Energy Use and Emissions for Electricity Generation” documents the method for calculating \(\text{EF}_{\text{Indirect, Elec}, i}\), and provides the values used.)

\(E_j\) = Watt-hour meter reported indirect grid electricity used in PHEV operating mode \(j\) (kWh; for CD mode, \(E_j\) = the amount of grid electricity used to recharge the TB; for CS mode, \(E_j = 0\).)
\[ EF_{Upstream, Gas, i} \]

Upstream energy use or emission factor for gasoline production for specie \( i \) (\( \text{g/gallon} \) for energy and \( \text{CO}_2 \), otherwise \( \text{mg/gallon} \). Section “Upstream Energy Use and Emissions for Gasoline Production” documents the method for calculating \( EF_{Upstream, Gas, i} \), and provides the values used.)

\[ T_j \]

OBD reported travel time in PHEV operating mode \( j \) (s)

\[ s \]

Number \( s \) second

\[ EF'_{Direct Gas, i, j} \]

1-Hz direct energy use or tailpipe emission rate for specie \( i \) in PHEV operating mode \( j \) at second \( s \) (\( \text{g/s} \) for energy and \( \text{CO}_2 \), otherwise \( \text{mg/s} \). \( EF'_{Direct Gas, i, j} \) is calculated by using combined post quality assurance PEMS, OBD and GPS data. The method for calculation is detailed elsewhere.\(^{14}\)

\[ \rho_{Gas} \]

Density of gasoline, \( 2791 \text{ g/gasoline} \(^{15}\)

\[ S_j \]

GPS reported travel distance in PHEV operating mode \( j \) (mile)

2.7 **Power Demand -- Vehicle Specific Power (VSP)**

VSP is a proven indicator of the power demand and energy consumption of a vehicle, taking into account changes in kinetic and potential energy, rolling resistance, and aerodynamic drag.\(^{16}\) For a light duty vehicle, VSP is:\(^{16}\)
\[ VSP = v \times \left[ 1.1 \times a + 9.81 \times \frac{r}{100} + 0.132 + 0.000302 \times v^3 \right] \]  

(2)

Where,

- \( VSP \) = Vehicle specific power (kW/ton)
- \( v \) = Vehicle speed (m/s)
- \( a \) = Vehicle acceleration (m/s\(^2\))
- \( r \) = Road grade (%)

VSP-based modal models are widely used to estimate energy use and direct tailpipe pollutant mass emission rates for light duty vehicles, such as CVs\(^{17,14}\), HEV\(^{,18}\), retrofitted PHEV\(^{19}\), and PHEV\(^{1}\), and for on road heavy duty vehicles, such as a plug in hybrid electric school bus\(^{20}\) and others\(^{14,21,22,23}\).

VSP is calculated at 1 Hz. A 14 mode VSP-based model developed by NC State for the U.S. EPA is used here\(^ {24}\). Table 3 shows the definitions of the 14 VSP modes. VSP values for VSP modes 1 and 2 are negative, representing deceleration or driving downhill. VSP modes 3 includes idling. Positive VSP in modes 4 to 14 represents steady speed driving, acceleration, or hill climbing\(^ {24}\).

Sandhu and Frey illustrated a method for calculating 1-Hz energy use and direct tailpipe pollutant (NO\(_x\), HC, CO, CO\(_2\)) mass emission rates, using combined post quality assurance.
PEMS, OBD and GPS dataset.\textsuperscript{14} Energy use and direct tailpipe pollutant mass emission rates were stratified into 14 VSP modes to estimate modal average energy use and exhaust gas emission rates.\textsuperscript{17,24}

For CVs, the 14 VSP modes have statistically different energy use and direct tailpipe pollutant mass emission rates from each other for a given specie, and none of them is dominant in the estimation of the energy economy and exhaust gas emissions.\textsuperscript{24} Energy use and direct tailpipe pollutant mass emission rates of CVs are approximately constant for negative VSP, and approximately linear with respect to positive VSP.\textsuperscript{17,24}

For a HEV, energy use and direct tailpipe pollutant mass emission rates were approximately constant for negative VSP. Energy use and direct tailpipe CO\textsubscript{2} mass emission rates of the HEV increased with positive power demand, especially for higher VSP modes 8 to 13, where the slope was larger, relative to lower VSP modes 3 to 7. Direct tailpipe CO and NO\textsubscript{x} mass emission rates of the HEV had a tendency to increase as VSP mode increased from 3 to 14.\textsuperscript{18}
Table 3 Vehicle Specific Power (VSP) Mode Definitions

<table>
<thead>
<tr>
<th>VSP Mode</th>
<th>VSP Inclusive Lower Bound (kW/ton)</th>
<th>VSP Exclusive Upper Bound (kW/ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$-\infty$</td>
<td>-2</td>
</tr>
<tr>
<td>2</td>
<td>-2</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>6</td>
<td>7</td>
<td>10</td>
</tr>
<tr>
<td>7</td>
<td>10</td>
<td>13</td>
</tr>
<tr>
<td>8</td>
<td>13</td>
<td>16</td>
</tr>
<tr>
<td>9</td>
<td>16</td>
<td>19</td>
</tr>
<tr>
<td>10</td>
<td>19</td>
<td>23</td>
</tr>
<tr>
<td>11</td>
<td>23</td>
<td>28</td>
</tr>
<tr>
<td>12</td>
<td>28</td>
<td>33</td>
</tr>
<tr>
<td>13</td>
<td>33</td>
<td>39</td>
</tr>
<tr>
<td>14</td>
<td>39</td>
<td>$\infty$</td>
</tr>
</tbody>
</table>

2.8 Driving Cycles

Driving cycles were estimated in terms of travel time spent in each VSP mode. The travel time spent in each VSP mode was measured for each study route during eight days of
measurement. For each study route, the average and run-to-run variability of travel time spent in each VSP mode were calculated based on the real-world measurement.

2.9 Engine On and Engine Off

OBD reported engine speed and fuel use rate were used as indicators of engine on or off operation. To quantify the sensitivity of energy use and emissions of PHEVs to engine on and off operation, and different power demand, energy use and pollutant mass emission rates for engine on and off for the CD mode were quantified for the 14 VSP modes. The total energy use and pollutant mass emission rate for engine on or off for the CD mode for a given VSP mode is:

\[
ER_{i,CD}^{m,n} = \left( EF_{Indirect, Elec, i} \times \sum_{s=1}^{n_{s,I}} er_{Indirect, Elec, CD}^{m,n,s} + EF_{Indirect, RB, i} \times \sum_{s=1}^{n_{s,I}} er_{Indirect, RB, CD}^{m,n,s} \right) + \frac{EF_{Upstream, Gas, i} \times \sum_{s=1}^{n_{s,G}} er_{Direct Gas, energy, CD}^{m,n,s} + \sum_{s=1}^{n_{s,G}} er_{Direct Gas, i, CD}^{m,n,s}}{\rho_{Gas}} \right) \times \frac{1}{t_{CD}^{m,n}} (3)
\]

Where,

\[m\] = VSP mode, from 1 to 14

\[n\] = Engine on or off

\[ER_{i,CD}^{m,n}\] = Total energy use or emission rate for specie \(i\) in VSP mode \(m\) during engine on or off \(n\) for the CD mode (g/s for energy and CO\(_2\),
otherwise mg/s.)

\[ er_{\text{Indirect, Elec, CD}}^{m,n,s} = 1\text{-Hz indirect grid electricity use rate in VSP mode } m \text{ during engine on or off } n \text{ for the CD mode at second } s \text{ (kWh/s. )} \]

\[ EF_{\text{Indirect, RB, i}} = \text{Energy use or emission factor from regenerative braking (For energy, } EF_{\text{Indirect, RB, i}} \text{ is assumed to be equal to } EF_{\text{Indirect, Elec, energy}}; \text{ and for others, } EF_{\text{Indirect, RB, i}} \text{ is equal to 0, since there is no emission related to regenerative braking.)} \]

\[ er_{\text{Indirect, RB, CD}}^{m,n,s} = 1\text{-Hz regenerative braking electricity use rate in VSP mode } m \text{ during engine on or off } n \text{ for the CD mode at second } s \text{ (kWh/s. )} \]

\[ er_{\text{Direct Gas, i, CD}}^{m,n,s} = 1\text{-Hz direct energy use or tailpipe emission rate for specie } i \text{ in VSP mode } m \text{ during engine on or off } n \text{ for the CD mode at second } s \text{ (g/s for energy and CO}_2\text{, otherwise mg/s. )} \]
using combined post quality assurance PEMS, OBD and GPS data, and then stratified into 14 VSP modes during engine on or off for the CD mode. The method for calculation is detailed elsewhere.\textsuperscript{14} 

\[ t_{CD}^{m,n} = \text{Travel time in VSP mode } m \text{ during engine on or off } n \text{ for the CD mode (s)} \]

### 2.10 Cold Start and Hot Stabilized Running

Cold start event is related to \( T_{EC} \) and \( T_{cat} \), and affects fuel use and direct tailpipe emission rates.\textsuperscript{25, 26, 27, 28} Thus, \( T_{EC} \) and \( T_{cat} \) were used as indicators of cold start or hot stabilized running when the engine is on. Trends of \( T_{EC} \) and \( T_{cat} \) data were used to infer rules for identifying cold start or hot stabilized running.

To quantify the sensitivity of fuel use and direct tailpipe emissions of PHEVs to cold start and hot stabilized running when engine is on, cycle average fuel use and direct tailpipe emission rates for cold start or hot stabilized running are quantified. An average cold start driving cycle is used as the same basis for comparison. The driving cycle used is estimated in terms of the average travel time spent in each VSP mode for an average cold start. Fuel use and direct tailpipe emission rates for each of cold start and hot stabilized running are quantified for the 14 VSP modes, both based on engine on operation. The cycle average fuel
use and direct tailpipe pollutant emission rates for cold start and hot stabilized running are calculated as:

\[
CER_{i,k} = \sum_{m=1}^{14} \left( \frac{\sum_{s=1}^{OT_{k,m}} cer_{m,On,k,s}^{Direct Gas, i,j}}{OT_{k,m}} \times CT_m \right) + \sum_{m=1}^{14} CT_m
\]

(4)

Where,

\[k = \text{“Cold” for Cold start, } k = \text{“Hot” for hot stabilized running}\]

\[CER_{i,k} = \text{Cycle average fuel use or direct tailpipe emission rate for specie } i \text{ and cold start or hot stabilized running } k \text{ (g/s for fuel and CO}_2 \text{, otherwise mg/s)}\]

\[\text{cer}_{m,On,k,s}^{Direct Gas, i,j} = \text{1-Hz fuel use or tailpipe pollutant mass emission rate for specie } i \text{ and cold start or hot stabilized running } k \text{ in VSP mode } m \text{ at second } s \text{ (g/s for fuel and CO}_2 \text{, otherwise mg/s. } \text{cer}_{m,On,k,s}^{Direct Gas, i,j} \text{ is calculated by using combined post quality assurance PEMS, OBD and GPS data for engine on, and then stratified into 14 VSP modes during cold start or hot stabilized running. The method for calculation is detailed elsewhere.}^{14}\]

\[OT_{k,m} = \text{Travel time spent in VSP mode } m \text{ for cold start or hot stabilized running } k \text{ (s)}\]
CT_m = Travel time spent in VSP mode m for an average cold start driving cycle (s)

2.11 Energy Use and Emission Rates Prediction Model

In this section, methods are given for engine on and off rules, mesoscale predictive model and microscale predictive model.

2.11.1 Engine On and Off Rules

Classification and regression trees (CART) analysis is used to identify the externally observable variables affecting engine operation, on or off. CART is a recursive portioning method for generating a binary tree.\textsuperscript{29,30} Binary splits are made with the selected variable that best differentiates between the categories of the dependent variable, and each node is split into two child branches.\textsuperscript{29,30} The basic principle of CART is to reduce deviance in the dataset by stratifying it.

Based on internally observable variables engine speed and fuel use, each second of data is classified as engine “On”, “Off”, “Shutdown”, or “Startup”. Since compared to engine “On” or “Off”, the sample size for engine “Shutdown” or “Startup” is smaller by an order of magnitude, engine “Shutdown” and “Startup” are treated as engine “Off” and “On” in the CART analysis, respectively. Vehicle speed, acceleration, road grade, and VSP are evaluated
as predictors of engine operation categories. Based on 1 Hz speed, acceleration, road grade and VSP, each second of data for eight days of measurement is stratified as engine “On” or “Off”.

MATLAB was used to perform the CART analysis. MATLAB uses 10-fold cross validation to train and validate the CART classification trees. The original dataset is randomly divided into 10 equal sized sub-datasets, nine of which are used as the training dataset to develop the CART classification tree, and one of which is used as validation dataset to test the CART classification tree. The CART classification trees are based on second-by-second measurement data to stratify 1 Hz engine status using variable vehicle speed, acceleration, road grade, or VSP. The trees are first grown to the full size, exhausting all the possible splits. Each split uses the threshold of a variable to partition data. The tree-growing process stops when data cannot be further stratified based on the variables selected. The trees are then pruned back to the root by setting the maximum numbers of splits to smaller values, relative to the fully-grown tree. The overall performances of fully-grown and pruned trees are evaluated by the tree complexities in terms of numbers of splits and the cross validation classification errors, which indicate the misclassification rates in the validation datasets for the result CART classification trees. Smaller classification error is usually achieved at the cost of increased tree complexity.
2.11.2 Mesoscale Predictive Model — Cycle Average Energy Use and Emission Rates

A mesoscale predictive model is developed to determine the duration and travel distance of CD mode, and to estimate the cycle average energy use and emissions for PHEVs with respect to CD and CS modes, based on in-use measurement.

2.11.2.1 Duration and Travel Distance in Charge Depleting (CD) Mode

The duration and travel distance for the CD mode is determined by the initial TB SOC when the PHEV starts operating (SOC\text{start}), and TB electricity use rates with respect to second-by-second VSP and engine status predicted by implementing the derived engine on and off rules (ER_{TB, Elec, On, m} and ER_{TB, Elec, Off, m}; and m is VSP mode, from 1 to 14.). The TB SOC at which the PHEV switches from CD mode to CS mode (SOC\text{end}), is determined by the average TB SOC, at which the operation modes changed from CD to CS mode during eight days of measurement, which was 23.4%. Figure 7 shows the procedure for determining the duration and travel distance in CD mode, given a driving cycle. Table 4 explains the variables and parameters in this model.
Figure 7 Flow Diagram of the Procedure for the Prediction of Duration and Travel Distance in Charge Depleting (CD) Mode

Note: Variables and parameters in this model are explained in Table 4.
Table 4 Variables and Parameters for the Prediction of Duration and Travel Distance in Charge Depleting (CD) Mode

<table>
<thead>
<tr>
<th>Input Variables from User</th>
<th>Calibrated Parameters&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Predicted Variables by Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOC&lt;sub&gt;end&lt;/sub&gt;: The TB SOC at which PHEV switches from CD to CS mode (%)</td>
<td>Grid electricity for 1% TB SOC is provided in section 2.9.</td>
<td>S&lt;sub&gt;CD&lt;/sub&gt;: Travel distance in CD Mode (mile)</td>
</tr>
<tr>
<td>SOC&lt;sub&gt;start&lt;/sub&gt;: Initial TB SOC (%)</td>
<td>v: speed (mph)</td>
<td>Gasoline equivalent fuel use for each kWh of electricity is provided in section 3.2.</td>
</tr>
<tr>
<td></td>
<td>a: acceleration (mph/s)</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>r: road grade (%)</td>
<td>ER&lt;sub&gt;TB, Elec, n, m&lt;/sub&gt;: VSP-based modal gasoline equivalent TB electricity use rates for engine on or off n in VSP mode m in CD mode (g/s)&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

Note:

<sup>a</sup> The values for the calibrated parameters are shown in Appendix C.

<sup>b</sup> The values for TB electricity use rates for engine on and off in CD mode are gasoline equivalent fuel use.
2.11.2.2 Cycle Average Energy Use and Emission Rates in Charge Depleting (CD) Mode

For a given PHEV and driving cycle, the cycle average total energy use and emission rates for CO$_2$, CO, HC, NO$_x$, SO$_x$, PM$_{2.5}$, and PM$_{10}$, are based on the percentage of travel time spent in each VSP mode, the percentage of travel time for engine operation (engine on or off) in each VSP mode, and PHEV operating mode (CD or CS mode).

In CD mode, energy use and emissions come from electricity and gasoline when the engine is on. When the engine is off, energy use and emissions come from consumption of stored electricity from the grid. Figure 8 shows the procedure for determining CD mode cycle average energy use and emission rates, given a driving cycle. Table 5 explains the variables and parameters in this model. The cycle average total energy use and emission rates for CD mode are calculated as:

$$CAER_{CD,C,i} = \sum_{m=1}^{14} \bar{f}_{C,m} \times \left[ (VER_{CD,Elec,On,i,m} + VER_{CD,Gas,On,i,m}) \times f_{On,m} + VER_{CD,Elec,Off,i,m} \times f_{Off,m} \right]$$  (5)

Where,

$CD$ = Charge Depleting Operating Mode

$C$ = Driving cycle $C$
\[ CAER_{CD,C,i} = \text{Cycle average energy use or emission rate in CD mode including both engine on and off operation for driving cycle } C, \text{ and specie } i \]

(The units for energy and CO\(_2\) are g/s, and the others are mg/s.)

\[ f_{C,m} = \text{Fraction of travel time for driving cycle } C \text{ in VSP mode } m \]

\[ VER_{CD,Elec,On,i,m} = \text{VSP-based modal mass rate from electricity for engine on in CD mode for specie } i, \text{ and VSP mode } m \text{ (The units for energy and CO\(_2\) are g/s, and the others are mg/s.)} \]

\[ VER_{CD,Gas,On,i,m} = \text{VSP-based modal mass rate from gasoline for engine on in CD mode for specie } i, \text{ and VSP mode } m \text{ (The units for energy and CO\(_2\) are g/s, and the others are mg/s.)} \]

\[ f_{On,m} = \text{Fraction of travel time for engine on in VSP mode } m \]

\[ VER_{CD,Elec,Off,i,m} = \text{VSP-based modal mass rate from electricity for engine off in CD mode for specie } i, \text{ and VSP mode } m \text{ (The units for energy and CO\(_2\) are g/s, and the others are mg/s.)} \]

\[ f_{Off,m} = \text{Fraction of travel time for engine off in VSP mode } m \]
Figure 8 Flow Diagram of the Procedure for the Prediction of Cycle Average Energy Use and Emission Rates in Charge Depleting (CD) Mode

Note: Variables and parameters in this model are explained in Table 5.
Table 5 Variables and Parameters for the Prediction of Cycle Average Energy Use and Emission Rates in Charge Depleting (CD) Mode

<table>
<thead>
<tr>
<th>Input Variables from User</th>
<th>Calibrated Parameters$^a$</th>
<th>Predicted Variables by Model$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>v: speed (mph)</td>
<td>$VER_{CD, Elec, On, i, m}$</td>
<td>$f_{C, m}$</td>
</tr>
<tr>
<td>a: acceleration (mph/s)</td>
<td>$VER_{CD, Gas, On, i, m}$</td>
<td>$f_{On, m}$</td>
</tr>
<tr>
<td>r: road grade (%)</td>
<td>$VER_{CD, Elec, Off, i, m}$</td>
<td>$f_{Off, m}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$CAER_{CD, C, i}$</td>
</tr>
</tbody>
</table>

Note:

$^a$ The calibrated parameters are defined in Equation (5). The values for the calibrated parameters are shown in Appendix D.

$^b$ The predicted variables are defined in Equation (5).

2.11.2.3 Cycle Average Energy Use and Emission Rates in Charge Sustaining (CS) Mode

In CS mode, energy use and emissions occurred when the engine is on and consuming gasoline. When the engine is off, energy use comes from regenerative braking, which is the energy recovered from vehicle operation. Thus, there is no emission related to regenerative braking. Figure 9 shows the procedure for determining CS mode cycle average energy use and emission rates, given a driving cycle. Table 6 explains the variables and parameters in
this model. The cycle average total energy use and emission rates for CS mode are calculated as:

\[
CAER_{CS,C,i} = \sum_{m=1}^{14} f_{C,m} \times VER_{CS,\text{Gas},\text{On},i,m} \times f_{\text{On},m}
\]  

(6)

Where,

\(CS\) = Charge Sustaining Operating Mode

\(CAER_{CS,C,i}\) = Cycle average energy use or emission rate in CS mode for driving cycle \(C\), and specie \(i\) (The units for energy and \(CO_2\) are g/s, and the others are mg/s.)

\(VER_{CS,\text{Gas},\text{On},i,m}\) = VSP-based modal mass rate from gasoline for engine on in CS mode for specie \(i\), and VSP mode \(m\) (The units for energy and \(CO_2\) are g/s, and the others are mg/s.)
Figure 9 Flow Diagram of the Procedure for the Prediction of Cycle Average Energy Use and Emission Rates in Charge Sustaining (CS) Mode

Note: Variables and parameters in this model are explained in Table 6.
Table 6 The Variables and Parameters for the Prediction of Cycle Average Energy Use and Emission Rates in Charge Sustaining (CS) Mode

<table>
<thead>
<tr>
<th>Input Variables from User</th>
<th>Calibrated Parameters(^a)</th>
<th>Predicted Variables by Model(^b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(v): speed (mph)</td>
<td>(\text{(VER_{CS,,\text{Gas,,On,,i,,m}})})</td>
<td>(\text{(f_{C,,m})})</td>
</tr>
<tr>
<td>(a): acceleration (mph/s)</td>
<td>--</td>
<td>(\text{(f_{\text{On,,m}})})</td>
</tr>
<tr>
<td>(r): road grade (%)</td>
<td>--</td>
<td>(\text{(CAER_{CS,,C,,i})})</td>
</tr>
</tbody>
</table>

**Note:**

\(^a\) The calibrated parameters are defined in Equation (6). The values for the calibrated parameters are shown in Appendix E.

\(^b\) The predicted variables \(f_{C,\,m}\) and \(f_{\text{On,\,m}}\) are defined in Equation (5). The predicted variable \(CAER_{CS,\,C,\,i}\) is defined in Equation (6).

### 2.11.3 Microscale Predictive Model — Second-by-Second Emission Rates

The second-by-second emission rates are determined by 1 Hz VSP and engine status predicted by implementing the derived engine on and off rules. The predicted second-by-second emission rates are compared with the observed second-by-second emission rates. An algorithm was developed in MATLAB to estimate the second-by-second emission rates for both CD and CS modes. The algorithm is documented in Appendix F and G for CD and CS modes.
2.12 References


5 Boroujeni, B. Y., & Frey, H. C. (2014). Road grade quantification based on global positioning system data obtained from real-world vehicle fuel use and emissions measurements. Atmospheric Environment, 85, 179-186.


21 Frey, H. C., & Kim, K. (2009). In-use measurement of the activity, fuel use, and emissions of eight cement mixer trucks operated on each of petroleum diesel and soy-based B20 biodiesel. Transportation Research Part D: Transport and Environment, 14(8), 585-592.


CHAPTER 3  RESULTS

Results are given for upstream energy use and emission rates for gasoline production, indirect energy use and emission rates for electricity production, quality assurance, CD and CS modes, driving cycles, engine on and off, cold start and hot stabilized running, and energy use and emission rates prediction model.

3.1  Gasoline Production Energy Use and Emission Rates

Upstream energy use and emission rates for gasoline production are from crude oil recovery and transportation, and gasoline refining, transportation and distribution. Table 7 shows the percentage of energy use and emissions associated with each key step in the gasoline production process.\(^1\)

Based on the upstream energy use and emission factors from the GREET 1 2014 model,\(^1\) the upstream energy use and emissions related to the amount of gasoline consumed during the measurement were included in the analysis of energy use and emission rates for the PHEV. Table 8 shows the upstream energy use and emission factors for gasoline production. A gasoline equivalent energy use of 0.30 gallons is needed to produce 1 gallon of gasoline. The density for reformulated or low-sulfur gasoline (RFG) is 2791 g/gallon.\(^2\) Thus, to produce 1 gallon of gasoline, the gasoline equivalent energy use is 823 g. Upstream emissions to
produce 1 gallon of gasoline are $1.61 \times 10^3$ g CO$_2$, $2.79 \times 10^3$ mg CO, $3.40 \times 10^3$ mg VOC, $5.98 \times 10^3$ mg NO$_x$, $4.73 \times 10^3$ mg SO$_x$, $0.42 \times 10^3$ mg PM$_{2.5}$, and $0.59 \times 10^3$ mg PM$_{10}$.

Table 7 The Percentage of Total Gasoline Production Energy Use and Emissions by Production Process

<table>
<thead>
<tr>
<th>Energy Use and Emissions</th>
<th>Crude Oil</th>
<th>Refining: Feed Inputs$^a$ (%)</th>
<th>Refining: Combustion (%)</th>
<th>Refining: Non-Combustion$^b$ (%)</th>
<th>Gasoline</th>
<th>Transportation (%)</th>
<th>Distribution (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovery (%)</td>
<td>Transportation to U.S. refineries (%)</td>
<td>73.7</td>
<td>0.0</td>
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Note:

$^a$ The feed inputs are used of residual oil, natural gas, butane, electricity, and hydrogen, and inputs of feedstocks other than crude oil.

$^b$ Non-combustion process includes crude cracking (both thermal and catalytic), hydrocarbon reforming, catalyst regeneration, sulfur recovery, and blowdown systems.
Table 8 Upstream Energy Use and Emission Factors for Gasoline Production

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<th>Energy Use Factor (gallon/gallon)</th>
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<th>CO</th>
<th>VOC</th>
<th>NOₓ</th>
<th>SOₓ</th>
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Note: Gasoline production process includes crude oil recovery and transportation, and gasoline refining, transportation and distribution.

3.2 Electricity Production Indirect Energy Use and Emission Rates

Indirect energy use and emissions for electricity production are from feedstock recovery, production and transportation, and electricity generation and transmission.

Table 9 shows the percentage of electricity generation by energy source for year 2011 for each state and for the U.S. national energy mix. Coal is the main energy resource for states such as, West Virginia (WV), Kentucky (KY), Wyoming (WY), Indiana (IN), Missouri (MO), Utah (UT), Ohio (OH), North Dakota (ND), Nebraska (NE), and New Mexico (NM). Petroleum is the main energy resource for state Hawaii (HI). Natural gas is the main energy resource for states such as Rhode Island (RI) and Delaware (DE). Nuclear is the main energy
resource for state Vermont (VT). Water is the main energy resource for states such as, Idaho (ID), Washington (WA), and Oregon (OR). For North Carolina (NC), 51% of electricity generation is from coal, 34% is from nuclear, and 9% is from natural gas. For the U.S., 42% of electricity generation is from coal, 25% is from natural gas, and 19% is from nuclear.

Table 10 shows the energy use and emission factors related to feedstock recovery, production and transportation for electricity generation for each state and for the U.S. national energy mix, based on GREET 1 2014 using Table 9 as input data. The ratio of highest to lowest emission factors among the states of pollutant CO\textsubscript{2} is 29, CO 18, HC 23, NO\textsubscript{x} 23, SO\textsubscript{x} 177, PM\textsubscript{2.5} 43, and PM\textsubscript{10} 83. The variability among the states is caused by the different electricity generation mix. The states with coal as their main energy resource tend to have high PM\textsubscript{10} emission factors. The states with coal, petroleum, or natural gas as their main energy resource tend to have high HC emission factors. The states with petroleum as their main energy resource tend to have high CO\textsubscript{2}, NO\textsubscript{x}, SO\textsubscript{x} and PM\textsubscript{2.5} emission factors. The states with petroleum or natural gas as their main energy resource tend to have high CO emission factors.

Table 11 shows the energy use and emission factors for electricity generation at power plants for each state and for the U.S. national energy mix. Table 12 shows the total energy use and
emission factors for electricity production for each state and for the U.S. national energy mix, which include the energy use and emissions related to feedstock recovery, production and transportation (Table 10), and the energy use and emissions for electricity generation at power plants (Table 11).

For NC, total energy use for generating 1 kWh of grid electricity is 10,217 Btu of thermal energy. The lower heating value for reformulated or low-sulfur gasoline (RFG) is 113,602 Btu/gallon,\(^3\) and the density for RFG is 2791 g/gallon.\(^2\) Thus, each kWh of grid electricity corresponds to a gasoline equivalent fuel use of 0.09 gallons, which equals 251 g gasoline. For NC, total emissions for 1 kWh of grid electricity are 529 g CO\(_2\), 296 mg CO, 56 mg VOC, 455 mg NO\(_x\), 703 mg SO\(_x\), 63 mg PM\(_{2.5}\), and 118 mg PM\(_{10}\). Energy use and emission factors data from NC are mainly used in this work. Energy use and emission factors data from states such as WV, HI, RI, VT, and ID, whose main energy resources come from coal, petroleum, gas, nuclear, and water, respectively, are used to evaluate the effect of electricity generation resource mix on energy use and emissions of the PHEV in CD mode. Energy use and emissions factors data from each state are used to study the statewide energy use and emissions of the PHEV in CD mode in U.S.
Results are presented based on NC, with sensitivity analysis for other states. These emission factors are based on the average energy mix and assume that PHEVs are charged at random time of day. If TB charging were to occur overnight, then the emission rates would be based on baseload generation mixes (e.g. coal, nuclear), whereas if TB charging occurred during peak generation hours, the emission rates would be influenced by peaking generation (e.g. natural gas, oil). The sensitivity of grid electricity emissions to different generation mix is, however, quite evident from comparison of substantially different generation mixes among the states. For example, 98 percent of power generated in RI is from natural gas, whereas 96 percent of electricity generation in WV is from coal. Thus, these states are surrogate data sources for the marginal emissions of natural gas and coal, respectively.
Table 9 The Percentage of Energy Resource for Electricity Generation for Year 2011 State-by-State and for the U.S. National Energy Mix

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<th>State</th>
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<th>Gas (%)</th>
<th>Nuclear (%)</th>
<th>Water (%)</th>
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Note: The energy use factors for electricity generation at power plants were estimated from the fuel consumption for electricity generation data and net electricity generation data reported by the U.S. EIA. The emission factors for generating electricity at power plants were estimated from emission inventory data for electricity generation from each major energy source (e.g. coal, petroleum, gas, and biomass) reported by the U.S. EPA, and net electricity generation data reported by the U.S. EIA.

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Note: The total energy use and emission factors for electricity production for each state and for the U.S. national energy mix, include the energy use and emissions related to feedstock recovery, production and transportation (Table 10), and the energy use and emissions for generating electricity at power plants (Table 11).

3.3 Quality Assurance

Less than 3% of data were excluded from the final quality assured dataset. The causes for errors were invalid IAT, two gas analyzers “zeroing” simultaneously, invalid RPM, and two gas analyzers recording negative exhaust HC concentrations which were statistically different from zero.
3.4 Charge Depleting (CD) and Charge Sustaining (CS) Modes

Based on the second-by-second TB SOC and engine speed data, CD mode was defined as the operation that ends when the TB SOC stabilizes, and the engine turns on. The rest of the operation was defined as CS mode. Based on eight days of measurement, when the operation modes of the study PHEV changed from CD to CS mode, the TB SOC varied from 23.1% to 23.9% on a daily basis, with an average of 23.4% and a standard deviation of 0.3%.

To illustrate the trends of TB SOC and engine speed over travel time, measurement data from January 21, 2013 was chosen as an example, which is typical of other days. Based on measurements from January 21, 2013, Figure 10 and Figure 11 show the second-by-second TB SOC and engine speed data for the PHEV. In general, the TB SOC decreased in CD mode and maintained within a narrow range in CS mode. The engine speed increased rapidly when CD mode ended, indicating that the engine was turning on.

In CD mode, the PHEV mainly uses grid electricity stored in the TB for propulsion. However, there are time periods during which the TB is not used because of the engine turning on or is recharged because of regenerative braking. For example, as shown in Figure 10, the TB SOC stayed at 57.6% during the time that the engine was on after the second engine start. The TB SOC increased from 45.5% to 46.7% in a short period, during which the
PHEV decelerated from 38 mph to 2 mph. However, such situations are not frequent and, when they occur, they are short in duration. The general trend of the TB SOC during CD mode is decreasing.

In CS mode, the engine mainly provides propulsion. Regenerative braking also happens during CS mode. The engine turns off under situations of low power demand that can be met solely with the electric motor, or no power demand when driving downhill, decelerating, or braking.

Figure 10 Second-by-Second Traction Battery State of Charge for Charge Depleting (CD) and Charge Sustaining (CS) Modes for a 2013 Toyota Prius Plug-In Hybrid Measured on January 21, 2013 in Raleigh/Research Triangle Park, North Carolina Area
Figure 11 Second-by-Second Engine Speed for Charge Depleting (CD) and Charge Sustaining (CS) Modes for a 2013 Toyota Prius Plug-In Hybrid Measured on January 21, 2013 in Raleigh/Research Triangle Park, North Carolina Area
3.4.1 Comparison between Charge Depleting (CD) and Charge Sustaining (CS) Modes

Figure 12 shows the daily average energy use and pollutant mass emission rates for CD and CS modes, based on eight days of measurement, based on used of NC electric power. During CD mode, the total energy use and emissions include indirect energy use and emissions for electricity production (including feedstock recovery, production and transportation, and electricity generation and transmission), upstream energy use and emissions for gasoline production (including crude oil recovery and transportation, and gasoline refining, transportation and distribution), and direct gasoline consumption and tailpipe emissions. During CD mode, the energy use and emissions are mainly from indirect energy use and emissions for electricity production, except for HC emission. During CS mode, the total energy use and emissions include upstream energy use and emissions for gasoline production, and direct gasoline consumption and tailpipe emissions. During CS mode, the energy use and CO\textsubscript{2} emission are mainly from direct gasoline consumption. The other emissions are mainly from upstream emissions for gasoline production. Thus, for a PHEV, even though pollutant tailpipe emissions might be low, the electricity and gasoline production related emissions significantly increase the total PHEV operation implied emissions.
Figure 12 The Daily Average Energy Use and Pollutant Mass Emission Rates for Charge Depleting (CD) and Charge Sustaining (CS) Modes for a 2013 Toyota Prius Plug-In Hybrid Measured from January 18, 2013 to January 25, 2013 in Raleigh/Research Triangle Park, North Carolina Area, Based on North Carolina Electric Power

Note: Error bars indicate 95% confidence intervals on the mean based on day-to-day variability (Sample Size = 8). For CD mode, the total energy use and emissions include indirect energy use and emissions for electricity production (including feedstock recovery, production and transportation, and electricity generation and transmission), upstream energy use and emissions for gasoline production (including crude oil recovery and transportation, and gasoline refining, transportation and distribution), and direct gasoline consumption and tailpipe emissions. For CS mode, the total energy use and emissions include upstream energy use and emissions for gasoline production, and direct gasoline consumption and tailpipe emissions.
When the PHEV operates in CD mode, its average total fuel economy is 34 mpg. INL measured four 2013 Toyota Prius Plug-In Hybrid Vehicles in trips where the vehicles were propelled by the TB only; the average electricity consumption was 356 Wh/mile, which is equivalent to energy economy of 31 mpg.\textsuperscript{9} When the PHEV operated in CS mode, its average total fuel economy was 41 mpg, and its direct fuel economy was 53 mpg. The rated combined city and highway fuel economy of the 2013 Toyota Prius Plug-In Hybrid in CS mode is 50 mpg.\textsuperscript{10} INL found that the average CS mode fuel economy was 51 mpg.\textsuperscript{9} The results of energy economy for CD and CS mode obtained from the measurements made here agree with the INL reported data.

Figure 12 shows that the total energy use rate for CD mode is higher than that for CS mode. The same result was observed by Graver \textit{et al.}\textsuperscript{11} With the current electricity generation efficiency and transmission loss for NC electric power, PHEV operating in CD versus CS mode is less energy efficient.

Figure 12 shows that, for CD mode, emissions are mainly from indirect emissions from electric grid, except for HC emission, which has the lowest emission factor for electricity generation. For CS mode, the CO\textsubscript{2} emissions are mainly from direct gasoline consumption, and the other emissions are mainly from upstream gasoline production. For a PHEV, electric
grid, upstream gasoline, and tailpipe emission sources are all important, and none of them should be neglected.

Figure 12 shows that the total CO$_2$ emission rate for CD mode is not significantly different from that for CS mode. For CD mode, CO, NO$_x$, SO$_x$, PM$_{2.5}$, and PM$_{10}$ emission rates are larger, and the HC emission rate is lower, relative to CS mode. More than 50% of power generated in NC is from coal, which leads to relatively high CD mode emission factors for electricity generation, in terms of NO$_x$, SO$_x$, PM$_{2.5}$ and PM$_{10}$. However, PHEV operating in CD mode would shift a significant amount of on-road CO$_2$ emission to sites of power plants, changing the type of transportation CO$_2$ emission source from mobile to point, which would be easier to regulate and control.
Total energy use and emission rates for CD mode are related to grid electricity. Grid-related indirect energy use and emissions vary with electricity generation resource mix. Table 13 shows the daily average energy use and pollutant mass emission rates for CD mode for different U.S. states. For example, states such as HI and WV, where 74% and 96% of electricity is generated by oil and coal, respectively, are among the states with the highest energy use and pollutant emission factors for electricity production. If the PHEV was operated in a state with an energy mix similar to that of HI and WV, total energy use and pollutant mass emission rates for CD mode would be significantly higher than those for CS mode, except for HC. For states such as RI and VT, around 98% and 72% of electricity is generated by gas and nuclear, respectively. If the PHEV was operated in a state with an energy mix similar to that of RI and VT, total energy use rate for CD mode would still be higher than that for CS mode, however, total emission rates for CD mode would be lower than those for CS mode, except for CO. In ID, 80% of electricity is generated by hydropower. ID is among the states with the lowest energy use and emission factors for electricity production. If the PHEV was operated in a state with an energy mix similar to that of ID, total energy use rate for CD mode would still be higher than that for CS mode, however, total emission rates for CD mode would be significantly lower than those for CS mode for each pollutant.
Table 13 The Daily Average Energy Use and Pollutant Mass Emission Rates for Charge Depleting (CD) for Different U.S. States and Charge Sustaining (CS) Modes for a 2013 Toyota Prius Plug-In Hybrid Measured from January 18, 2013 to January 25, 2013 in Raleigh/Research Triangle Park, North Carolina Area

<table>
<thead>
<tr>
<th>Mode</th>
<th>State</th>
<th>Main Energy Resource</th>
<th>Energy Use (g/mile)</th>
<th>CO₂</th>
<th>CO</th>
<th>HC</th>
<th>NOₓ</th>
<th>SOₓ</th>
<th>PM₂.₅</th>
<th>PM₁₀</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD</td>
<td>HI</td>
<td>Oil</td>
<td>90.4</td>
<td>255.5</td>
<td>289.6</td>
<td>55.0</td>
<td>730.5</td>
<td>581.8</td>
<td>54.4</td>
<td>65.4</td>
</tr>
<tr>
<td></td>
<td>WV</td>
<td>Coal</td>
<td>84.4</td>
<td>295.2</td>
<td>111.8</td>
<td>51.0</td>
<td>241.5</td>
<td>331.8</td>
<td>34.7</td>
<td>62.0</td>
</tr>
<tr>
<td>CD</td>
<td>RI</td>
<td>Gas</td>
<td>72.7</td>
<td>167.1</td>
<td>153.2</td>
<td>47.3</td>
<td>112.5</td>
<td>51.3</td>
<td>5.2</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>VT</td>
<td>Nuclear</td>
<td>87.2</td>
<td>47.2</td>
<td>114.8</td>
<td>28.2</td>
<td>44.5</td>
<td>21.9</td>
<td>2.6</td>
<td>3.6</td>
</tr>
<tr>
<td></td>
<td>ID</td>
<td>Water</td>
<td>80.6</td>
<td>54.4</td>
<td>77.4</td>
<td>28.4</td>
<td>36.0</td>
<td>23.1</td>
<td>2.5</td>
<td>3.4</td>
</tr>
<tr>
<td>CS</td>
<td>--</td>
<td>--</td>
<td>69.0</td>
<td>199.5</td>
<td>78.1</td>
<td>71.2</td>
<td>118.1</td>
<td>91.8</td>
<td>8.0</td>
<td>11.2</td>
</tr>
</tbody>
</table>

Note:

\(^a\) HI = Hawaii, WV = West Virginia, RI = Rhode Island, VT = Vermont, ID = Idaho.
The ratio of highest to lowest CD mode CO\textsubscript{2} emission rates among the states is 6.5. The ratio of highest to lowest CD mode CO emission rates among the states is 4.2. The ratio of highest to lowest CD mode HC emission rates among the states is 2.6. The ratio of highest to lowest CD mode NO\textsubscript{x} emission rates among the states is 25. The ratio of highest to lowest CD mode SO\textsubscript{x} emission rates among the states is 51. The ratio of highest to lowest CD mode PM\textsubscript{2.5} emission rates among the states is 27. The ratio of highest to lowest CD mode PM\textsubscript{10} emission rates among the states is 27. Five U.S. states shown in Table 13, represent the large interstate variability in emission rates.

With the current electricity generation efficiency and transmission loss, PHEV CD mode operation is less energy efficient, compared to CS mode, based on the electricity mix in every state. With the current grid electricity HC emission rates, the PHEV total CD mode HC emission rate in every state is lower than or similar to that for CS mode. For 30 states, there would be a lower total CO\textsubscript{2} emission rate in CD versus CS mode. Compared to CS mode, oil and coal are not so desirable energy resources for electricity generated to charge PHEV, in terms of CO\textsubscript{2}, CO, NO\textsubscript{x}, SO\textsubscript{x}, PM\textsubscript{2.5}, and PM\textsubscript{10} emissions. Gas and nuclear are better energy resources, in terms of CO\textsubscript{2}, NO\textsubscript{x}, SO\textsubscript{x}, PM\textsubscript{2.5} and PM\textsubscript{10} emissions. Hydro is the best among these five energy resources. Reduced CO\textsubscript{2} and other pollutant emissions can be achieved if PHEV operates in CD versus CS mode in state such as ID.
3.4.2 Charge Depleting (CD) Mode

In this section, results are given for PHEV operation in CD mode. The vehicle activity, energy use and emissions on different study routes were analyzed to evaluate the effect of road type on vehicle activity, energy use and emissions. The energy use and emissions are also evaluated based on the energy mix of each of 50 U.S. states and the District of Columbia (DC).

3.4.2.1 Vehicle Activity on Different Study Routes

Table 14 shows the vehicle activity on each study route for the PHEV in CD mode. Based on eight days of measurement, the 2013 Toyota Prius Plug-in Hybrid operated in CD mode for an average distance of 12.5 miles. CD mode typically occurred on only one route per day in one travel direction. Some routes were measured for the entire travel distance in CD mode, such as A out, B out, C out and D. Some routes were only measured for less than 1 mile in the last few minutes of CD mode, such as A in, B in, C in and 1 out. CD mode was not measured on other routes, such as Routes 1 in, 2, or 3, because their origins were a substantial distance from the start of data collection. The number of complete runs on each route is small, because there can be only one CD mode operating period per day.
Table 14 Vehicle Activity on Each Study Route for Charge Depleting (CD) Mode for a 2013 Toyota Prius Plug-In Hybrid Measured from January 18, 2013 to January 25, 2013 in Raleigh/Research Triangle Park, North Carolina Area

<table>
<thead>
<tr>
<th>Route</th>
<th>Direction</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>I</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of Runs</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Duration (s)</td>
<td>2854</td>
<td>218</td>
<td>3169</td>
<td>294</td>
<td>4009</td>
</tr>
<tr>
<td></td>
<td>Distance (miles)</td>
<td>20.7</td>
<td>0.7</td>
<td>23.9</td>
<td>0.8</td>
<td>32.6</td>
</tr>
<tr>
<td></td>
<td>Number of Engine Starts</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Engine On Duration (s)</td>
<td>191</td>
<td>158</td>
<td>432</td>
<td>0</td>
<td>857</td>
</tr>
<tr>
<td></td>
<td>Engine On Distance (miles)</td>
<td>0.3</td>
<td>0.2</td>
<td>2.9</td>
<td>0</td>
<td>8.5</td>
</tr>
<tr>
<td></td>
<td>Average Speed (mph)</td>
<td>26.2</td>
<td>12.0</td>
<td>27.1</td>
<td>10.3</td>
<td>29.3</td>
</tr>
<tr>
<td></td>
<td>Number of Engine Starts per Mile</td>
<td>0.05</td>
<td>1.37</td>
<td>0.13</td>
<td>0</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>Engine On Duration Percentage (%)</td>
<td>6.7</td>
<td>72.5</td>
<td>13.6</td>
<td>0</td>
<td>21.4</td>
</tr>
<tr>
<td></td>
<td>Engine On Distance Percentage (%)</td>
<td>1.4</td>
<td>26.8</td>
<td>12.0</td>
<td>0</td>
<td>26.2</td>
</tr>
<tr>
<td></td>
<td>Average Duration Between Engine Starts (s)</td>
<td>2854</td>
<td>218</td>
<td>1056</td>
<td>--</td>
<td>1002</td>
</tr>
<tr>
<td></td>
<td>Average Distance Between Engine Starts (miles)</td>
<td>20.7</td>
<td>0.7</td>
<td>8.0</td>
<td>--</td>
<td>8.1</td>
</tr>
<tr>
<td></td>
<td>Average Engine On Duration per Engine Start (s)</td>
<td>191</td>
<td>158</td>
<td>144</td>
<td>--</td>
<td>214</td>
</tr>
<tr>
<td></td>
<td>Average Engine On Distance per Engine Start (miles)</td>
<td>0.3</td>
<td>0.2</td>
<td>1.0</td>
<td>--</td>
<td>2.1</td>
</tr>
</tbody>
</table>
The number of engine starts per mile for Routes A out, B out, C out and D is small, varying from 0.05 to 0.13. For Route A out, the number of engine starts per mile, engine on duration percentage, engine on distance percentage, and average engine on distance per engine start are the smallest among these four routes, and the average duration between engine starts and average distance between engine starts are the largest among these four routes. The average engine on duration per engine start for Route A out is smaller than Routes C out and D, but larger than Route B out. Even though average speeds for these four routes do not differ much, varying from 26.2 mph to 29.3 mph, the percentage of freeway for Route A out is the smallest among these four routes, as shown in Table 1. With the least travel distance on the freeway for Route A out, less time was spent at high speed. This is the reason why Route A out has smallest number of engine starts per mile. The percentages of travel distance by freeway for the other three routes do not differ much, varying from 44% to 50%. This is the reason why the number of engine starts per mile for these three routes do not differ much, varying from 0.10 to 0.13.

Routes A in, B in, C in and 1 out were measured in the last few minutes of CD mode. Less than 1 mile of each of these routes was measured for CD mode. More data need to be collected to get a conclusive result of the number of engine starts per mile for these routes.
3.4.2.2 Energy Use and Emission Rates on Different Study Routes

Figure 13 shows the energy use and pollutant mass emission rates for Routes A out, B out, C out, and D for CD mode. The total energy use and emission rates include indirect energy use and emissions for electricity production (including feedstock recovery, production and transportation, and electricity generation and transmission), upstream energy use and emissions for gasoline production (including crude oil recovery and transportation, and gasoline refining, transportation and distribution), and direct gasoline consumption and tailpipe emissions. Figure 13 indicates that the energy use and emissions are mainly from indirect energy use and emissions for electricity production, except for HC. For CD mode, the differences between routes do not seem to have much effect on the total energy use and pollutant mass emission rates.
Figure 13 The Energy Use and Pollutant Mass Emission Rates for Routes A out, B out, C out, and D for Charge Depleting (CD) Mode for a 2013 Toyota Prius Plug-In Hybrid Measured from January 18, 2013 to January 25, 2013 in Raleigh/Research Triangle Park, North Carolina Area

*Note:* Error bars indicate the range of minimum to maximum. The total energy use and emissions includes indirect energy use and emissions for electricity production (including feedstock recovery, production and transportation, and electricity generation and transmission), upstream energy use and emissions for gasoline production (including crude oil recovery and transportation, and gasoline refining, transportation and distribution), and direct gasoline consumption and tailpipe emissions.
3.4.2.3 Interstate Variability in Energy Use and Emission Rates

To evaluate the variability in energy use and emission rates for the PHEV operating in the CD mode related to electricity generation energy mix, the energy use and emission rates based on the energy mix for each of 50 U.S. states and DC are shown in Figure 14 for energy, Figure 15 for CO₂, Figure 16 for CO, Figure 17 for HC, Figure 18 for NOₓ, Figure 19 for SOₓ, Figure 20 for PM₂.₅, and Figure 21 for PM₁₀.

The analysis here is based on the assumption that the vehicle operates in the real world under conditions observed in the NC field measurements, but that the electricity would be obtained from an energy mix similar to that of any other state. Thus, references to “state” below refer only to electricity energy mix, not changes in climate or topography that might also affect on road power demand.
Figure 14 The Daily Average Energy Use Rate Versus State for Charge Depleting (CD) Mode

Note: Error bars indicate 95% confidence intervals on the mean based on day-to-day variability (Sample Size = 8). The energy use rate includes indirect energy use for electricity production (including feedstock recovery, production and transportation, and electricity generation and transmission), upstream energy use for gasoline production (including crude oil recovery and transportation, and gasoline refining, transportation and distribution), and direct energy use of gasoline consumption.
Figure 15 The Daily Average Carbon Dioxide (CO$_2$) Emission Rate Versus State for Charge Depleting (CD) Mode

Note: Error bars indicate 95% confidence intervals on the mean based on day-to-day variability (Sample Size = 8). The CO$_2$ emission rate includes indirect emissions for electricity production (including feedstock recovery, production and transportation, and electricity generation and transmission), upstream emissions from gasoline production (including crude oil recovery and transportation, and gasoline refining, transportation and distribution), and direct tailpipe emissions.
Figure 16 The Daily Average Carbon Monoxide (CO) Emission Rate Versus State for Charge Depleting (CD) Mode

Note: Error bars indicate 95% confidence intervals on the mean based on day-to-day variability (Sample Size = 8). The CO emission rate includes indirect emissions for electricity production (including feedstock recovery, production and transportation, and electricity generation and transmission), upstream emissions from gasoline production (including crude oil recovery and transportation, and gasoline refining, transportation and distribution), and direct tailpipe emissions.
Figure 17 The Daily Average Hydrocarbon (HC) Emission Rate Versus State for Charge Depleting (CD) Mode

Note: Error bars indicate 95% confidence intervals on the mean based on day-to-day variability (Sample Size = 8). The HC emission rate includes indirect emissions for electricity production (including feedstock recovery, production and transportation, and electricity generation and transmission), upstream emissions from gasoline production (including crude oil recovery and transportation, and gasoline refining, transportation and distribution), and direct tailpipe emissions.
Figure 18 The Daily Average Oxide of Nitrogen (NO$_x$) Emission Rate Versus State for Charge Depleting (CD) Mode

Note: Error bars indicate 95% confidence intervals on the mean based on day-to-day variability (Sample Size = 8). The NO$_x$ emission rate includes indirect emissions for electricity production (including feedstock recovery, production and transportation, and electricity generation and transmission), upstream emissions from gasoline production (including crude oil recovery and transportation, and gasoline refining, transportation and distribution), and direct tailpipe emissions.
Figure 19 The Daily Average Oxide of Sulfur (SO\textsubscript{x}) Emission Rate Versus State for Charge Depleting (CD) Mode

*Note:* Error bars indicate 95% confidence intervals on the mean based on day-to-day variability (Sample Size = 8). The SO\textsubscript{x} emission rate includes indirect emissions for electricity production (including feedstock recovery, production and transportation, and electricity generation and transmission), upstream emissions from gasoline production (crude oil recovery and transportation, and gasoline refining, transportation and distribution), and direct tailpipe emissions, which are calculated by gasoline use rate and the maximum sulfur concentration of gasoline.
Figure 20 The Daily Average Particulate Matter with Diameters of 2.5 Micrometers or Less (PM$_{2.5}$) Emission Rate Versus State for Charge Depleting (CD) Mode

Note: Error bars indicate 95% confidence intervals on the mean based on day-to-day variability (Sample Size = 8). The PM$_{2.5}$ emission rate includes indirect emissions for electricity production (including feedstock recovery, production and transportation, and electricity generation and transmission), upstream emissions from gasoline production (including crude oil recovery and transportation, and gasoline refining, transportation and distribution), and direct tailpipe emissions, which are not measured during the measurement and are assumed as 0.
Figure 21 The Daily Average Particulate Matter with Diameters of 10 Micrometers or Less (PM$_{10}$) Emission Rate Versus State for Charge Depleting (CD) Mode

Note: Error bars indicate 95% confidence intervals on the mean based on day-to-day variability (Sample Size = 8). The PM$_{10}$ emission rate includes indirect emissions for electricity production (including feedstock recovery, production and transportation, and electricity generation and transmission), upstream emissions from gasoline production (including crude oil recovery and transportation, and gasoline refining, transportation and distribution), and direct tailpipe emissions, which are not measured during the measurement and are assumed as 0.
The ratio of highest to lowest energy use rates in CD mode among the states is 1.6. The energy use rates are similar among the states, except for DC, whose main electricity generation resource is petroleum. States such as HI, Alaska (AK), and DC, with a significant share of petroleum as their electricity generation resource, have highest energy use rates.

The ratio of highest to lowest CO$_2$ emission rates in CD mode among the states is 6.5. For states with the highest CO$_2$ emission rates, more than 65% of the electricity is generated either from coal or petroleum. For 10 states with the lowest CO$_2$ emission rates, more than 70% of the electricity is generated from natural gas, nuclear, water and wind.

The ratio of highest to lowest CO emission rates in CD mode among the states is 4.2. The CO emission rates do not differ much among the states, except for 4 states with the highest values, which is caused by a significant share of natural gas or petroleum.

The ratio of highest to lowest HC emission rates in CD mode among the states is 2.6. The HC emission rates do not vary much among the states, except for AK, whose main energy resource is natural gas. For 5 states with the lowest HC emission rates, more than 75% of the electricity is generated from non-fossil fuels.

The ratio of highest to lowest emission rates in CD mode among the states of pollutant NO$_x$ is 25, SO$_x$ 51, PM$_{2.5}$ 27, and PM$_{10}$ 27. For NO$_x$, AK and HI have the highest emission rates,
whose main energy resources are natural gas and petroleum, respectively. For SO$_x$, OH and DC have the highest emission rates, whose main energy resources are coal and petroleum, respectively. For PM$_{2.5}$ and PM$_{10}$, OH and HI have the highest emission rates, whose main energy resources are coal and petroleum, respectively.

States such as ID, VT, and WA, where more than 85% of electricity is generated from non-fossil fuels, have the lowest CO$_2$, HC, NO$_x$, SO$_x$, PM$_{2.5}$ and PM$_{10}$ emission rates. The interstate variability in emission rates for electricity generation are not only caused by variability in electricity generation resource mix, but also vary depending on electricity generation and air pollution control technologies used.$^{12}$ Thus, some interstate variability in emission rates might be caused by these other factors.
3.4.3 Charge Sustaining (CS) Mode

In this section, results are given for PHEV operation in CS mode. The vehicle activity, energy use and emission rates on different study routes are analyzed to evaluate the effect of road type on vehicle activity, energy use and emission rates.

3.4.3.1 Vehicle Activity on Different Study Routes

Table 15 shows the vehicle activity on each study route for the PHEV in the CS mode. Compared to CD mode, the PHEV tends to have more engine starts, and the number of engine starts per mile tends to be higher for the same study route.
Table 15 The Vehicle Activity on Each Study Route for Charge Sustaining (CS) Mode for a 2013 Toyota Prius Plug-In Hybrid Measured from January 18, 2013 to January 25, 2013 in Raleigh/Research Triangle Park, North Carolina Area

<table>
<thead>
<tr>
<th>Route Direction</th>
<th>A</th>
<th>A</th>
<th>B</th>
<th>B</th>
<th>C</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>1</th>
<th>1</th>
<th>2</th>
<th>2</th>
<th>3</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Runs</td>
<td>5</td>
<td>7</td>
<td>1</td>
<td>3</td>
<td>8</td>
<td>8</td>
<td>3</td>
<td>3</td>
<td>8</td>
<td>8</td>
<td>2</td>
<td>2</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Duration (s)</td>
<td>8219</td>
<td>9542</td>
<td>1417</td>
<td>4080</td>
<td>9163</td>
<td>10992</td>
<td>2581</td>
<td>2192</td>
<td>9642</td>
<td>10944</td>
<td>3012</td>
<td>3400</td>
<td>13548</td>
<td>13791</td>
</tr>
<tr>
<td>Distance (miles)</td>
<td>54.3</td>
<td>69.6</td>
<td>11.9</td>
<td>33.3</td>
<td>25.1</td>
<td>8.1</td>
<td>116.0</td>
<td>130.7</td>
<td>36.6</td>
<td>41.2</td>
<td>123.8</td>
<td>123.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of Engine Starts</td>
<td>252</td>
<td>262</td>
<td>43</td>
<td>103</td>
<td>225</td>
<td>220</td>
<td>47</td>
<td>40</td>
<td>86</td>
<td>88</td>
<td>39</td>
<td>52</td>
<td>244</td>
<td>246</td>
</tr>
<tr>
<td>Engine On Duration (s)</td>
<td>2816</td>
<td>3581</td>
<td>620</td>
<td>1947</td>
<td>4050</td>
<td>4382</td>
<td>1492</td>
<td>354</td>
<td>6822</td>
<td>7513</td>
<td>2127</td>
<td>2364</td>
<td>7922</td>
<td>7724</td>
</tr>
<tr>
<td>Engine On Distance (miles)</td>
<td>26.6</td>
<td>36.5</td>
<td>6.8</td>
<td>21.6</td>
<td>48.0</td>
<td>56.4</td>
<td>20.0</td>
<td>2.7</td>
<td>107.3</td>
<td>120.5</td>
<td>32.5</td>
<td>35.9</td>
<td>97.2</td>
<td>94.4</td>
</tr>
<tr>
<td>Average Speed (mph)</td>
<td>23.8</td>
<td>26.3</td>
<td>30.3</td>
<td>29.4</td>
<td>28.0</td>
<td>29.3</td>
<td>35.1</td>
<td>13.3</td>
<td>43.3</td>
<td>43.0</td>
<td>43.8</td>
<td>43.7</td>
<td>32.9</td>
<td>32.3</td>
</tr>
<tr>
<td>Number of Engine Starts per Mile</td>
<td>4.6</td>
<td>3.8</td>
<td>3.6</td>
<td>3.1</td>
<td>3.2</td>
<td>2.5</td>
<td>1.9</td>
<td>4.9</td>
<td>0.7</td>
<td>0.7</td>
<td>1.1</td>
<td>1.3</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Engine On Duration Percentage (%)</td>
<td>34.3</td>
<td>37.5</td>
<td>43.8</td>
<td>47.7</td>
<td>44.2</td>
<td>39.9</td>
<td>57.8</td>
<td>16.1</td>
<td>70.8</td>
<td>68.6</td>
<td>70.6</td>
<td>69.5</td>
<td>58.5</td>
<td>56.0</td>
</tr>
<tr>
<td>Engine On Distance Percentage (%)</td>
<td>48.9</td>
<td>52.5</td>
<td>56.8</td>
<td>64.9</td>
<td>67.4</td>
<td>63.1</td>
<td>79.7</td>
<td>33.7</td>
<td>92.5</td>
<td>92.2</td>
<td>88.9</td>
<td>87.2</td>
<td>78.5</td>
<td>76.1</td>
</tr>
<tr>
<td>Average Duration Between Engine Starts (s)</td>
<td>33</td>
<td>36</td>
<td>33</td>
<td>40</td>
<td>41</td>
<td>50</td>
<td>55</td>
<td>55</td>
<td>112</td>
<td>124</td>
<td>77</td>
<td>65</td>
<td>56</td>
<td>56</td>
</tr>
<tr>
<td>Average Distance Between Engine Starts (miles)</td>
<td>0.2</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.4</td>
<td>0.5</td>
<td>0.2</td>
<td>1.3</td>
<td>1.4</td>
<td>0.9</td>
<td>0.8</td>
<td>0.5</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Average Engine On Duration per Engine Start (s)</td>
<td>11</td>
<td>14</td>
<td>14</td>
<td>19</td>
<td>18</td>
<td>20</td>
<td>32</td>
<td>9</td>
<td>79</td>
<td>85</td>
<td>55</td>
<td>45</td>
<td>32</td>
<td>31</td>
</tr>
<tr>
<td>Average Engine On Distance per Engine Start (miles)</td>
<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
<td>0.2</td>
<td>0.3</td>
<td>0.4</td>
<td>0.1</td>
<td>1.2</td>
<td>1.4</td>
<td>0.8</td>
<td>0.7</td>
<td>0.4</td>
<td>0.4</td>
<td></td>
</tr>
</tbody>
</table>
For CS mode, number of engine starts per mile on each route is linearly dependent on the average speed on each route, as shown in Figure 22. The number of engine starts per mile decreases linearly with increasing speed. Figure 23 and Figure 24 show that engine on duration percentage and engine on distance percentage, respectively, increase linearly with increasing speed. The engine tends to stay on longer after an engine start to meet high power demand at high speed. Thus, the frequency of the engine turning on decreases with increasing speed.

For the average duration and distance between engine starts shown in Figure 25 and Figure 26, respectively, and the average engine on duration and distance per engine start shown in Figure 27 and Figure 28, respectively, the linear relationship between them and speed is not strong. When the vehicle is driving at high speed above 40 mph in CS mode on Route 1 out, 1 in, 2 out, or 2 in, with an average speed of 43.5 mph, the average duration and distance between engine starts, and the average engine on duration and distance per engine start tend to vary.
Figure 22 Number of Engine Starts per Mile vs. Average Speed on Each Route for Charge Sustaining (CS) Mode

Figure 23 Engine On Duration Percentage vs. Average Speed on Each Route for Charge Sustaining (CS) Mode
Figure 24 Engine On Distance Percentage vs. Average Speed on Each Route for Charge Sustaining (CS) Mode

\[ y = 1.9511x + 6.8335 \]
\[ R^2 = 0.9223 \]

Figure 25 Average Duration Between Engine Starts vs. Average Speed on Each Route for Charge Sustaining (CS) Mode

\[ y = 2.1759x - 11.142 \]
\[ R^2 = 0.4703 \]
Figure 26 Average Distance Between Engine Starts vs. Average Speed on Each Route for Charge Sustaining (CS) Mode

Figure 27 Average Engine On Duration per Engine Start vs. Average Speed on Each Route for Charge Sustaining (CS) Mode
3.4.3.2 Energy Use and Emission Rates on Different Study Routes

To evaluate the variability in energy use and emission rates for the PHEV operating in the CS mode on different study routes, the energy use and emission rates on each route for CS mode are shown in Figure 29 for energy, Figure 30 for CO₂, Figure 31 for CO, Figure 32 for HC, Figure 33 for NOₓ, Figure 34 for SO₂, Figure 35 for PM₂.₅, and Figure 36 for PM₁₀. For CS mode, the energy use and emissions include upstream energy use and emissions for gasoline production (including crude oil recovery and transportation, and gasoline refining, transportation and distribution), and direct gasoline consumption and tailpipe emissions.
Most of the CO, HC, NO\textsubscript{x}, SO\textsubscript{x}, PM\textsubscript{2.5}, and PM\textsubscript{10} emissions come from upstream gasoline production, which is related to the amount of gasoline consumed during measurement. Average energy use and emission rates do not vary much among different study routes. The ratio of highest to lowest energy use and emission rates in CS mode among the routes is 1.2.

![Figure 29 The Daily Average Energy Use Rate Versus Route for Charge Sustaining (CS) Mode](image)

*Note: Error bars indicate 95% confidence intervals on the mean based on run-to-run variability (Number of Runs on Each Route are 12, 4, 15, 3, 2, 16, 4, and 14 for Routes A, B, C, D, E, 1, 2, and 3). The energy use rate includes upstream energy use for gasoline production (including crude oil recovery and transportation, and gasoline refining, transportation and distribution), and direct energy use of gasoline consumption.*
Figure 30 The Daily Average Carbon Dioxide (CO₂) Emission Rate Versus Route for Charge Sustaining (CS) Mode

Note: Error bars indicate 95% confidence intervals on the mean based on run-to-run variability (Number of Runs on Each Route are 12, 4, 15, 3, 2, 16, 4, and 14 for Routes A, B, C, D, E, 1, 2, and 3.). The CO₂ emission rate includes indirect emissions from upstream emissions from gasoline production (including crude oil recovery and transportation, and gasoline refining, transportation and distribution), and direct tailpipe emissions.
Figure 31 The Daily Average Carbon Monoxide (CO) Emission Rate Versus Route for Charge Sustaining (CS) Mode

Note: Error bars indicate 95% confidence intervals on the mean based on run-to-run variability (Number of Runs on Each Route are 12, 4, 15, 3, 2, 16, 4, and 14 for Routes A, B, C, D, E, 1, 2, and 3.). The CO emission rate includes indirect emissions from upstream emissions from gasoline production (including crude oil recovery and transportation, and gasoline refining, transportation and distribution), and direct tailpipe emissions.
Figure 32 The Daily Average Hydrocarbon (HC) Emission Rate Versus Route for Charge Sustaining (CS) Mode

Note: Error bars indicate 95% confidence intervals on the mean based on run-to-run variability (Number of Runs on Each Route are 12, 4, 15, 3, 2, 16, 4, and 14 for Routes A, B, C, D, E, 1, 2, and 3). The HC emission rate includes indirect emissions from upstream emissions from gasoline production (including crude oil recovery and transportation, and gasoline refining, transportation and distribution), and direct tailpipe emissions.
Figure 33 The Daily Average Oxide of Nitrogen ($\text{NO}_x$) Emission Rate Versus Route for Charge Sustaining (CS) Mode

Note: Error bars indicate 95% confidence intervals on the mean based on run-to-run variability (Number of Runs on Each Route are 12, 4, 15, 3, 2, 16, 4, and 14 for Routes A, B, C, D, E, 1, 2, and 3.). The $\text{NO}_x$ emission rate includes indirect emissions from upstream emissions from gasoline production (including crude oil recovery and transportation, and gasoline refining, transportation and distribution), and direct tailpipe emissions.
Figure 34 The Daily Average Oxide of Sulfur ($SO_x$) Emission Rate Versus Route for Charge Sustaining (CS) Mode

Note: Error bars indicate 95% confidence intervals on the mean based on run-to-run variability (Number of Runs on Each Route are 12, 4, 15, 3, 2, 16, 4, and 14 for Routes A, B, C, D, E, 1, 2, and 3.). The $SO_x$ emission rate includes indirect emissions from upstream emissions from gasoline production (including crude oil recovery and transportation, and gasoline refining, transportation and distribution), and direct tailpipe emissions, which are calculated by gasoline use rate and the maximum sulfur concentration of gasoline.
Figure 35 The Daily Average Particulate Matter with Diameters of 2.5 Micrometers or Less (PM$_{2.5}$) Emission Rate Versus Route for Charge Sustaining (CS) Mode

Note: Error bars indicate 95% confidence intervals on the mean based on run-to-run variability (Number of Runs on Each Route are 12, 4, 15, 3, 2, 16, 4, and 14 for Routes A, B, C, D, E, 1, 2, and 3.). The PM$_{2.5}$ emission rate includes indirect emissions from upstream emissions from gasoline production (including crude oil recovery and transportation, and gasoline refining, transportation and distribution), and direct tailpipe emissions, which are not measured during the measurement and are assumed as 0.
Figure 36 The Daily Average Particulate Matter with Diameters of 10 Micrometers or Less (PM$_{10}$) Emission Rate Versus Route for Charge Sustaining (CS) Mode

*Note:* Error bars indicate 95% confidence intervals on the mean based on run-to-run variability (Number of Runs on Each Route are 12, 4, 15, 3, 2, 16, 4, and 14 for Routes A, B, C, D, E, 1, 2, and 3.). The PM$_{10}$ emission rate includes indirect emissions from upstream emissions from gasoline production (including crude oil recovery and transportation, and gasoline refining, transportation and distribution), and direct tailpipe emissions, which are not measured during the measurement and are assumed as 0.
3.5 Driving Cycles

The driving cycle for each study route was estimated based on the distribution of travel time in each VSP mode, as shown in Figure 37 for Route A, Figure 38 for Route B, Figure 39 for Route C, Figure 40 for Route D, Figure 41 for Route E, Figure 42 for Route 1, Figure 43 for Route 2, and Figure 44 for Route 3. For all of the study routes, 90% of the total travel time was spent in VSP modes 1 to 8. From VSP modes 6 to 14, the amount of travel time spent in each VSP mode decreases with increasing VSP mode. Because of the speed limits posted on public roads, it is difficult to reach or maintain the power demand at high levels, such as in VSP modes 9 to 14.

Figure 37 The Travel Time Distribution in Each Vehicle Specific Power Mode for Route A

Note: Error bars indicate 95% confidence intervals on the mean based on run-to-run variability.
Figure 38 The Travel Time Distribution in Each Vehicle Specific Power Mode for Route B

Note: Error bars indicate 95% confidence intervals on the mean based on run-to-run variability.

Figure 39 The Travel Time Distribution in Each Vehicle Specific Power Mode for Route C

Note: Error bars indicate 95% confidence intervals on the mean based on run-to-run variability.
Figure 40 The Travel Time Distribution in Each Vehicle Specific Power Mode for Route D

Note: Error bars indicate 95% confidence intervals on the mean based on run-to-run variability.

Number of Runs: 3
Average Travel Time: 1207 seconds

Figure 41 The Travel Time Distribution in Each Vehicle Specific Power Mode for Route E

Note: Error bars indicate 95% confidence intervals on the mean based on run-to-run variability.

Number of Runs: 3
Average Travel Time: 800 seconds
Figure 42 The Travel Time Distribution in Each Vehicle Specific Power Mode for Route 1

Note: Error bars indicate 95% confidence intervals on the mean based on run-to-run variability.

Figure 43 The Travel Time Distribution in Each Vehicle Specific Power Mode for Route 2

Note: Error bars indicate 95% confidence intervals on the mean based on run-to-run variability.
Figure 44 The Travel Time Distribution in Each Vehicle Specific Power Mode for Route 3

*Note: Error bars indicate 95% confidence intervals on the mean based on run-to-run variability.*

Routes A, B, and C between NC State and North Raleigh share some of the same roads. The percentage of total travel time spent in each VSP mode is similar. Half of total travel time was spent in VSP modes 1 through 3, and 95% of total travel time was spent in VSP modes 8 or lower.

The run-to-run variability of the travel time spent in each VSP mode for Routes D and E is relatively more than that for other routes, which is influenced by the relatively small number of runs on Routes D and E.
Routes 1, 2 and 3 are between North Raleigh and RTP. For Routes 1 and 2, the percentage of total travel time spent in each VSP mode is similar, because of the similar percentage of travel distance on freeways. Half of the total travel time on these two routes was spent in VSP modes 5 or lower, and 95% of total travel time was spent in VSP modes 10 or lower. Compared to Routes A, B, and C, a greater percentage of total travel time was spent in VSP modes 5 to 14 due to the higher percentage of travel distance on freeways. Since Route 3 is mainly comprised of minor and major arterials, a greater percentage of total travel time was spent in lower VSP modes compared to Routes 1 and 2. For example, half of the total travel time on Route 3 was spent in VSP modes 3 or lower.

3.6 Engine On and Engine Off

As shown in Figure 11, the engine turned on and off during the measurement. When engine speed is greater than or equal to 1000 rpm, the engine is usually running. More than 98% of data that had engine speed greater than or equal to 1000 rpm had fuel use greater than or equal to 0.70 l/hr. More than 88% of data that had engine speed greater than or equal to 500 rpm and less than 1000 rpm had fuel use greater than or equal to 0.70 l/hr. Thus, engine was defined as “on” when engine speed was greater than or equal to 500 rpm and fuel use was greater than or equal to 0.70 l/hr.
More than 95% of data that had engine speed less than 500 rpm had fuel use rates of less than or equal to 0.15 l/hr, which is inferred to be a condition of engine off.

To identify engine “startup” and “shutdown”, the remaining data were checked within their individual sequences of engine activity using forward differencing of engine speed ($\Delta$RPM$_i = $ RPM$_{i+1} - $ RPM$_i$). When engine transition was from “off” to “on”, $\Delta$RPM$_i$ was greater than 0. When engine transition was from “on” to “off”, $\Delta$RPM$_i$ was less than or equal to 0. Thus, the remaining seconds of data were defined as either “startup” or “shutdown,” depending on $\Delta$RPM$_i$.

Figure 45 and Figure 46 show the cumulative distributions of engine speed and fuel use, respectively, for engine “on”, “startup”, “shutdown”, and “off”. Even though the engine speed cutoff for “on” is as low as 500 rpm, less than 11% of engine “on” data had engine speed less than 1000 rpm, and less than 1% of engine “on” data had engine speed less than 900 rpm.
Figure 45 The Cumulative Distribution of Engine Speed for Engine “On”, Startup”, “Shutdown”, and “Off”, for All Vehicle Operation, Including Charge Depleting and Charge Sustaining Modes

*Note: Engine speed was 0 during engine “off”.*

Figure 46 The Cumulative Distribution of Engine Fuel Use for Engine “On”, “Startup”, “Shutdown”, and “Off”, for All Vehicle Operation, Including Charge Depleting and Charge Sustaining Modes

*Note: The scale for horizontal axis (Fuel Use (l/hr)) is logarithmic.*
For engine “off”, 100% of 1 Hz engine speed was 0, and 91% of 1 Hz fuel use was less than 0.1 l/hr. The OBD scan tool reports a fuel flow rate of as high as 0.15 l/hr even when the engine speed is 0. Thus, such values are inferred to be a de minimis level that is not significantly different than 0. In contrast, even though only 23% of “startup” data had engine speed greater than 100 rpm, 72% of “startup” data had fuel flow rate values between 0.15 l/hr and 0.7 l/hr. This range of fuel flow is substantially higher than the de minimis rate of engine “off”, but not as high as for engine “on”. Thus, the “startup” fuel flow rate represents a transition from “off” to “on”. For engine “on”, engine speed exceeded 500 rpm 100% of the time and exceeded 1000 rpm 90% of the time, while fuel flow rate exceeded 1.0 l/hr 93% of the time. Hence, engine “on” fuel flow rate was consistently higher than for the transition during startup.

“Shutdown” tended to have higher engine speed than “startup”, since prior to “shutdown” the engine had been running typically at over 1000 rpm. “Shutdown” appeared to involve fuel cut-off during which engine speed coasted down to 0. However, there are cases for which the engine restarted before it had fully shut off. Typically, “startup” took less time than “shutdown”. The amount of “shutdown” time was a factor of five greater than for “startup”. The average “startup” duration per engine start was 0.36 seconds, and the average
“shutdown” duration per engine shutdown was 2.06 seconds. This means for most engine starts, the engine switched directly from off to on.

### 3.6.1 Charge Depleting (CD) Mode

In this section, results are given for the PHEV operating in CD mode. The energy use and emission rates are evaluated in each VSP mode for both engine on and off for CD mode. The sample size for engine “shutdown” or “startup” was much smaller than “on” or “off”. Thus, energy use and pollutant mass emission rates for engine “shutdown” or “startup” are not included for CD mode. For both engine on and off, sample size in each VSP mode is shown in Table 16. There is no data point for VSP modes 13 and 14. For VSP modes 3 to 12, sample size decreases with increasing VSP modes for both engine on and off. In CD mode, engine on accounts for only 12% of total time.

For engine on, the total energy use and emissions include upstream energy use and emissions for gasoline production (including crude oil recovery and transportation, and gasoline refining, transportation and distribution), direct gasoline consumption and tailpipe emissions, energy use from regenerative braking (there is no emission related to regenerative braking), and indirect energy use and emissions for electricity production (including feedstock recovery, production and transportation, and electricity generation and transmission). For
engine off, the total energy use and emissions include energy use from regenerative braking, and indirect energy use and emissions for electricity production.

Table 16 The Travel Time Spent in Each Vehicle Specific Power (VSP) Mode for Charge Depleting (CD) Mode During Engine On and Off for a 2013 Toyota Prius Plug-In Hybrid Measured from January 18, 2013 to January 25, 2013 in Raleigh/Research Triangle Park, North Carolina Area

<table>
<thead>
<tr>
<th>VSP Mode</th>
<th>Engine On (s)</th>
<th>Engine Off (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>99</td>
<td>2270</td>
</tr>
<tr>
<td>2</td>
<td>59</td>
<td>1191</td>
</tr>
<tr>
<td>3</td>
<td>1165</td>
<td>5098</td>
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<tr>
<td>4</td>
<td>167</td>
<td>1973</td>
</tr>
<tr>
<td>5</td>
<td>139</td>
<td>1695</td>
</tr>
<tr>
<td>6</td>
<td>115</td>
<td>1009</td>
</tr>
<tr>
<td>7</td>
<td>101</td>
<td>719</td>
</tr>
<tr>
<td>8</td>
<td>31</td>
<td>480</td>
</tr>
<tr>
<td>9</td>
<td>31</td>
<td>228</td>
</tr>
<tr>
<td>10</td>
<td>42</td>
<td>126</td>
</tr>
<tr>
<td>11</td>
<td>19</td>
<td>54</td>
</tr>
<tr>
<td>12</td>
<td>1</td>
<td>11</td>
</tr>
<tr>
<td>13</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>14</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>All</td>
<td>1969</td>
<td>14854</td>
</tr>
</tbody>
</table>
Figure 47 shows the energy use rate versus VSP mode for engine on and off for CD mode. For engine on, total energy use is mainly from direct gasoline consumption. For engine off, total energy use is mainly from indirect energy use for electricity production. Total energy use rates for engine on and off increase approximately with increasing VSP modes. For VSP modes 1 to 6, energy use rates are larger for engine on, relative to engine off. For VSP modes 7 to 12, energy use rates are not significantly different between engine on and off. Thus, when the PHEV operates under the lower power demand in CD mode, it is more energy-efficient to operate solely on electricity.

Negative electricity use rates mean that the TB is recharged by either regenerative braking or excess energy from the ICE. For engine on, the TB was found to be recharged in VSP modes 1 to 4. For engine off, the TB was found to be recharged in VSP modes 1 and 2. For VSP modes 1 and 2, the recharging rates are lower for engine on, compared to engine off. The discharging rates are lower for engine on, compared to engine off for VSP modes 5 to 10. Graver et al. also found that recharging and discharging rates of the TB are lower when the engine is on.\textsuperscript{11} The TB discharging rates are within a small range, signifying a limited discharging rate.
Figure 47 The Energy Use Rate Versus Vehicle Specific Power (VSP) Mode for Engine On and Off for Charge Depleting (CD) Mode for a 2013 Toyota Prius Plug-In Hybrid Measured from January 18, 2013 to January 25, 2013 in Raleigh/Research Triangle Park, North Carolina Area, Based on North Carolina Electric Power

Note: Error bars indicate 95% confidence intervals on the mean based on second-by-second variability in total energy use. Sample size in each VSP mode is shown in Table 16. There is no data point for VSP modes 13 and 14. For engine on, the total energy use includes upstream energy use for gasoline production (including crude oil recovery and transportation, and gasoline refining, transportation and distribution), direct gasoline consumption, energy use from regenerative braking, and indirect energy use for electricity production (including feedstock recovery, production and transportation, and electricity generation and transmission). For engine off, the total energy use includes energy use from regenerative braking, and indirect energy use for electricity production.
Figure 48 shows the CO$_2$ emission rate versus VSP mode for engine on and off for CD mode. For engine on, the total CO$_2$ emission rate is mainly from direct tailpipe emissions. For engine off, the total CO$_2$ emission rate is only from indirect emissions for electricity production. Total CO$_2$ emission rates for engine on and off increase approximately with increasing VSP modes. For VSP modes 1 to 10, CO$_2$ emission rates are larger for engine on by more than 40%, relative to engine off. For VSP modes 11 and 12, CO$_2$ emission rates are not significantly different between engine on and off. Thus, when the PHEV operates solely on electricity in CD mode, its CO$_2$ emissions are lower.

Figure 49 shows the CO emission rate versus VSP mode for engine on and off for CD mode. For engine on, the total CO emission rate is mainly from upstream emissions from gasoline production and direct tailpipe emissions. For engine off, the total CO emission rate is only from indirect emissions for electricity production. For engine on, CO emission rates increase approximately with increasing VSP modes from modes 4 to 9. For engine off, CO emission rates increase approximately with increasing VSP modes. For VSP modes 1 to 9, CO emission rates are larger for engine on by more than 44%, relative to engine off. For VSP modes 10 to 12, CO emission rates are not significantly different between engine on and off. Thus, when the PHEV operates solely on electricity in CD mode, its CO emissions are lower.
Figure 48 The Carbon Dioxide (CO₂) Emission Rate Versus Vehicle Specific Power (VSP) Mode for Engine On and Off for Charge Depleting (CD) Mode for a 2013 Toyota Prius Plug-In Hybrid Measured from January 18, 2013 to January 25, 2013 in Raleigh/Research Triangle Park, North Carolina Area, Based on North Carolina Electric Power

**Note:** Error bars indicate 95% confidence intervals on the mean based on second-by-second variability in total emission. Sample size in each VSP mode is shown in Table 16. There is no data point for VSP modes 13 and 14. For engine on, the total CO₂ emission includes upstream emission for gasoline production (including crude oil recovery and transportation, and gasoline refining, transportation and distribution), direct tailpipe emission, and indirect emission for electricity production (including feedstock recovery, production and transportation, and electricity generation and transmission). For engine off, the total CO₂ emission includes indirect emission for electricity production.
Figure 49 The Carbon Monoxide (CO) Emission Rate Versus Vehicle Specific Power (VSP) Mode for Engine On and Off for Charge Depleting (CD) Mode for a 2013 Toyota Prius Plug-In Hybrid Measured from January 18, 2013 to January 25, 2013 in Raleigh/Research Triangle Park, North Carolina Area, Based on North Carolina Electric Power

Note: Error bars indicate 95% confidence intervals on the mean based on second-by-second variability in total emission. Sample size in each VSP mode is shown in Table 16. There is no data point for VSP modes 13 and 14. For engine on, the total CO emission includes upstream emission for gasoline production (including crude oil recovery and transportation, and gasoline refining, transportation and distribution), direct tailpipe emission, and indirect emission for electricity production (including feedstock recovery, production and transportation, and electricity generation and transmission). For engine off, the total CO emission includes indirect emission for electricity production.
Figure 50 shows the HC emission rate versus VSP mode for engine on and off for CD mode. For engine on, the total HC emission rate is mainly from upstream emissions from gasoline production. For engine off, the total HC emission rate is only from indirect emissions for electricity production. Total HC emission rates for engine on and off increase approximately with increasing VSP modes. For VSP modes 1 to 12, HC emission rates are larger for engine on by more than 4.4 times, relative to engine off. Thus, when the PHEV operates solely on electricity in CD mode, its HC emissions are lower.

Figure 51 shows the NO\textsubscript{x} emission rate versus VSP mode for engine on and off for CD mode. For engine on, the total NO\textsubscript{x} emission rate is mainly from upstream emissions for gasoline production. For engine off, the total NO\textsubscript{x} emission rate is only from indirect emissions for electricity production. Total NO\textsubscript{x} emission rates for engine on and off increase approximately with increasing VSP modes. For VSP modes 1 to 6, NO\textsubscript{x} emission rates are larger for engine on by more than 17%, relative to engine off. For VSP modes 7 to 12, NO\textsubscript{x} emission rates are not significantly different between engine on and off. Thus, when the PHEV operates solely on electricity in CD mode, its NO\textsubscript{x} emissions are lower.
Figure 50 The Hydrocarbon (HC) Emission Rate Versus Vehicle Specific Power (VSP) Mode for Engine On and Off for Charge Depleting (CD) Mode for a 2013 Toyota Prius Plug-In Hybrid Measured from January 18, 2013 to January 25, 2013 in Raleigh/Research Triangle Park, North Carolina Area, Based on North Carolina Electric Power

Note: Error bars indicate 95% confidence intervals on the mean based on second-by-second variability in total emission. Sample size in each VSP mode is shown in Table 16. There is no data point for VSP modes 13 and 14. For engine on, the total HC emission includes upstream emission for gasoline production (including crude oil recovery and transportation, and gasoline refining, transportation and distribution), direct tailpipe emission, and indirect emission for electricity production (including feedstock recovery, production and transportation, and electricity generation and transmission). For engine off, the total HC emission includes indirect emission for electricity production.
Figure 51 The Oxide of Nitrogen (NO$_x$) Emission Rate Versus Vehicle Specific Power (VSP) Mode for Engine On and Off for Charge Depleting (CD) Mode for a 2013 Toyota Prius Plug-In Hybrid Measured from January 18, 2013 to January 25, 2013 in Raleigh/Research Triangle Park, North Carolina Area, Based on North Carolina Electric Power.

Note: Error bars indicate 95% confidence intervals on the mean based on second-by-second variability in total emission. Sample size in each VSP mode is shown in Table 16. There is no data point for VSP modes 13 and 14. For engine on, the total NO$_x$ emission includes upstream emission for gasoline production (including crude oil recovery and transportation, and gasoline refining, transportation and distribution), direct tailpipe emission, and indirect emission for electricity production (including feedstock recovery, production and transportation, and electricity generation and transmission). For engine off, the total NO$_x$ emission includes indirect emission for electricity production.
Figure 52 shows the SO\(_x\) emission rate versus VSP mode for engine on and off for CD mode. For engine on, the total SO\(_x\) emission rate is mainly from upstream emissions from gasoline production. For engine off, the total SO\(_x\) emission rate is only from indirect emissions for electricity production. Total SO\(_x\) emission rates for engine on and off increase approximately with increasing VSP modes. For VSP modes 1 to 6, SO\(_x\) emission rates do not differ much between engine on and off. For VSP modes 7 to 12, SO\(_x\) emission rates are smaller for engine on, relative to engine off.

Figure 53 shows the PM\(_{2.5}\) emission rate versus VSP mode for engine on and off for CD mode. For engine on, the total PM\(_{2.5}\) emission rate is mainly from upstream emissions for gasoline production. For engine off, the total PM\(_{2.5}\) emission rate is only from indirect emissions for electricity production. Total PM\(_{2.5}\) emission rates for engine on and off increase approximately with increasing VSP modes. For VSP modes 1 to 6, PM\(_{2.5}\) emission rates do not differ much between engine on and off. For VSP modes 7 to 12, PM\(_{2.5}\) emission rates are smaller for engine on, relative to engine off.

Figure 54 shows the PM\(_{10}\) emission rate versus VSP mode for engine on and off for CD mode. For engine on, the total PM\(_{10}\) emission rate is mainly from upstream emissions from gasoline production. For engine off, the total PM\(_{10}\) emission rate is only from indirect
emissions for electricity production. Total PM$_{10}$ emission rates for engine on and off increase approximately with increasing VSP modes. For VSP modes 1 to 6, PM$_{10}$ emission rates do not differ much between engine on and off. For VSP modes 7 to 12, PM$_{10}$ emission rates are smaller for engine on, relative to engine off.

Figure 52 The Oxide of Sulfur (SO$_x$) Emission Rate Versus Vehicle Specific Power (VSP) Mode for Engine On and Off for Charge Depleting (CD) Mode for a 2013 Toyota Prius Plug-In Hybrid Measured from January 18, 2013 to January 25, 2013 in Raleigh/Research Triangle Park, North Carolina Area, Based on North Carolina Electric Power

Note: Error bars indicate 95% confidence intervals on the mean based on second-by-second variability in total emission. Sample size in each VSP mode is shown in Table 16. There is no data point for VSP modes 13 and 14. For engine on, the total SO$_x$ emission includes upstream emission for gasoline production (including crude oil recovery and transportation, and gasoline refining, transportation and distribution), direct tailpipe emission (which are calculated by gasoline use rate and the maximum sulfur concentration of gasoline), and indirect emission for electricity production (including feedstock recovery, production and transportation, and electricity generation and transmission). For engine off, the total SO$_x$ emission includes indirect emission for electricity production.
Figure 53 The Particulate Matter with Diameters of 2.5 Micrometers or Less (PM$_{2.5}$) Emission Rate Versus Vehicle Specific Power (VSP) Mode for Engine On and Off for Charge Depleting (CD) Mode for a 2013 Toyota Prius Plug-In Hybrid Measured from January 18, 2013 to January 25, 2013 in Raleigh/Research Triangle Park, North Carolina Area, Based on North Carolina Electric Power

Note: Error bars indicate 95% confidence intervals on the mean based on second-by-second variability in total emission. Sample size in each VSP mode is shown in Table 16. There is no data point for VSP modes 13 and 14. For engine on, the total PM$_{2.5}$ emission includes upstream emission for gasoline production (including crude oil recovery and transportation, and gasoline refining, transportation and distribution), direct tailpipe emission (which are not measured during the measurement and are assumed as 0), and indirect emission for electricity production (including feedstock recovery, production and transportation, and electricity generation and transmission). For engine off, the total PM$_{2.5}$ emission includes indirect emission for electricity production.
Figure 54 The Particulate Matter with Diameters of 10 Micrometers or Less (PM$_{10}$) Emission Rate Versus Vehicle Specific Power (VSP) Mode for Engine On and Off for Charge Depleting (CD) Mode for a 2013 Toyota Prius Plug-In Hybrid Measured from January 18, 2013 to January 25, 2013 in Raleigh/Research Triangle Park, North Carolina Area, Based on North Carolina Electric Power

Note: Error bars indicate 95% confidence intervals on the mean based on second-by-second variability in total emission. Sample size in each VSP mode is shown in Table 16. There is no data point for VSP modes 13 and 14. For engine on, the total PM$_{10}$ emission includes upstream emission for gasoline production (including crude oil recovery and transportation, and gasoline refining, transportation and distribution), direct tailpipe emission (which are not measured during the measurement and are assumed as 0), and indirect emission for electricity production (including feedstock recovery, production and transportation, and electricity generation and transmission). For engine off, the total PM$_{10}$ emission includes indirect emission for electricity production.
3.6.2 Charge Sustaining (CS) Mode

In this section, results are given for PHEV operation in CS mode. Energy use and emission rates are evaluated in each VSP mode for both engine on and off for CS mode. The sample size for engine “shutdown” or “startup” was much smaller than “on” or “off”. Thus, energy use and pollutant mass emission rates for engine “shutdown” or “startup” are not included for CS mode. For both engine on and off, sample size in each VSP mode is shown in Table 17.

In CS mode, engine on time accounts for 45% of total time. Engine on time accounts for 91% of time spent in VSP modes 5 to 14. This means that engine tends to turn on when there is moderate to high power demand.

For engine on, the total energy use and emission rates include upstream energy use and emission rates for gasoline production (including crude oil recovery and transportation, and gasoline refining, transportation and distribution), direct gasoline consumption and tailpipe emission rates, and energy use rates from regenerative braking. For engine off, the total energy use rate includes energy use from regenerative braking. There is no emission when engine is off for CS mode. This is because the energy stored in the traction battery that is used in these situations is either from regenerative braking or from prior ICE operation, for which emissions occurred and were accounted for.
Table 17 The Travel Time Spent in Each Vehicle Specific Power (VSP) Mode for Charge Sustaining (CS) Mode During Engine On and Off for a 2013 Toyota Prius Plug-In Hybrid Measured from January 18, 2013 to January 25, 2013 in Raleigh/Research Triangle Park, North Carolina Area

<table>
<thead>
<tr>
<th>VSP Mode</th>
<th>Engine On (s)</th>
<th>Engine Off (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3482</td>
<td>12300</td>
</tr>
<tr>
<td>2</td>
<td>1289</td>
<td>5083</td>
</tr>
<tr>
<td>3</td>
<td>1819</td>
<td>36360</td>
</tr>
<tr>
<td>4</td>
<td>4338</td>
<td>5262</td>
</tr>
<tr>
<td>5</td>
<td>7463</td>
<td>2434</td>
</tr>
<tr>
<td>6</td>
<td>8739</td>
<td>1094</td>
</tr>
<tr>
<td>7</td>
<td>7928</td>
<td>402</td>
</tr>
<tr>
<td>8</td>
<td>6341</td>
<td>130</td>
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<tr>
<td>9</td>
<td>3875</td>
<td>34</td>
</tr>
<tr>
<td>10</td>
<td>2917</td>
<td>5</td>
</tr>
<tr>
<td>11</td>
<td>1834</td>
<td>0</td>
</tr>
<tr>
<td>12</td>
<td>724</td>
<td>1</td>
</tr>
<tr>
<td>13</td>
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<td>0</td>
</tr>
<tr>
<td>14</td>
<td>45</td>
<td>0</td>
</tr>
<tr>
<td>All</td>
<td>51019</td>
<td>63105</td>
</tr>
</tbody>
</table>
Figure 55 shows the energy use rate versus VSP mode for engine on and off for CS mode. For engine on, total energy use is mainly from direct gasoline consumption. For engine off, total energy use is from regenerative braking for VSP modes 1 and 2. Total energy use rates for engine on and off increase with increasing VSP modes. For VSP modes 1 to 9, energy use rates are larger for engine on, relative to engine off. For VSP modes 10 to 14, there is either no data point, or very few data points for engine off.

Negative electricity use rate from regenerative braking in VSP modes 1 and 2 is a result either of TB recharging by regenerative braking or excess energy from the ICE. For both engine on and off, the TB can be recharged in VSP modes 1 and 2. For VSP modes 1 and 2, the recharging rates are lower for engine on, compared to engine off. The discharging rates are lower for engine on, compared to engine off for VSP modes 3 to 9. Graver et al. also found that recharging and discharging rates of the TB are lower when the engine is on.\textsuperscript{11}

Figure 56 shows the CO$_2$ emission rate versus VSP mode for engine on for CS mode. There is no CO$_2$ emission when the engine is off in CS mode. For engine on, total CO$_2$ emissions are mainly from direct tailpipe emissions. Approximately 15\% of the total CO$_2$ emissions are from upstream gasoline production. Total CO$_2$ emission rates increase with increasing positive VSP modes.
Figure 55 The Energy Use Rate Versus Vehicle Specific Power (VSP) Mode for Engine On and Off for Charge Sustaining (CS) Mode for a 2013 Toyota Prius Plug-In Hybrid Measured from January 18, 2013 to January 25, 2013 in Raleigh/Research Triangle Park, North Carolina Area, Based on North Carolina Electric Power

Note: Error bars indicate 95% confidence intervals on the mean based on second-by-second variability in total energy use. Sample size in each VSP mode is shown in Table 17. There is no data point for engine off in VSP modes 11, 13 and 14. For VSP modes 10 and 12, there were only 5 seconds and 1 second of engine off data, which are not shown. For engine on, the total energy use includes upstream energy use for gasoline production (including crude oil recovery and transportation, and gasoline refining, transportation and distribution), direct gasoline consumption, and energy use from regenerative braking. For engine off, the total energy use includes energy use from regenerative braking.
Figure 56 The Carbon Dioxide (CO₂) Emission Rate Versus Vehicle Specific Power (VSP) Mode for Engine On for Charge Sustaining (CS) Mode for a 2013 Toyota Prius Plug-In Hybrid Measured from January 18, 2013 to January 25, 2013 in Raleigh/Research Triangle Park, North Carolina Area, Based on North Carolina Electric Power

Note: Error bars indicate 95% confidence intervals on the mean based on second-by-second variability in total emission. Sample size in each VSP mode is shown in Table 17. For engine on, the total CO₂ emission includes upstream emission for gasoline production (including crude oil recovery and transportation, and gasoline refining, transportation and distribution), and direct tailpipe emission. For engine off, there is no emission.
The relationships between emission rates versus VSP mode for engine on for CS mode are shown in Figure 57 for CO, Figure 58 for HC, Figure 59 for NO\textsubscript{x}, Figure 60 for SO\textsubscript{x}, Figure 61 for PM\textsubscript{2.5}, and Figure 62 for PM\textsubscript{10}. These pollutants are not emitted when the engine is off in CS mode. For engine on, the total CO, HC, NO\textsubscript{x}, and SO\textsubscript{x} emissions are mainly from upstream emissions for gasoline production, which are related to the amount of gasoline consumed during measurement. Thus, the total CO, HC, NO\textsubscript{x}, SO\textsubscript{x}, PM\textsubscript{2.5} and PM\textsubscript{10} emission rates increase approximately with increasing VSP modes. Since PM\textsubscript{2.5} and PM\textsubscript{10} emissions are not measured, and since direct PM emissions from gasoline vehicles are very low,\textsuperscript{13} PM\textsubscript{2.5} and PM\textsubscript{10} emissions are assumed to be only from upstream emissions for gasoline production.
Figure 57 The Carbon Monoxide (CO) Emission Rate Versus Vehicle Specific Power (VSP) Mode for Engine On for Charge Sustaining (CS) Mode for a 2013 Toyota Prius Plug-In Hybrid Measured from January 18, 2013 to January 25, 2013 in Raleigh/Research Triangle Park, North Carolina Area, Based on North Carolina Electric Power

Note: Error bars indicate 95% confidence intervals on the mean based on second-by-second variability in total emission. Sample size in each VSP mode is shown in Table 17. For engine on, the total CO emission includes upstream emission for gasoline production (including crude oil recovery and transportation, and gasoline refining, transportation and distribution), and direct tailpipe emission. For engine off, there is no emission.
Figure 58 The Hydrocarbon (HC) Emission Rate Versus Vehicle Specific Power (VSP) Mode for Engine On for Charge Sustaining (CS) Mode for a 2013 Toyota Prius Plug-In Hybrid Measured from January 18, 2013 to January 25, 2013 in Raleigh/Research Triangle Park, North Carolina Area, Based on North Carolina Electric Power

Note: Error bars indicate 95% confidence intervals on the mean based on second-by-second variability in total emission. Sample size in each VSP mode is shown in Table 17. For engine on, the total HC emission includes upstream emission for gasoline production (including crude oil recovery and transportation, and gasoline refining, transportation and distribution), and direct tailpipe emission. For engine off, there is no emission.
Figure 59 The Oxide of Nitrogen (NO$_x$) Emission Rate Versus Vehicle Specific Power (VSP) Mode for Engine for Charge Sustaining (CS) Mode for a 2013 Toyota Prius Plug-In Hybrid Measured from January 18, 2013 to January 25, 2013 in Raleigh/Research Triangle Park, North Carolina Area, Based on North Carolina Electric Power

*Note: Error bars indicate 95% confidence intervals on the mean based on second-by-second variability in total emission. Sample size in each VSP mode is shown in Table 17. For engine on, the total NO$_x$ emission includes upstream emission for gasoline production (including crude oil recovery and transportation, and gasoline refining, transportation and distribution), and direct tailpipe emission. For engine off, there is no emission.*
Figure 60: The Oxide of Sulfur (SO₃) Emission Rate Versus Vehicle Specific Power (VSP) Mode for Engine On for Charge Sustaining (CS) Mode for a 2013 Toyota Prius Plug-In Hybrid Measured from January 18, 2013 to January 25, 2013 in Raleigh/Research Triangle Park, North Carolina Area, Based on North Carolina Electric Power

Note: Error bars indicate 95% confidence intervals on the mean based on second-by-second variability in total emission. Sample size in each VSP mode is shown in Table 17. For engine on, the total SO₃ emission includes upstream emission for gasoline production (including crude oil recovery and transportation, and gasoline refining, transportation and distribution), and direct tailpipe emission (which are calculated by gasoline use rate and the maximum sulfur concentration of gasoline). For engine off, there is no emission.
Figure 61 The Particulate Matter with Diameters of 2.5 Micrometers or Less (PM$_{2.5}$) Emission Rate Versus Vehicle Specific Power (VSP) Mode for Engine On for Charge Sustaining (CS) Mode for a 2013 Toyota Prius Plug-In Hybrid Measured from January 18, 2013 to January 25, 2013 in Raleigh/Research Triangle Park, North Carolina Area, Based on North Carolina Electric Power

Note: Error bars indicate 95% confidence intervals on the mean based on second-by-second variability in total emission. Sample size in each VSP mode is shown in Table 17. For engine on, the total PM$_{2.5}$ emission includes upstream emission for gasoline production (including crude oil recovery and transportation, and gasoline refining, transportation and distribution), and direct tailpipe emission (which are not measured during the measurement and are assumed as 0). For engine off, there is no emission.
Figure 62 The Particulate Matter with Diameters of 10 Micrometers or Less (PM$_{10}$) Emission Rate Versus Vehicle Specific Power (VSP) Mode for Engine On for Charge Sustaining (CS) Mode for a 2013 Toyota Prius Plug-In Hybrid Measured from January 18, 2013 to January 25, 2013 in Raleigh/Research Triangle Park, North Carolina Area, Based on North Carolina Electric Power

Note: Error bars indicate 95% confidence intervals on the mean based on second-by-second variability in total emission. Sample size in each VSP mode is shown in Table 17. For engine on, the total PM$_{2.5}$ emission includes upstream emission for gasoline production (including crude oil recovery and transportation, and gasoline refining, transportation and distribution), and direct tailpipe emission (which are not measured during the measurement and are assumed as 0). For engine off, there is no emission.
The fraction of the total CO emissions from upstream gasoline production is 71%. As shown in Table 7, 81% of upstream CO emissions are from crude oil recovery, feed inputs for gasoline production and intermediate products combustion during gasoline production. The feed inputs include residual oil, natural gas, butane, electricity, and hydrogen, and inputs of feedstocks other than crude oil. The intermediate products for combustion are pet coke and refinery still gas.\(^1\)

The fraction of the total HC emissions from upstream gasoline production is 91%. As shown in Table 7, 80% of upstream HC emissions are from feed inputs for gasoline production and non-combustion process during gasoline production. Non-combustion process includes crude cracking (both thermal and catalytic), hydrocarbon reforming, catalyst regeneration, sulfur recovery, and blowdown systems.

The fraction of the total NO\(_x\) emissions from upstream gasoline production is 97%. As shown in Table 7, 88% of upstream NO\(_x\) emissions are from crude oil recovery and transportation, feed inputs for gasoline production and intermediate products combustion during gasoline production.
The fraction of the total SO\textsubscript{x} emissions from upstream gasoline production is 97%. As shown in Table 7, 79% of upstream SO\textsubscript{x} emissions are from crude oil transportation, feed inputs for gasoline production and intermediate products combustion during gasoline production.

3.7 Cold Start and Hot Stabilized Running

The purpose of this section is to quantify the sensitivity of fuel use and direct tailpipe emissions of PHEVs to cold start and hot stabilized running when the engine is on. Cold start is associated with low coolant and catalyst temperature and with high emission rates of products of incomplete combustion, such as CO and HC. Therefore, cold start was identified based on \( T_{EC} \), \( T_{cat} \), CO and HC concentrations. As an example of trends and relationships for these variables, second-by-second \( T_{EC} \), \( T_{cat} \), and concentrations of CO and HC measured on January 21, 2013, are shown in Figure 63, Figure 64, Figure 65, and Figure 66, respectively.

When the vehicle was at ambient temperature, \( T_{EC} \) and \( T_{cat} \) were approximately 20 °C. Initially during a cold start, the CO emission rate was approximately 150 mg/s, and HC emission rate was approximately 2.5 mg/s. When the vehicle was hot stabilized, \( T_{EC} \) was around 90 °C, \( T_{cat} \) was around 600 °C. The peak CO emission rate during hot stabilized operation was approximately 57% lower than the peak rates during cold start, and the peak HC emission rate was approximately 66% lower. Cold start was defined as when engine
turned on in condition of $T_{EC}$ less than 90 °C and $T_{cat}$ less than 600 °C. For $T_{EC}$ and $T_{cat}$ less than these values, the CO and HC emission rates were significantly greater, compared to hot stabilized emission rates.

Figure 63 Second-by-Second the Engine Coolant Temperature Data for a 2013 Toyota Prius Plug-In Hybrid Measured on January 21, 2013 in Raleigh/Research Triangle Park, North Carolina Area (S# indicates an engine start.)
Figure 64 Second-by-Second the Catalyst Temperature Data for a 2013 Toyota Prius Plug-In Hybrid Measured on January 21, 2013 in Raleigh/Research Triangle Park, North Carolina Area (S# indicates an engine start.)

Figure 65 Second-by-Second the Carbon Monoxide (CO) Concentration Data for a 2013 Toyota Prius Plug-In Hybrid Measured on January 21, 2013 in Raleigh/Research Triangle Park, North Carolina Area (S# indicates an engine start.)
Figure 66 Second-by-Second the Hydrocarbons (HC) Concentration Data for a 2013 Toyota Prius Plug-In Hybrid Measured on January 21, 2013 in Raleigh/Research Triangle Park, North Carolina Area (S# indicates an engine start.)

There were periods during which both $T_{EC}$ and $T_{cat}$ dropped as a result of extended engine shutoff, which might cause partial cold start. However, the engine startup after short periods of engine off activity during hot stabilized operation had little or no effect on the CO and HC emission. Therefore, only the first few engine start events were classified as cold start. For example, only the first four engine starts were counted as cold start for the measurement on January 21, 2013, including the three engine starts in CD mode and the first engine start in CS mode. Figure 67 shows that cold start has little or no effect on the NO$_x$ emission rate for this particular vehicle.
Figure 67 Second-by-Second the Oxide of Nitrogen (NO$_x$) Concentration Data for a 2013 Toyota Prius Plug-In Hybrid Measured on January 21, 2013 in Raleigh/Research Triangle Park, North Carolina Area (S# indicates an engine start.)

3.7.1 Cycle Average Energy Use and Emission Rates

To quantify the sensitivity of fuel use and direct tailpipe emissions of PHEVs to cold start and hot stabilized running when the engine is on, cycle average fuel use and direct tailpipe emission rates for cold start and for hot stabilized running were quantified. The driving cycle used was estimated in terms of the average travel time spent in each VSP mode for an average cold start. There were 14 cold start events that occurred during measurement. In total, there were 2440 seconds in cold starts, with an average of 174 seconds per cold start.
The number of seconds in each VSP mode for an average cold start cycle is shown in Table 18.

Figure 68 shows the cycle average energy use and direct tailpipe emission rates for cold start and hot stabilized running based on average cold start cycle. The TB discharging rates for cold start and hot stabilized running are not significantly different. The average fuel use and direct tailpipe CO₂ emission rates for cold start are 13% less than those for hot stabilized running. The average direct tailpipe CO emission rate for cold start is 4.5 times greater than that for hot stabilized running. The average direct tailpipe HC emission rate for cold start is 6.2 times greater than that for hot stabilized running. The higher CO and HC emission rates during cold start might be in part caused by the catalytic converter being ineffective at controlling emissions of CO, and HC.¹⁴,¹⁵,¹⁶ The TB discharging and tailpipe NOₓ emission rates are not significantly different between cold start and hot stabilized running.
Table 18 The Average Cold Start Cycle Time Distribution Versus Vehicle Specific Power (VSP) Mode

<table>
<thead>
<tr>
<th>VSP Mode</th>
<th>Number of Seconds in an Average Cold Start Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9</td>
</tr>
<tr>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td>3</td>
<td>102</td>
</tr>
<tr>
<td>4</td>
<td>16</td>
</tr>
<tr>
<td>5</td>
<td>11</td>
</tr>
<tr>
<td>6</td>
<td>13</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>9</td>
<td>3</td>
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<td>0</td>
</tr>
<tr>
<td>13</td>
<td>0</td>
</tr>
<tr>
<td>14</td>
<td>0</td>
</tr>
</tbody>
</table>

Note: For VSP modes 13 and 14, there is no data point, and for VSP 12, there are 0.14 seconds of data, shown as 0. There were 14 cold start events occurred during measurement. In total, there were 2440 seconds in cold starts, with an average of 174 seconds per cold start.
Figure 68 Cycle Average Energy Use and Direct Tailpipe Emission Rates for Cold Start and Hot Stabilized Running Based on Average Cold Start Cycle

Note: Error bars indicate 95% confidence intervals on the mean based on vehicle specific power (VSP) based modal energy use and direct tailpipe emission rates and average cold start cycle time fraction in each VSP mode. Numbers of seconds in average cold start cycle in each VSP mode are shown in Table 18. The variability on cycle average energy use and direct tailpipe emission rates comes from the variability of the VSP-based modal energy use and direct tailpipe emission rates.
3.7.2 Energy Use and Emission Rates Versus Vehicle Specific Power (VSP)

To quantify the sensitivity of engine on energy use and direct tailpipe emission rates to variation in power demand for cold start and hot stabilized running, the energy use and emission rates are evaluated in each VSP mode. For both cold start and hot stabilized running, the sample size in each VSP mode is shown in Table 19. There are no data for cold start in VSP modes 13 and 14. The sample size for cold start is much smaller than for hot stabilized running in each VSP mode. Thus, the confidence intervals on the modal mean energy use and emission rates for cold start are wider than for hot stabilized running.

Figure 69 shows the TB discharging rate versus VSP mode for cold start and engine on hot stabilized running. For both cold start and hot stabilized running, the TB is recharged from regenerative braking for VSP modes 1 and 2. For VSP modes 3 and 14, the TB is discharging. For cold start, the TB discharging rate increases approximately from VSP modes 3 to 5, and the mean values for VSP modes 6 to 9 are approximately the same. For hot stabilized running, the TB discharging rate increases approximately from VSP modes 3 to 6, and the mean values for VSP modes 7 to 14 range from 0.61 to 0.97 Wh/s. The similarity in discharge rate among these modes implies that the discharge rate may be controlled within a limiting upper bound. For VSP modes 5, and 10 to 12, the differences of TB discharging
rates between cold start and hot stabilized running are statistically significant. For other VSP modes, the differences are not statistically significant.

Table 19 The Total Travel Time Spent in Each Vehicle Specific Power (VSP) Mode for Cold Start and Hot Stabilized Running During Engine On for a 2013 Toyota Prius Plug-In Hybrid Measured from January 18, 2013 to January 25, 2013 in Raleigh/Research Triangle Park, North Carolina Area

<table>
<thead>
<tr>
<th>VSP Mode</th>
<th>Hot Stabilized Running (s)</th>
<th>Cold Start (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3451</td>
<td>130</td>
</tr>
<tr>
<td>2</td>
<td>1249</td>
<td>99</td>
</tr>
<tr>
<td>3</td>
<td>1556</td>
<td>1428</td>
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<tr>
<td>4</td>
<td>4278</td>
<td>227</td>
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<tr>
<td>5</td>
<td>7454</td>
<td>148</td>
</tr>
<tr>
<td>6</td>
<td>8676</td>
<td>178</td>
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<tr>
<td>7</td>
<td>7932</td>
<td>97</td>
</tr>
<tr>
<td>8</td>
<td>6333</td>
<td>39</td>
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<tr>
<td>9</td>
<td>3863</td>
<td>43</td>
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<td>10</td>
<td>2924</td>
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<td>11</td>
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<td>14</td>
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<tr>
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<tr>
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<td>0</td>
</tr>
<tr>
<td>14</td>
<td>45</td>
<td>0</td>
</tr>
</tbody>
</table>
Figure 69 The Average Traction Battery (TB) Discharging Rate Versus Vehicle Specific Power (VSP) Mode for Cold Start and Hot Stabilized Running During Engine On for a 2013 Toyota Prius Plug-In Hybrid Measured from January 18, 2013 to January 25, 2013 in Raleigh/Research Triangle Park, North Carolina Area

Note: There is no data point for cold start in VSP modes 13 and 14, and the value for VSP modes 10 to 12 is 0. Error bars indicate 95% confidence intervals on the mean based on second-by-second variability. Sample size in each VSP mode is shown in Table 19. For VSP modes 5, and 10 to 12, the differences of TB discharging rates between cold start and hot stabilized running, are statistically significant, and for other VSP modes, the differences are not statistically significant.
Figure 70 shows the direct fuel use rate versus VSP mode for cold start and hot stabilized running during engine on. For both cold start and hot stabilized running, fuel use rate increases monotonically over the positive VSP modes. For VSP modes 2 to 4, 7, 9, 10, and 12, the differences of fuel use rates between cold start and hot stabilized running are statistically significant. For other VSP modes, the differences are not statistically significant.

Note: There is no data point for cold start in VSP modes 13 and 14. Error bars indicate 95% confidence intervals on the mean based on second-by-second variability. Sample size in each VSP mode is shown in Table 19. For VSP modes 2 to 4, 7, 9, 10, and 12, the differences of fuel use rates between cold start and hot stabilized running, are statistically significant, and for other VSP modes, the differences are not statistically significant.
Figure 71 shows the tailpipe CO\textsubscript{2} emission rate versus VSP mode for cold start and hot stabilized running during engine on. For both cold start and hot stabilized running, tailpipe CO\textsubscript{2} emission rate increases approximately with increasing VSP modes. For VSP modes 2 to 4, 7, 9, 10, and 12, the differences of tailpipe CO\textsubscript{2} emission rates between cold start and hot stabilized running are statistically significant. For other VSP modes, the differences are not statistically significant.

![Figure 71 The Average Tailpipe Carbon Dioxide (CO\textsubscript{2}) Emission Rate Versus Vehicle Specific Power (VSP) Mode for Cold Start and Hot Stabilized Running During Engine On for a 2013 Toyota Prius Plug-In Hybrid Measured from January 18, 2013 to January 25, 2013 in Raleigh/Research Triangle Park, North Carolina Area](image)

Note: There is no data point for cold start in VSP modes 13 and 14. Error bars indicate 95% confidence intervals on the mean based on second-by-second variability. Sample size in each VSP mode is shown in Table 19. For VSP modes 2 to 4, 7, 9, 10, and 12, the differences of CO\textsubscript{2} emission rates between cold start and hot stabilized running, are statistically significant, and for other VSP modes, the differences are not statistically significant.
Figure 72 shows the tailpipe CO emission rate versus VSP mode for cold start and hot stabilized running during engine on. There is not a clear trend in modal average rates versus VSP mode for either cold start or hot stabilized running. The values for CO concentrations for 76% of cold start time are lower than the gas analyzer detection limit, 0.008%. The values for CO concentrations for 94% of hot stabilized running time are lower than the gas analyzer detection limit. For VSP modes 3, 5 to 7, and 9, tailpipe CO emission rates for cold start are statistically higher than those for hot stabilized running. For other VSP modes, the differences are not statistically significant.

Figure 73 shows the tailpipe HC emission rate versus VSP mode for cold start and hot stabilized running during engine on. There is not a clear trend in modal average rates versus VSP mode for cold start. The values for HC concentrations for 63% of cold start time are lower than the gas analyzer detection limit, 15 ppm. The values for HC concentrations for 94% of hot stabilized running time are lower than the gas analyzer detection limit. For hot stabilized running, tailpipe HC emission rate increases with increasing VSP modes. For VSP modes 1, 3 to 9, and 11, tailpipe HC emission rates for cold start are statistically higher than those for hot stabilized running. For other VSP modes, the differences are not statistically significant.
Figure 72 The Average Tailpipe Carbon Monoxide (CO) Emission Rate Versus Vehicle Specific Power (VSP) Mode for Cold Start and Hot Stabilized Running During Engine On for a 2013 Toyota Prius Plug-In Hybrid Measured from January 18, 2013 to January 25, 2013 in Raleigh/Research Triangle Park, North Carolina Area

Note: There is no data point for cold start in VSP modes 13 and 14. Error bars indicate 95% confidence intervals on the mean based on second-by-second variability. Sample size in each VSP mode is shown in Table 19. For VSP modes 3, 5 to 7, and 9, the differences of CO emission rates between cold start and hot stabilized running, are statistically significant, and for other VSP modes, the differences are not statistically significant.
Figure 73 The Average Tailpipe Hydrocarbon (HC) Emission Rate Versus Vehicle Specific Power (VSP) Mode for Cold Start and Hot Stabilized Running During Engine On for a 2013 Toyota Prius Plug-In Hybrid Measured from January 18, 2013 to January 25, 2013 in Raleigh/Research Triangle Park, North Carolina Area

Note: There is no data point for cold start in VSP modes 13 and 14. Error bars indicate 95% confidence intervals on the mean based on second-by-second variability. Sample size in each VSP mode is shown in Table 19. For VSP modes 1, 3 to 9, and 11, the differences of HC emission rates between cold start and hot stabilized running, are statistically significant, and for other VSP modes, the differences are not statistically significant.
Figure 74 shows the tailpipe NO$_x$ emission rate versus VSP mode for cold start and hot stabilized running during engine on. There is not a clear trend in modal average rates versus VSP mode for either cold start or hot stabilized running. The values for NO$_x$ concentrations for 94% of cold start time are lower than the gas analyzer detection limit, 8 ppm. The values for NO$_x$ concentrations for 93% of hot stabilized running time are lower than the gas analyzer detection limit. For VSP modes 1, 2, and 4 to 12, the differences of NO$_x$ emission rates between cold start and hot stabilized running, are statistically significant, and for other VSP modes, the differences are not statistically significant. However, since the values for NO$_x$ emission rates are low, the absolute differences between cold start and hot stabilized running are small.
Figure 74 The Average Tailpipe Oxides of Nitrogen (NO$_x$) Emission Rate Versus Vehicle Specific Power (VSP) Mode for Cold Start and Hot Stabilized Running During Engine On for a 2013 Toyota Prius Plug-In Hybrid Measured from January 18, 2013 to January 25, 2013 in Raleigh/Research Triangle Park, North Carolina Area

*Note: There is no data point for cold start in VSP modes 13 and 14. Error bars indicate 95% confidence intervals on the mean based on second-by-second variability. Sample size in each VSP mode is shown in Table 19. For VSP modes 1, 2, and 4 to 12, the differences of NO$_x$ emission rates between cold start and hot stabilized running, are statistically significant, and for other VSP modes, the differences are not statistically significant.*
3.8 Energy Use and Emission Rates Prediction Model

In this section, results are given for engine on and off rules, a mesoscale predictive model and a microscale predictive model.

3.8.1 Engine On and Off Rules

Synthesized engine rules for “on” operation in CD and CS modes derived from the CART analysis are summarized in Table 20 and Table 21. The fully-grown CART classification trees for CD and CS modes are pruned to reduce complexity. However, reduced complexity increases classification errors of the classification trees. For CD mode, the error changes from 0.058 to 0.098, which means 4.0% more of the CD mode validation dataset would be misclassified. For CS mode, the error changes from 0.067 to 0.082, which means 1.5% more of the CS mode validation dataset would be misclassified. The pruned trees are much less complex and perform only slightly worse than the fully-grown classification trees.

In CD mode, at low and high vehicle speed, road grade was identified as the key predictor of engine operation. At moderate vehicle speed, acceleration was identified as the key predictor of engine operation. The engine is on at various combinations of low vehicle speed and high road grade, high vehicle speed and low road grade, or moderate vehicle speed and high acceleration. With increasing speed, the road grade threshold at which engine is on decreases.
For example, at a speed of 30 mph or greater, with road grade of 4.12% or higher, regardless of acceleration, the engine is on. However, at a speed of 40 mph or greater, the engine is on regardless of road grade, if the acceleration is greater than or equal to 2.5 mph/s.

Table 20 The Summary of Plug-In Hybrid Electric Vehicle Engine On Rules in Charge Depleting (CD) Mode for a 2013 Toyota Prius Plug-In Hybrid

<table>
<thead>
<tr>
<th>Driving Condition</th>
<th>Speed (mph)</th>
<th>Road Grade (%)</th>
<th>Acceleration (mph/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(0, 35]</td>
<td>[4.12, +∞)</td>
<td>--</td>
</tr>
<tr>
<td>2</td>
<td>(35, 45]</td>
<td>--</td>
<td>[2.5, +∞)</td>
</tr>
<tr>
<td>3</td>
<td>(45, 55]</td>
<td>[1.97, +∞)</td>
<td>--</td>
</tr>
<tr>
<td>4</td>
<td>(55, 60]</td>
<td>[-0.34, +∞)</td>
<td>--</td>
</tr>
<tr>
<td>5</td>
<td>(60, +∞)</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

Table 21 The Summary of Plug-In Hybrid Electric Vehicle Engine On Rules in Charge Sustaining (CS) Mode for a 2013 Toyota Prius Plug-In Hybrid

<table>
<thead>
<tr>
<th>Driving Condition</th>
<th>Speed (mph)</th>
<th>VSP (kW/ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(0, 40]</td>
<td>[4.58, +∞)</td>
</tr>
<tr>
<td>2</td>
<td>(40, +∞)</td>
<td>--</td>
</tr>
</tbody>
</table>
In CS mode, speed and VSP are identified as the predictors of engine operation. The engine is on under conditions of high speed, or low to moderate speed and high power demand.

Based on the rules shown in Table 20 and Table 21, two MATLAB programs were developed to determine the engine status for each second of data for CD and CS modes, respectively. The programs are presented in Appendix A for CD mode, and Appendix B for CS mode.

The observed and predicted travel time spent in each VSP mode during engine on and off is given in Table 22 and Table 23, for CD and CS modes, respectively, based on second-by-second prediction for eight days of measurement on the PHEV.
Table 22 The Observed and Predicted Travel Time Spent in Each Vehicle Specific Power (VSP) Mode for Charge Depleting (CD) Mode During Engine On and Off for a 2013 Toyota Prius Plug-In Hybrid Measured from January 18, 2013 to January 25, 2013 in Raleigh/Research Triangle Park, North Carolina Area

<table>
<thead>
<tr>
<th>VSP Mode</th>
<th>Engine On</th>
<th>Engine Off</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed Sample Size (s)</td>
<td>Predicted Sample Size (s)&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>1</td>
<td>124</td>
<td>87</td>
</tr>
<tr>
<td>2</td>
<td>74</td>
<td>73</td>
</tr>
<tr>
<td>3</td>
<td>1464</td>
<td>683</td>
</tr>
<tr>
<td>4</td>
<td>212</td>
<td>249</td>
</tr>
<tr>
<td>5</td>
<td>177</td>
<td>241</td>
</tr>
<tr>
<td>6</td>
<td>147</td>
<td>232</td>
</tr>
<tr>
<td>7</td>
<td>146</td>
<td>233</td>
</tr>
<tr>
<td>8</td>
<td>74</td>
<td>171</td>
</tr>
<tr>
<td>9</td>
<td>56</td>
<td>120</td>
</tr>
<tr>
<td>10</td>
<td>69</td>
<td>93</td>
</tr>
<tr>
<td>11</td>
<td>37</td>
<td>65</td>
</tr>
<tr>
<td>12</td>
<td>5</td>
<td>33</td>
</tr>
<tr>
<td>13</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>14</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1-14</td>
<td>2585</td>
<td>2280</td>
</tr>
</tbody>
</table>

**Note:**

<sup>a.</sup> Engine operation is predicted in terms of vehicle speed, road grade and acceleration using the engine control rules summarized in Table 20.

<sup>b.</sup> Difference = (Predicted Sample Size – Observed Sample Size) / Observed Sample Size × 100%.
Table 23 The Observed and Predicted Travel Time Spent in Each Vehicle Specific Power (VSP) Mode for Charge Sustaining (CS) Mode During Engine On and Off for a 2013 Toyota Prius Plug-In Hybrid Measured from January 18, 2013 to January 25, 2013 in Raleigh/Research Triangle Park, North Carolina Area

<table>
<thead>
<tr>
<th>VSP Mode</th>
<th>Engine On</th>
<th></th>
<th></th>
<th>Engine Off</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed Sample Size (s)</td>
<td>Predicted Sample Size (s)&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Absolute Difference (s)</td>
<td>Relative Difference (%)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Observed Sample Size (s)</td>
<td>Predicted Sample Size (s)&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>1</td>
<td>5613</td>
<td>5518</td>
<td>-95</td>
<td>-1.7</td>
<td>14263</td>
<td>14358</td>
</tr>
<tr>
<td>2</td>
<td>1819</td>
<td>1634</td>
<td>-185</td>
<td>-10.2</td>
<td>5937</td>
<td>6122</td>
</tr>
<tr>
<td>3</td>
<td>2825</td>
<td>972</td>
<td>-1853</td>
<td>-65.6</td>
<td>41812</td>
<td>43665</td>
</tr>
<tr>
<td>4</td>
<td>5563</td>
<td>4007</td>
<td>-1556</td>
<td>-28.0</td>
<td>6473</td>
<td>8029</td>
</tr>
<tr>
<td>5</td>
<td>8514</td>
<td>10197</td>
<td>1683</td>
<td>19.8</td>
<td>3172</td>
<td>1489</td>
</tr>
<tr>
<td>6</td>
<td>9405</td>
<td>10778</td>
<td>1373</td>
<td>14.6</td>
<td>1373</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>8304</td>
<td>8851</td>
<td>547</td>
<td>6.6</td>
<td>547</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>6608</td>
<td>6783</td>
<td>175</td>
<td>2.6</td>
<td>175</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>3989</td>
<td>4038</td>
<td>49</td>
<td>1.2</td>
<td>49</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>2976</td>
<td>2992</td>
<td>16</td>
<td>0.5</td>
<td>16</td>
<td>0</td>
</tr>
<tr>
<td>11</td>
<td>1863</td>
<td>1864</td>
<td>1</td>
<td>0.1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>12</td>
<td>732</td>
<td>734</td>
<td>2</td>
<td>0.3</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>13</td>
<td>227</td>
<td>227</td>
<td>0</td>
<td>0.0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>14</td>
<td>45</td>
<td>45</td>
<td>0</td>
<td>0.0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1-14</td>
<td>58483</td>
<td>58640</td>
<td>157</td>
<td>0.3</td>
<td>73820</td>
<td>73663</td>
</tr>
</tbody>
</table>

Note:

<sup>a</sup> Engine operation is predicted in terms of vehicle speed, and VSP using the engine control rules summarized in Table 21.

<sup>b</sup> Difference = (Predicted Sample Size − Observed Sample Size) / Observed Sample Size × 100%.
For CD mode, the difference between observed and predicted engine on travel time in each VSP mode varies from -53.3% to 560.0%, and the difference between total observed and predicted engine on travel time is -11.8%. Even though the relative difference between observed and predicted engine on travel time in each VSP mode is large, except for VSP mode 2, the absolute difference is small compared to the total travel time in CD mode.

For CD mode and engine off, the difference between observed and predicted travel time in each VSP mode varies from -71.8% to 9.1%, and the difference between total observed and predicted engine off travel time is 1.6%. For VSP modes 1 to 6, the relative difference between observed and predicted engine off travel time is within 10%. For VSP modes 7 to 10, even though the relative difference between observed and predicted engine off travel time is large, the absolute difference is small, compared to the total travel time in CD mode.

For CS mode, the difference between observed and predicted engine on travel time in each VSP mode varies from -65.6% to 19.8%, and the difference between total observed and predicted engine on travel time is 0.3%. Even though the relative difference between observed and predicted engine on travel time from VSP modes 3 to 6 is large, the absolute difference is small, compared to the total travel time in CS mode.
For CS mode and engine off, the difference between observed and predicted travel time in each VSP mode varies from -100.0% to 24.0%, and the difference between total observed and predicted engine off travel time is -0.2%. Even though the relative difference between observed and predicted engine off travel time from VSP modes 4 to 12 is large, the absolute difference is small, compared to the total travel time in CS mode. Table 24 shows the observed and predicted number of engine starts per mile and average engine on duration per engine start for CD and CS modes. Number of engine starts per mile and average engine on duration per engine start are related. The predicted number of engine starts per mile tend to be larger than the observed values. Conversely, for average engine on duration per engine start, the predicted values tend to be lower. This means that the engine operation rules for CD and CS modes are not good at predicting number of engine start.
Table 24 The Observed and Predicted Number of Engine Starts per Mile and Average Engine On Duration per Engine Start for Charge Depleting (CD) and Charge Sustaining (CS) Modes for a 2013 Toyota Prius Plug-In Hybrid Measured from January 18, 2013 to January 25, 2013 in Raleigh/Research Triangle Park, North Carolina Area

<table>
<thead>
<tr>
<th>Mode</th>
<th>Number of Engine Starts per Mile</th>
<th>Average Engine On Duration per Engine Start (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed</td>
<td>Predicted</td>
</tr>
<tr>
<td>CD</td>
<td>0.17</td>
<td>0.78</td>
</tr>
<tr>
<td>CS</td>
<td>2.33</td>
<td>4.98</td>
</tr>
</tbody>
</table>

Note:

<sup>a</sup> Difference = (Predicted Number of Engine Starts per Mile − Observed Number of Engine Starts per Mile) / Observed Number of Engine Starts per Mile × 100%.

<sup>b</sup> Difference = (Predicted Average Engine On Duration per Engine Start − Observed Average Engine On Duration per Engine Start) / Observed Average Engine On Duration per Engine Start × 100%.

There were cases where during a certain period of time the engine was observed as on in the real world and the vehicle was predicted to be mainly in the engine on driving condition as indicated in Table 20 and Table 21. During this period, the estimated vehicle driving condition switched to the engine off category for a few seconds. However, in the real world, the vehicle engine did not shut off. Thus, the model predicted one false engine shutdown and one false engine startup in this period. Similarly, there were cases where during a certain period of time the engine was observed as off in the real world and the vehicle was predicted
to be mainly in the engine off driving condition. During this period, the predicted vehicle driving condition switched to the engine on category for a few seconds. However, in the real world, the vehicle engine did not turn on. Thus, the model predicted one false engine startup and one false engine shutdown in this period. It is possible that the control logic for the engine prevents very short periods of engine on or engine off operation. However, the prediction model does not impose any limitation regarding a delayed response or a minimum number of seconds of operation once the engine status (on or off) has changed. A future version of the prediction model might incorporate logic to prevent a change in engine status of the change would be very short in duration.

There were cases where the model just missed a correct prediction by a small margin of the values of the variables used for prediction. For example, in CS mode, at a speed of 40 mph, with VSP of $\geq 4.5 \text{ kW/ton}$ and $< 4.58 \text{ kW/ton}$ ($4.58 \text{ kW/ton}$ is the cutoff value used for prediction as indicated in Table 21), the engine was usually observed as on in the real world. However, the vehicle was predicted to be in the engine off driving condition. This could be improved by checking if the variables are within a certain small margin of the cutoff values used for prediction, and if so, checking the engine status within a certain period of time.
Table 25 shows the percentage of seconds during which the engine status is predicted correctly for CD and CS modes. For CD mode, only 34% of engine on data are predicted correctly, and 93% of engine off data are predicted correctly. For CS mode, 91% of engine on data are predicted correctly, and 93% of engine off data are predicted correctly. This means that the engine operation rules for CD mode are good at predicting engine off, but not engine on, and engine operation rules for CS mode are good at predicting both engine on and off. One reason might be that the engine rarely turns on in CD mode. Thus, there is a relatively small engine on sample size in CD mode, compared to the engine off sample size in CD mode, engine on sample size in CS mode, and engine off sample size in CS mode. This could mean that there is not a large enough sample size from which to develop robust engine on rules for CD mode.
Table 25: The Percentage of Seconds During Which the Engine Status is Predicted Correctly for Charge Depleting (CD) and Charge Sustaining (CS) Modes for a 2013 Toyota Prius Plug-In Hybrid Measured from January 18, 2013 to January 25, 2013 in Raleigh/Research Triangle Park, North Carolina Area

<table>
<thead>
<tr>
<th>Mode</th>
<th>Predicted Duration (s)</th>
<th>Observed Duration (s)</th>
<th>Percentage of True Positive (%)</th>
<th>Percentage of True Negative (%)</th>
<th>Percentage of Accuracy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Engine On</td>
<td>Engine Off</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>True Positive</td>
<td>False Positive</td>
<td>True Negative</td>
<td>False Negative</td>
<td></td>
</tr>
<tr>
<td>CD</td>
<td>881</td>
<td>1399</td>
<td>18158</td>
<td>1682</td>
<td>34.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2585</td>
<td>19535</td>
<td>93.0</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
<td>86.1</td>
</tr>
<tr>
<td>CS</td>
<td>53174</td>
<td>5466</td>
<td>68354</td>
<td>5309</td>
<td>90.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>58483</td>
<td>73820</td>
<td>92.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>91.9</td>
</tr>
</tbody>
</table>

**Note:**

- **a.** Percentage of True Positive = True Positive / Observed Duration for Engine On $\times$ 100%
- **b.** Percentage of True Negative = True Negative / Observed Duration for Engine Off $\times$ 100%
- **c.** Percentage of Accuracy = (True Positive + True Negative) / (Observed Duration for Engine On + Observed Duration for Off) $\times$ 100%

### 3.8.2 Mesoscale Predictive Model — Cycle Average Energy Use and Emission Rates

The mesoscale predictive model is evaluated by comparing the observed and predicted CD mode duration and travel distance, and cycle average energy use and emissions for PHEVs with respect to CD and CS modes.
3.8.2.1 Duration and Travel Distance in Charge Depleting (CD) Mode

Based on initial TB SOC when PHEV starts operating (SOC\textsubscript{start}), TB SOC at which PHEV switches from CD to CS mode (SOC\textsubscript{end}), and engine on and off TB electricity use rate for CD mode in 14 VSP modes, a MATLAB program was developed to estimate the duration and travel distance for the CD mode. The program is presented in Appendix C.

Different TB SOC\textsubscript{end} parameter values were evaluated in the model, such as the lowest, highest and average values of observed TB SOC\textsubscript{end} from 8 days of measurement. Using these three different TB SOC\textsubscript{end} parameter values, the estimation of the duration and travel distance for the CD mode does not differ much. For the lowest value of observed TB SOC\textsubscript{end}, the percentage differences in observed and predicted duration vary from -2.1% to 23.0%, and the percentage differences in observed and predicted distance vary from -4.9% to 18.7%. For the highest value of observed TB SOC\textsubscript{end}, the percentage differences in observed and predicted duration vary from -2.4% to 21.2%, and the percentage differences in observed and predicted distance vary from -5.3% to 16.6%. Therefore, changing the SOC\textsubscript{end} parameter value does not lead to significant improvement, and the average value of observed TB SOC\textsubscript{end} from 8 days of measurement is used as the parameter in the model.
The observed and predicted duration and travel distance in CD mode based on 8 days of measurements are given in Table 26. The percentage differences in duration vary from -2.2% to 21.6%. The percentage differences in distance vary from -6.1% to 15.2%. The difference between observed and predicted duration and travel distance for the first six days of measurement is within 10%. The difference between observed and predicted duration and travel distance for the last two days of measurements shows relatively large error.
Table 26 The Observed and Predicted Duration and Travel Distance for Charge Depleting (CD) Mode for a 2013 Toyota Prius Plug-In Hybrid Measured from January 18, 2013 to January 25, 2013 in Raleigh/Research Triangle Park, North Carolina Area

<table>
<thead>
<tr>
<th>Date</th>
<th>Duration</th>
<th>Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed (s)</td>
<td>Predicted (s)</td>
</tr>
<tr>
<td>18-Jan</td>
<td>4126</td>
<td>4165</td>
</tr>
<tr>
<td>19-Jan</td>
<td>2234</td>
<td>2403</td>
</tr>
<tr>
<td>20-Jan</td>
<td>3118</td>
<td>3049</td>
</tr>
<tr>
<td>21-Jan</td>
<td>2338</td>
<td>2363</td>
</tr>
<tr>
<td>22-Jan</td>
<td>2570</td>
<td>2636</td>
</tr>
<tr>
<td>23-Jan</td>
<td>2980</td>
<td>3000</td>
</tr>
<tr>
<td>24-Jan</td>
<td>1935</td>
<td>2352</td>
</tr>
<tr>
<td>25-Jan</td>
<td>2831</td>
<td>3166</td>
</tr>
<tr>
<td>All</td>
<td>22132</td>
<td>23134</td>
</tr>
</tbody>
</table>

Note:

<sup>a</sup> Difference = (Predicted Duration – Observed Duration) / Observed Duration × 100%.

<sup>b</sup> Difference = (Predicted Distance – Observed Distance) / Observed Distance × 100%.
3.8.2.2 Cycle Average Energy Use and Emission Rates in Charge Depleting (CD) Mode

A MATLAB program was developed to estimate the cycle average energy use and emission rates in CD mode. The program is presented in Appendix D.

The observed and predicted cycle average energy use and CO$_2$ emission rates in CD mode for 8 days of measurement are given in Table 27. The observed and predicted cycle average CO and HC emission rates in CD mode for 8 days of measurement are given in Table 28. The observed and predicted cycle average NO$_x$ and SO$_x$ emission rates in CD mode for 8 days of measurement are given in Table 29. The observed and predicted cycle average PM$_{2.5}$ and PM$_{10}$ emission rates in CD mode for 8 days of measurement are given in Table 30.
Table 27: The Observed and Predicted Energy Use and CO\textsubscript{2} Emission Rates for Charge Depleting (CD) Mode for a 2013 Toyota Prius Plug-In Hybrid Measured from January 18, 2013 to January 25, 2013 in Raleigh/Research Triangle Park, North Carolina Area

<table>
<thead>
<tr>
<th>Measurement Date</th>
<th>Energy Use (g/s)</th>
<th>Difference (%)\textsuperscript{a}</th>
<th>CO\textsubscript{2} (g/s)</th>
<th>Difference (%)\textsuperscript{b}</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed</td>
<td>Predicted</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18-Jan-13</td>
<td>0.21</td>
<td>0.34</td>
<td>65.3</td>
<td>0.43</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.84</td>
</tr>
<tr>
<td>19-Jan-13</td>
<td>0.38</td>
<td>0.40</td>
<td>5.1</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.89</td>
</tr>
<tr>
<td>20-Jan-13</td>
<td>0.35</td>
<td>0.31</td>
<td>-9.9</td>
<td>0.79</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.68</td>
</tr>
<tr>
<td>21-Jan-13</td>
<td>0.48</td>
<td>0.43</td>
<td>-9.6</td>
<td>1.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.00</td>
</tr>
<tr>
<td>22-Jan-13</td>
<td>0.44</td>
<td>0.44</td>
<td>-0.9</td>
<td>1.02</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.02</td>
</tr>
<tr>
<td>23-Jan-13</td>
<td>0.37</td>
<td>0.33</td>
<td>-12.6</td>
<td>0.86</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.72</td>
</tr>
<tr>
<td>24-Jan-13</td>
<td>0.56</td>
<td>0.60</td>
<td>8.4</td>
<td>1.27</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.49</td>
</tr>
<tr>
<td>25-Jan-13</td>
<td>0.38</td>
<td>0.33</td>
<td>-12.0</td>
<td>0.86</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.73</td>
</tr>
<tr>
<td>All Measurement</td>
<td>0.37</td>
<td>0.38</td>
<td>2.3</td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.89</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.0</td>
</tr>
</tbody>
</table>

Note:

\textsuperscript{a} Difference = (Predicted Energy Use Rate – Observed Energy Use Rate) / Observed Energy Use Rate \times 100%.

\textsuperscript{b} Difference = (Predicted CO\textsubscript{2} Emission Rate – Observed CO\textsubscript{2} Emission Rate) / Observed CO\textsubscript{2} Emission Rate \times 100%.
Table 28 The Observed and Predicted CO and HC Emission Rates for Charge Depleting (CD) Mode for a 2013 Toyota Prius Plug-In Hybrid Measured from January 18, 2013 to January 25, 2013 in Raleigh/Research Triangle Park, North Carolina Area

<table>
<thead>
<tr>
<th>Measurement Date</th>
<th>CO (mg/s)</th>
<th>Difference (%)&lt;sup&gt;a&lt;/sup&gt;</th>
<th>HC (mg/s)</th>
<th>Difference (%)&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed</td>
<td>Predicted</td>
<td></td>
<td>Observed</td>
</tr>
<tr>
<td>18-Jan-13</td>
<td>0.24</td>
<td>0.79</td>
<td>224.4</td>
<td>0.05</td>
</tr>
<tr>
<td>19-Jan-13</td>
<td>0.45</td>
<td>0.51</td>
<td>15.1</td>
<td>0.08</td>
</tr>
<tr>
<td>20-Jan-13</td>
<td>1.32</td>
<td>0.39</td>
<td>-70.5</td>
<td>0.22</td>
</tr>
<tr>
<td>21-Jan-13</td>
<td>0.99</td>
<td>0.58</td>
<td>-41.8</td>
<td>0.25</td>
</tr>
<tr>
<td>22-Jan-13</td>
<td>0.60</td>
<td>0.70</td>
<td>16.0</td>
<td>0.26</td>
</tr>
<tr>
<td>23-Jan-13</td>
<td>0.54</td>
<td>0.41</td>
<td>-25.4</td>
<td>0.23</td>
</tr>
<tr>
<td>24-Jan-13</td>
<td>0.87</td>
<td>0.90</td>
<td>3.9</td>
<td>0.29</td>
</tr>
<tr>
<td>25-Jan-13</td>
<td>0.53</td>
<td>0.43</td>
<td>-19.2</td>
<td>0.20</td>
</tr>
<tr>
<td>All Measurement</td>
<td>0.67</td>
<td>0.58</td>
<td>-12.6</td>
<td>0.19</td>
</tr>
</tbody>
</table>

Note:

<sup>a</sup> Difference = (Predicted CO Emission Rate − Observed CO Emission Rate) / Observed CO Emission Rate × 100%.

<sup>b</sup> Difference = (Predicted HC Emission Rate − Observed HC Emission Rate) / Observed HC Emission Rate × 100%.
Table 29 The Observed and Predicted NO\textsubscript{x} and SO\textsubscript{x} Emission Rates for Charge Depleting (CD) Mode for a 2013 Toyota Prius Plug-In Hybrid Measured from January 18, 2013 to January 25, 2013 in Raleigh/Research Triangle Park, North Carolina Area

<table>
<thead>
<tr>
<th>Measurement Date</th>
<th>NO\textsubscript{x} (mg/s)</th>
<th>Difference (%)\textsuperscript{a}</th>
<th>SO\textsubscript{x} (mg/s)</th>
<th>Difference (%)\textsuperscript{b}</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed</td>
<td>Predicted</td>
<td></td>
<td>Observed</td>
</tr>
<tr>
<td>18-Jan-13</td>
<td>0.37</td>
<td>0.61</td>
<td>63.4</td>
<td>0.57</td>
</tr>
<tr>
<td>19-Jan-13</td>
<td>0.69</td>
<td>0.73</td>
<td>5.8</td>
<td>1.06</td>
</tr>
<tr>
<td>20-Jan-13</td>
<td>0.62</td>
<td>0.56</td>
<td>-9.6</td>
<td>0.86</td>
</tr>
<tr>
<td>21-Jan-13</td>
<td>0.85</td>
<td>0.79</td>
<td>-7.2</td>
<td>1.15</td>
</tr>
<tr>
<td>22-Jan-13</td>
<td>0.78</td>
<td>0.78</td>
<td>-0.5</td>
<td>1.06</td>
</tr>
<tr>
<td>23-Jan-13</td>
<td>0.67</td>
<td>0.58</td>
<td>-14.3</td>
<td>0.91</td>
</tr>
<tr>
<td>24-Jan-13</td>
<td>0.99</td>
<td>1.07</td>
<td>8.4</td>
<td>1.38</td>
</tr>
<tr>
<td>25-Jan-13</td>
<td>0.69</td>
<td>0.57</td>
<td>-17.3</td>
<td>0.94</td>
</tr>
<tr>
<td>All Measurement</td>
<td>0.67</td>
<td>0.68</td>
<td>1.7</td>
<td>0.94</td>
</tr>
</tbody>
</table>

Note:

\textsuperscript{a} \textit{Difference} = (\textit{Predicted NO}\textsubscript{x} Emission Rate – \textit{Observed NO}\textsubscript{x} Emission Rate) / \textit{Observed NO}\textsubscript{x} Emission Rate \times 100%.

\textsuperscript{b} \textit{Difference} = (\textit{Predicted SO}\textsubscript{x} Emission Rate – \textit{Observed SO}\textsubscript{x} Emission Rate) / \textit{Observed SO}\textsubscript{x} Emission Rate \times 100%.
Table 30 The Observed and Predicted PM$_{2.5}$ and PM$_{10}$ Emission Rates for Charge Depleting (CD) Mode for a 2013 Toyota Prius Plug-In Hybrid Measured from January 18, 2013 to January 25, 2013 in Raleigh/Research Triangle Park, North Carolina Area

<table>
<thead>
<tr>
<th>Measurement Date</th>
<th>PM$_{2.5}$ (mg/s)</th>
<th>Difference (%)$^a$</th>
<th>PM$_{10}$ (mg/s)</th>
<th>Difference (%)$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed</td>
<td>Predicted</td>
<td></td>
<td>Observed</td>
</tr>
<tr>
<td>18-Jan-13</td>
<td>0.05</td>
<td>0.07</td>
<td>29.3</td>
<td>0.10</td>
</tr>
<tr>
<td>19-Jan-13</td>
<td>0.10</td>
<td>0.10</td>
<td>0.2</td>
<td>0.18</td>
</tr>
<tr>
<td>20-Jan-13</td>
<td>0.08</td>
<td>0.08</td>
<td>-2.0</td>
<td>0.14</td>
</tr>
<tr>
<td>21-Jan-13</td>
<td>0.10</td>
<td>0.10</td>
<td>-2.9</td>
<td>0.19</td>
</tr>
<tr>
<td>22-Jan-13</td>
<td>0.10</td>
<td>0.09</td>
<td>-1.6</td>
<td>0.17</td>
</tr>
<tr>
<td>23-Jan-13</td>
<td>0.08</td>
<td>0.07</td>
<td>-9.0</td>
<td>0.15</td>
</tr>
<tr>
<td>24-Jan-13</td>
<td>0.12</td>
<td>0.12</td>
<td>-3.8</td>
<td>0.22</td>
</tr>
<tr>
<td>25-Jan-13</td>
<td>0.08</td>
<td>0.07</td>
<td>-15.1</td>
<td>0.15</td>
</tr>
<tr>
<td><strong>All Measurement</strong></td>
<td><strong>0.08</strong></td>
<td><strong>0.08</strong></td>
<td><strong>-1.1</strong></td>
<td><strong>0.15</strong></td>
</tr>
</tbody>
</table>

*Note:*

$^a$ Difference = \( \frac{\text{Predicted PM}_{2.5} \text{ Emission Rate} - \text{Observed PM}_{2.5} \text{ Emission Rate}}{\text{Observed PM}_{2.5} \text{ Emission Rate}} \times 100\% \).  

$^b$ Difference = \( \frac{\text{Predicted PM}_{10} \text{ Emission Rate} - \text{Observed PM}_{10} \text{ Emission Rate}}{\text{Observed PM}_{10} \text{ Emission Rate}} \times 100\% \).
As shown in Table 27, the energy use and CO₂ emission rates predictions for all measurements have overall average errors of 2.3% and 5.0%, respectively. As shown in Table 28, the CO and HC emission rates predictions for all measurements have errors of -12.6% and 12.2%, respectively. As shown in Table 29, the NOₓ and SOₓ emission rates predictions for all measurements have errors of 1.7% and -0.9% respectively. As shown in Table 30, the PM₂.₅ and PM₁₀ emission rates predictions for all measurements have errors of -1.1% and -1.9%, respectively. Thus, the predicted cycle average energy use and emission rates for all measurements have small overall errors. However, there is inter-daily variability in prediction errors. The energy use rates predictions for 7 out of 8 days of measurements have daily errors from -13% to 8%. The CO₂ emission rates predictions for 7 out of 8 days of measurements have daily errors from -17% to 18%. The CO emission rates predictions for 6 out of 8 days of measurements have daily errors from -42% to 16%. The HC emission rates predictions for 7 out of 8 days of measurements have daily errors from -56% to 73%. The NOₓ emission rates predictions for 7 out of 8 days of measurements have daily errors from -17% to 8%. The SOₓ emission rates predictions for 7 out of 8 days of measurements have daily errors from -15% to 0%. The PM₂.₅ emission rates predictions for 6 out of 8 days of measurements have daily errors from -9% to 0%. The PM₁₀ emission rates predictions for 6 out of 8 days of measurements have daily errors from -8% to 0%.
3.8.2.3 Cycle Average Energy Use and Emission Rates in Charge Sustaining (CS) Mode

A MATLAB program was developed to estimate the cycle average energy use and emission rates in CS mode based on a user input second by second driving cycle. The program is presented in Appendix E.

The observed and predicted cycle average energy use and CO\textsubscript{2} emission rates in CS mode for each of 8 days of measurements are given in Table 31. The observed and predicted cycle average CO and HC emission rates in CS mode for each of 8 days of measurements are given in Table 32. The observed and predicted cycle average NO\textsubscript{x} and SO\textsubscript{x} emission rates in CS mode for each of 8 days of measurements are given in Table 33. The observed and predicted cycle average PM\textsubscript{2.5} and PM\textsubscript{10} emission rates in CS mode for each of 8 days of measurements are given in Table 34.
Table 31 The Observed and Predicted Energy Use and CO$_2$ Emission Rates for Charge Sustaining (CS) Mode for a 2013 Toyota Prius Plug-In Hybrid Measured from January 18, 2013 to January 25, 2013 in Raleigh/Research Triangle Park, North Carolina Area

<table>
<thead>
<tr>
<th>Measurement Date</th>
<th>Energy Use (g/s)</th>
<th>Difference (%)</th>
<th>CO$_2$ (g/s)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed</td>
<td>Predicted</td>
<td>Observed</td>
<td>Predicted</td>
</tr>
<tr>
<td>18-Jan-13</td>
<td>0.38</td>
<td>0.42</td>
<td>10.6</td>
<td>1.10</td>
</tr>
<tr>
<td>19-Jan-13</td>
<td>0.45</td>
<td>0.49</td>
<td>10.7</td>
<td>1.29</td>
</tr>
<tr>
<td>20-Jan-13</td>
<td>0.49</td>
<td>0.51</td>
<td>4.7</td>
<td>1.40</td>
</tr>
<tr>
<td>21-Jan-13</td>
<td>0.54</td>
<td>0.54</td>
<td>-0.2</td>
<td>1.55</td>
</tr>
<tr>
<td>22-Jan-13</td>
<td>0.52</td>
<td>0.51</td>
<td>-0.7</td>
<td>1.49</td>
</tr>
<tr>
<td>23-Jan-13</td>
<td>0.44</td>
<td>0.44</td>
<td>0.5</td>
<td>1.26</td>
</tr>
<tr>
<td>24-Jan-13</td>
<td>0.62</td>
<td>0.61</td>
<td>-1.3</td>
<td>1.79</td>
</tr>
<tr>
<td>25-Jan-13</td>
<td>0.68</td>
<td>0.52</td>
<td>-23.3</td>
<td>1.97</td>
</tr>
<tr>
<td>All Measurement</td>
<td>0.50</td>
<td>0.50</td>
<td>0.7</td>
<td>1.43</td>
</tr>
</tbody>
</table>

Note:

a. Difference = (Predicted Energy Use Rate – Observed Energy Use Rate) / Observed Energy Use Rate × 100%.

b. Difference = (Predicted CO$_2$ Emission Rate – Observed CO$_2$ Emission Rate) / Observed CO$_2$ Emission Rate × 100%.
Table 32 The Observed and Predicted CO and HC Emission Rates for Charge Sustaining (CS) Mode for a 2013 Toyota Prius Plug-In Hybrid Measured from January 18, 2013 to January 25, 2013 in Raleigh/Research Triangle Park, North Carolina Area

<table>
<thead>
<tr>
<th>Measurement Date</th>
<th>CO (mg/s)</th>
<th>Difference (%)</th>
<th>HC (mg/s)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed</td>
<td>Predicted</td>
<td></td>
<td>Observed</td>
</tr>
<tr>
<td>18-Jan-13</td>
<td>0.37</td>
<td>0.45</td>
<td>24.1</td>
<td>0.42</td>
</tr>
<tr>
<td>19-Jan-13</td>
<td>0.53</td>
<td>0.53</td>
<td>0.8</td>
<td>0.45</td>
</tr>
<tr>
<td>20-Jan-13</td>
<td>0.57</td>
<td>0.55</td>
<td>-2.3</td>
<td>0.47</td>
</tr>
<tr>
<td>21-Jan-13</td>
<td>0.66</td>
<td>0.58</td>
<td>-11.6</td>
<td>0.54</td>
</tr>
<tr>
<td>22-Jan-13</td>
<td>0.48</td>
<td>0.56</td>
<td>17.1</td>
<td>0.54</td>
</tr>
<tr>
<td>23-Jan-13</td>
<td>0.47</td>
<td>0.48</td>
<td>2.3</td>
<td>0.47</td>
</tr>
<tr>
<td>24-Jan-13</td>
<td>0.56</td>
<td>0.66</td>
<td>18.5</td>
<td>0.65</td>
</tr>
<tr>
<td>25-Jan-13</td>
<td>1.02</td>
<td>0.56</td>
<td>-44.7</td>
<td>0.69</td>
</tr>
<tr>
<td>All Measurement</td>
<td>0.55</td>
<td>0.54</td>
<td>-0.9</td>
<td>0.51</td>
</tr>
</tbody>
</table>

Note:

a. Difference = \(\frac{(\text{Predicted CO Emission Rate} - \text{Observed CO Emission Rate})}{\text{Observed CO Emission Rate}} \times 100\%\).

b. Difference = \(\frac{(\text{Predicted HC Emission Rate} - \text{Observed HC Emission Rate})}{\text{Observed HC Emission Rate}} \times 100\%\).
Table 33: The Observed and Predicted NO<sub>x</sub> and SO<sub>x</sub> Emission Rates for Charge Sustaining (CS) Mode for a 2013 Toyota Prius Plug-In Hybrid Measured from January 18, 2013 to January 25, 2013 in Raleigh/Research Triangle Park, North Carolina Area

<table>
<thead>
<tr>
<th>Measurement Date</th>
<th>NO&lt;sub&gt;x&lt;/sub&gt; (mg/s)</th>
<th>Difference (%)</th>
<th>SO&lt;sub&gt;x&lt;/sub&gt; (mg/s)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed</td>
<td>Predicted</td>
<td>Observed</td>
<td>Predicted</td>
</tr>
<tr>
<td>18-Jan-13</td>
<td>0.67</td>
<td>0.72</td>
<td>8.1</td>
<td>0.51</td>
</tr>
<tr>
<td>19-Jan-13</td>
<td>0.76</td>
<td>0.84</td>
<td>11.1</td>
<td>0.59</td>
</tr>
<tr>
<td>20-Jan-13</td>
<td>0.83</td>
<td>0.87</td>
<td>4.5</td>
<td>0.65</td>
</tr>
<tr>
<td>21-Jan-13</td>
<td>0.91</td>
<td>0.92</td>
<td>0.5</td>
<td>0.71</td>
</tr>
<tr>
<td>22-Jan-13</td>
<td>0.87</td>
<td>0.88</td>
<td>1.1</td>
<td>0.69</td>
</tr>
<tr>
<td>23-Jan-13</td>
<td>0.74</td>
<td>0.75</td>
<td>1.6</td>
<td>0.58</td>
</tr>
<tr>
<td>24-Jan-13</td>
<td>1.06</td>
<td>1.04</td>
<td>-1.4</td>
<td>0.82</td>
</tr>
<tr>
<td>25-Jan-13</td>
<td>1.18</td>
<td>0.89</td>
<td>-24.5</td>
<td>0.90</td>
</tr>
<tr>
<td>All Measurement</td>
<td>0.85</td>
<td>0.85</td>
<td>0.7</td>
<td>0.66</td>
</tr>
</tbody>
</table>

Note:

a. \( \text{Difference} = \frac{(\text{Predicted NO}_x \text{ Emission Rate} - \text{Observed NO}_x \text{ Emission Rate})}{\text{Observed NO}_x \text{ Emission Rate}} \times 100\% \).

b. \( \text{Difference} = \frac{(\text{Predicted SO}_x \text{ Emission Rate} - \text{Observed SO}_x \text{ Emission Rate})}{\text{Observed SO}_x \text{ Emission Rate}} \times 100\% \).
Table 34 The Observed and Predicted PM$_{2.5}$ and PM$_{10}$ Emission Rates for Charge Sustaining (CS) Mode for a 2013 Toyota Prius Plug-In Hybrid Measured from January 18, 2013 to January 25, 2013 in Raleigh/Research Triangle Park, North Carolina Area

<table>
<thead>
<tr>
<th>Measurement Date</th>
<th>PM$_{2.5}$ (mg/s)</th>
<th>Difference (%)</th>
<th>PM$_{10}$ (mg/s)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed</td>
<td>Predicted</td>
<td></td>
<td>Observed</td>
</tr>
<tr>
<td>18-Jan-13</td>
<td>0.04</td>
<td>0.05</td>
<td>10.6</td>
<td>0.06</td>
</tr>
<tr>
<td>19-Jan-13</td>
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<td>0.06</td>
<td>10.7</td>
<td>0.07</td>
</tr>
<tr>
<td>20-Jan-13</td>
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<td>0.06</td>
<td>4.7</td>
<td>0.08</td>
</tr>
<tr>
<td>21-Jan-13</td>
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<td>0.06</td>
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<td>0.09</td>
</tr>
<tr>
<td>22-Jan-13</td>
<td>0.06</td>
<td>0.06</td>
<td>-0.7</td>
<td>0.08</td>
</tr>
<tr>
<td>23-Jan-13</td>
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<td>0.05</td>
<td>0.5</td>
<td>0.07</td>
</tr>
<tr>
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<td>0.07</td>
<td>-1.3</td>
<td>0.10</td>
</tr>
<tr>
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<td>0.06</td>
<td>-23.3</td>
<td>0.11</td>
</tr>
<tr>
<td>All Measurement</td>
<td>0.06</td>
<td>0.06</td>
<td>0.7</td>
<td>0.08</td>
</tr>
</tbody>
</table>

*Note:*

a. $\text{Difference} = (\text{Predicted PM}_{2.5} \ \text{Emission Rate} - \text{Observed PM}_{2.5} \ \text{Emission Rate}) / \text{Observed PM}_{2.5} \ \text{Emission Rate} \times 100\%.$

b. $\text{Difference} = (\text{Predicted PM}_{10} \ \text{Emission Rate} - \text{Observed PM}_{10} \ \text{Emission Rate}) / \text{Observed PM}_{10} \ \text{Emission Rate} \times 100\%.$
As shown in Table 31, the energy use and CO$_2$ emission rates predictions over all eight days have average errors of 0.7% each. As shown in Table 32, the CO and HC emission rates predictions over all eight days have average errors of -0.9% and 0.6%, respectively. As shown in Table 33, the NO$_x$ and SO$_x$ emission rates predictions over all eight days have average errors of 0.7% each. As shown in Table 34, the PM$_{2.5}$ and PM$_{10}$ emission rates predictions over all eight days have average errors of 0.7% each. The average prediction errors for energy use and emission rates are small.

For individual day of measurement, the prediction may subject to relatively large error. The energy use rates predictions for 5 out of 8 days of measurements have daily errors from -1% to 5%. The CO$_2$ emission rates predictions for 5 out of 8 days of measurements have daily errors from -1% to 5%. The CO emission rates predictions for 6 out of 8 days of measurements have daily errors from -12% to 19%. The HC emission rates predictions for 6 out of 8 days of measurements have daily errors from -3% to 13%. The NO$_x$ emission rates predictions for 6 out of 8 days of measurements have daily errors from -1% to 8%. The SO$_x$ emission rates predictions for 5 out of 8 days of measurements have daily errors from -1% to 5%. The PM$_{2.5}$ emission rates predictions for 5 out of 8 days of measurements have daily errors from -1% to 5%. The PM$_{10}$ emission rates predictions for 5 out of 8 days of measurements have daily errors from -1% to 5%. For the last day of measurement, the large
error is caused by the relatively poor prediction of engine on sample size in each VSP mode. The total observed engine on sample size is 5371 seconds in 14 VSP modes. However, the predicted engine on sample size is 923 seconds smaller than the observed. For the last day of measurement in CS mode, the PHEV was driven on Routes 1 and 2. Routes 1 and 2 are mainly comprised of freeway driving as shown in Table 1. The engine on rules developed here were on the basis of the whole measurement in CS mode, which was only comprised of 40% of freeway driving. Road type should be included in developing more robust engine on rules. Further work could incorporate road type as an explanatory variable in the CART analysis of predicting engine on and off operation. If CART analysis indicates that road type is a useful and significant explanatory variable, the challenge would be how to tell what type of road the vehicle is driving on. Using data collected at different road types, different pattern of v, a, r, or VSP might be found among different road types. Thus, the combinations of v, a, r, and VSP could be used to indicate what type of road the vehicle is driving on. For example, perhaps the model should be stratified by average speed over the last minute, which could give some idea of possible road type, coupled with instantaneous VSP.
3.8.3 Microscale Predictive Model — Second-by-Second Emission Rates

The microscale predictive model is evaluated by comparing the observed and predicted second-by-second tailpipe CO$_2$ emission rates for PHEVs with respect to two different operating modes.

3.8.3.1 Second-by-Second Tailpipe CO$_2$ Emission Rates in Charge Depleting (CD) Mode

A MATLAB program was developed to estimate the second-by-second tailpipe CO$_2$ emission rates in CD mode. The program is presented in Appendix F.

The observed and predicted second-by-second tailpipe CO$_2$ emission rates in CD mode are given in Figure 75 for measurement on January 18, 2013, in Figure 76 for measurement on January 19, 2013, in Figure 77 for measurement on January 20, 2013, in Figure 78 for measurement on January 21, 2013, in Figure 79 for measurement on January 22, 2013, in Figure 80 for measurement on January 23, 2013, in Figure 81 for measurement on January 24, 2013, and in Figure 82 for measurement on January 25, 2013. For all measurements in CD mode, only 34% of engine on data are predicted correctly, and 93% of engine off data are predicted correctly. One reason might be that the engine rarely turns on in CD mode. Thus, there is a relatively small engine on sample size in CD mode, compared to the total sample
size in CD mode. This could mean that there is not a large enough sample size from which to develop robust engine control rules for CD mode.

Figure 75 The Observed and Predicted Second-by-Second Tailpipe CO$_2$ Emission Rates for Charge Depleting (CD) Mode for a 2013 Toyota Prius Plug-In Hybrid Measured on January 18, 2013 in Raleigh/Research Triangle Park, North Carolina Area
Figure 76 The Observed and Predicted Second-by-Second Tailpipe CO$_2$ Emission Rates for Charge Depleting (CD) Mode for a 2013 Toyota Prius Plug-In Hybrid Measured on January 19, 2013 in Raleigh/Research Triangle Park, North Carolina Area

Figure 77 The Observed and Predicted Second-by-Second Tailpipe CO$_2$ Emission Rates for Charge Depleting (CD) Mode for a 2013 Toyota Prius Plug-In Hybrid Measured on January 20, 2013 in Raleigh/Research Triangle Park, North Carolina Area
Figure 78 The Observed and Predicted Second-by-Second Tailpipe CO₂ Emission Rates for Charge Depleting (CD) Mode for a 2013 Toyota Prius Plug-In Hybrid Measured on January 21, 2013 in Raleigh/Research Triangle Park, North Carolina Area

Figure 79 The Observed and Predicted Second-by-Second Tailpipe CO₂ Emission Rates for Charge Depleting (CD) Mode for a 2013 Toyota Prius Plug-In Hybrid Measured on January 22, 2013 in Raleigh/Research Triangle Park, North Carolina Area
Figure 80 The Observed and Predicted Second-by-Second Tailpipe CO₂ Emission Rates for Charge Depleting (CD) Mode for a 2013 Toyota Prius Plug-In Hybrid Measured on January 23, 2013 in Raleigh/Research Triangle Park, North Carolina Area

Figure 81 The Observed and Predicted Second-by-Second Tailpipe CO₂ Emission Rates for Charge Depleting (CD) Mode for a 2013 Toyota Prius Plug-In Hybrid Measured on January 24, 2013 in Raleigh/Research Triangle Park, North Carolina Area
3.8.3.2 Second-by-Second Tailpipe CO₂ Emission Rates in Charge Sustaining (CS) Mode

A MATLAB program was developed to estimate the second-by-second tailpipe CO₂ emission rates in CS mode. The program is presented in Appendix G.

The observed and predicted second-by-second tailpipe CO₂ emission rates in CS mode are given in Figure 83 for measurement on January 18, 2013, in Figure 84 for measurement on January 19, 2013, in Figure 85 for measurement on January 20, 2013, in Figure 86 for measurement on January 21, 2013, in Figure 87 for measurement on January 22, 2013, in
Figure 88 for measurement on January 23, 2013, in Figure 89 for measurement on January 24, 2013, and in Figure 90 for measurement on January 25, 2013. For all measurements in CS mode, 91% of engine on data are predicted correctly, and 93% of engine off data are predicted correctly. Thus, in CS mode, the predicted second-by-second tailpipe CO₂ emission rates match the observed ones well.

Figure 83 The Observed and Predicted Second-by-Second Tailpipe CO₂ Emission Rates for Charge Sustaining (CS) Mode for a 2013 Toyota Prius Plug-In Hybrid Measured on January 18, 2013 in Raleigh/Research Triangle Park, North Carolina Area
Figure 84 The Observed and Predicted Second-by-Second Tailpipe CO₂ Emission Rates for Charge Sustaining (CS) Mode for a 2013 Toyota Prius Plug-In Hybrid Measured on January 19, 2013 in Raleigh/Research Triangle Park, North Carolina Area

Figure 85 The Observed and Predicted Second-by-Second Tailpipe CO₂ Emission Rates for Charge Sustaining (CS) Mode for a 2013 Toyota Prius Plug-In Hybrid Measured on January 20, 2013 in Raleigh/Research Triangle Park, North Carolina Area
Figure 86 The Observed and Predicted Second-by-Second Tailpipe CO₂ Emission Rates for Charge Sustaining (CS) Mode for a 2013 Toyota Prius Plug-In Hybrid Measured on January 21, 2013 in Raleigh/Research Triangle Park, North Carolina Area

Figure 87 The Observed and Predicted Second-by-Second Tailpipe CO₂ Emission Rates for Charge Sustaining (CS) Mode for a 2013 Toyota Prius Plug-In Hybrid Measured on January 22, 2013 in Raleigh/Research Triangle Park, North Carolina Area
Figure 88 The Observed and Predicted Second-by-Second Tailpipe CO₂ Emission Rates for Charge Sustaining (CS) Mode for a 2013 Toyota Prius Plug-In Hybrid Measured on January 23, 2013 in Raleigh/Research Triangle Park, North Carolina Area

Figure 89 The Observed and Predicted Second-by-Second Tailpipe CO₂ Emission Rates for Charge Sustaining (CS) Mode for a 2013 Toyota Prius Plug-In Hybrid Measured on January 24, 2013 in Raleigh/Research Triangle Park, North Carolina Area
Figure 90 The Observed and Predicted Second-by-Second Tailpipe CO$_2$ Emission Rates for Charge Sustaining (CS) Mode for a 2013 Toyota Prius Plug-In Hybrid Measured on January 25, 2013 in Raleigh/Research Triangle Park, North Carolina Area
3.9 References


CHAPTER 4 CONCLUSIONS

The method demonstrated here for estimating PHEV energy use and emissions is applicable to estimate energy use and emissions of PHEVs real-world driving. The results given here illustrate the application of a detailed method. Although extensive measurements were made, they were for only one PHEV. This work can be extended in the future to other PHEVs.

Since the measurement was conducted on only one PHEV, the results of energy use and emission rates are not extendable to all PHEVs. Different PHEVs have different electric motor capacity, different hybridization, or different strategies to reduce cold start emissions. Additionally, due to limited time access to the PHEV, there are still some issues not addressed, such as, the sensitivity of engine and TB operation to the ambient temperature, and auxiliary power demand due to heating or air conditioning. All of these factors would affect the energy use and emissions of PHEVs. Driving at ambient temperature near 25 °C without the air conditioner was found to result in low fuel consumption. Therefore, the future work should include on-road real-world measurement on different production PHEVs, considering different climate zones and seasonal effects.

For a PHEV, the sources of energy use and emissions for CD and CS mode are different. Changes in upstream energy use and emissions for two sources of energy, grid electricity and
gasoline, can affect the overall environmental performance of PHEV operation. Thus, fuel cycles for two sources of energy, grid electricity and gasoline, should be taken into account when estimating energy use and emissions for PHEVs. The total energy use and pollutant emission rates vary depending on whether PHEV is in CD or CS mode, and the electricity generation resource mix of region where PHEV operates. With the current electricity generation efficiency and transmission loss in every state, PHEV operating in CS mode is still more energy efficient, relative to CD mode. For 30 states, there would be lower CO₂ emissions in CD versus CS mode. Although time of day of recharging the TB is not quantified, the implications can be inferred by comparing different electric power fuel mixes. If TB charging were to occur overnight, then the emission rates would be based on baseload generation (typically coal, nuclear), whereas if TB charging occurred during peak generation hours, the emission rates would be influenced by peaking generation (typically natural gas, oil). The sensitivity of grid electricity emissions to different generation mix, however, can be inferred from comparison of generation mixes among states. For example, 96 percent of electricity generation in WV is from coal, whereas 98 percent of power generated in RI is from natural gas. Thus, these states are surrogate data sources for the marginal emissions of coal and natural gas, respectively, that would be representative of baseload versus peaking electricity power generation in many states.
When a PHEV operates in CD mode, the total energy use and CO₂ emission rates differ depending on the power demand, and whether the engine is on or off. VSP is a good indicator of the power demand of the PHEV. The total energy use and CO₂ emission rates for engine on and off increase approximately with increasing VSP modes. This work focuses on a method for empirical quantification of energy use and emissions related to PHEV operation. The empirical models developed here, such as regarding the fraction of time for engine on versus off, and the energy use and emission rates versus VSP for CD and CS mode, can be incorporated into VSP-based modal models of vehicle energy use and emissions.

The PHEV is subject to multiple cold starts, and the locations where cold starts occur differ from CLDGVs. On average, total cold start period only accounts for 5% of the engine on period. However, total cold start tailpipe CO and HC emissions account for 26% and 18% of tailpipe emissions, respectively. Even though the total on-road emissions of PHEV are lower than those of CLDGVs, emissions at locations where cold starts happen are higher, particularly for pollutants CO and HC. Thus, another future work is to develop a microscale model for predicting locations of cold starts for PHEVs over a transportation network.

In CD mode, the engine on and off rules developed in this study depend on vehicle speed, road grade, and vehicle acceleration. In CS mode, the engine on and off rules developed in
this study depend on vehicle speed and VSP, which can be calculated from vehicle speed, vehicle acceleration, and road grade. Thus, the PHEV engine status can be predicted by externally observable variables. With derived PHEV energy use and emission rates based on in-use measurement, the engine on and off rules can be integrated with traditional travel demand models to estimate on-road vehicle emission inventories, identify emission hotspots on a transportation network, and predict locations and conditions where PHEV emissions will occur.

APPENDICES
APPENDIX A  Engine On Time in Charge Depleting Mode

A MATLAB program IS developed to determine whether engine is on or off for each second of data for CD mode.

For each day of measurement, the input file is named as “Input#.xlsx” (# = 1, 2, …, n. It signifies the number # input file.). For example, the input files should be named as “Input1.xlsx” for the first day measurement, “Input2.xlsx” for the second day measurement, and “Input3.xlsx” for the third day measurement, etc. The first column of the file, “Input#.xlsx”, contains the second-by-second vehicle speed (mph); the second column of this file contains the second-by-second acceleration (mph/s); and the third column of this file contains the second-by-second road grade (%). Two excel files are produced as output files, “SampleSize.xlsx” and “PredictedOnSampleSize.xlsx”, which give the results of sample size and engine on sample size in each VSP mode for each day of measurement. For example, the first row (Cell A1 to N1) contains the results in 14 VSP modes for the first day of measurement, the second row (Cell A2 to N2) contains the results in 14 VSP modes for the second day of measurement, and the third row (Cell A3 to N3) contains the results in 14 VSP modes for the third day of measurement.
The user is prompted to enter the number of input files. This is the flow of the MATLAB program for each input file: obtaining one second of measurement data; determining engine status for current second (Engine operation is predicted using the engine control rules summarized in Table 20.); calculating and determining VSP mode for current second (The 14 VSP modes are defined by Frey et al.\textsuperscript{1}); updating the sample size in the VSP mode for current second; if engine is determined as on for current second, updating the engine on sample size in the VSP mode for current second; and if there is next second of measurement data, going to the next second and following the flow, and if there is not, outputting the results.
This is the code:

```matlab
prompt = 'How many input files would you like to process? ';
x = input(prompt);
SampleSize = zeros(x,14);
PredictedOnSampleSize = zeros(x,14);
for i = 1:x
    num = xlsread(strcat('Input',num2str(i),'.xlsx'));
    VSS = num(:,1); ACC = num(:,2); RG = num(:,3);
    n = length(VSS);
    Predicted = zeros(n,1);
    VSP = zeros(n,1);
    for ii = 1:n
        VSP(ii) = VSS(ii)*0.44704*(1.1*ACC(ii)*0.44704+9.81*RG(ii)/100+0.132+0.000302*VSS(ii)*VSS(ii)*0.44704*0.44704);
    end
    for j = 1:n
        if VSS(j) <= 35
            if RG(j) >= 4.12
                Predicted(j) = 1;
            end
        elseif VSS(j) <= 45
            if ACC(j) >= 2.5
                Predicted(j) = 1;
            end
        elseif VSS(j) <= 55
            if RG(j) >= -0.34
                Predicted(j) = 1;
            end
        elseif VSS(j) <= 60
            if RG(j) >= -0.34
                Predicted(j) = 1;
            end
        else
```

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Predicted(j) = 1;
end

if VSP(j) < -2
    SampleSize(i,1) = SampleSize(i,1) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,1) = PredictedOnSampleSize(i,1) + 1;
    end
elseif VSP(j) < 0
    SampleSize(i,2) = SampleSize(i,2) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,2) = PredictedOnSampleSize(i,2) + 1;
    end
elseif VSP(j) < 1
    SampleSize(i,3) = SampleSize(i,3) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,3) = PredictedOnSampleSize(i,3) + 1;
    end
elseif VSP(j) < 4
    SampleSize(i,4) = SampleSize(i,4) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,4) = PredictedOnSampleSize(i,4) + 1;
    end
elseif VSP(j) < 7
    SampleSize(i,5) = SampleSize(i,5) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,5) = PredictedOnSampleSize(i,5) + 1;
    end
elseif VSP(j) < 10
    SampleSize(i,6) = SampleSize(i,6) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,6) = PredictedOnSampleSize(i,6) + 1;
    end
elseif VSP(j) < 13
    SampleSize(i,7) = SampleSize(i,7) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,7) = PredictedOnSampleSize(i,7) + 1;
    end
PredictedOnSampleSize(i,7) = PredictedOnSampleSize(i,7) + 1;
end

elseif VSP(j) < 16
SampleSize(i,8) = SampleSize(i,8) + 1;
if Predicted(j) == 1
    PredictedOnSampleSize(i,8) = PredictedOnSampleSize(i,8) + 1;
end

elseif VSP(j) < 19
SampleSize(i,9) = SampleSize(i,9) + 1;
if Predicted(j) == 1
    PredictedOnSampleSize(i,9) = PredictedOnSampleSize(i,9) + 1;
end

elseif VSP(j) < 23
SampleSize(i,10) = SampleSize(i,10) + 1;
if Predicted(j) == 1
    PredictedOnSampleSize(i,10) = PredictedOnSampleSize(i,10) + 1;
end

elseif VSP(j) < 28
SampleSize(i,11) = SampleSize(i,11) + 1;
if Predicted(j) == 1
    PredictedOnSampleSize(i,11) = PredictedOnSampleSize(i,11) + 1;
end

elseif VSP(j) < 33
SampleSize(i,12) = SampleSize(i,12) + 1;
if Predicted(j) == 1
    PredictedOnSampleSize(i,12) = PredictedOnSampleSize(i,12) + 1;
end

elseif VSP(j) < 39
SampleSize(i,13) = SampleSize(i,13) + 1;
if Predicted(j) == 1
    PredictedOnSampleSize(i,13) = PredictedOnSampleSize(i,13) + 1;
end

else
    SampleSize(i,14) = SampleSize(i,14) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,14) = PredictedOnSampleSize(i,14) + 1;
    end
end
end
end
end
xlswrite('SampleSize.xlsx', SampleSize);
xlswrite('PredictedOnSampleSize.xlsx', PredictedOnSampleSize);

APPENDIX B  Engine On Time in Charge Sustaining Mode

A MATLAB program is developed to determine whether engine is on or off for each second of data for CS mode.

For each day of measurement, the input file is named as “Input#.xlsx” (# = 1, 2, …, n. It signifies the number # input file.). For example, the input files should be named as “Input1.xlsx” for the first day measurement, “Input2.xlsx” for the second day measurement, and “Input3.xlsx” for the third day measurement, etc. The first column of the file, “Input#.xlsx”, contains the second-by-second vehicle speed (mph); the second column of this file contains the second-by-second acceleration (mph/s); and the third column of this file contains the second-by-second road grade (%). Two excel files are produced as output files, “SampleSize.xlsx” and “PredictedOnSampleSize.xlsx”, which give the results of sample size and engine on sample size in each VSP mode for each day of measurement. For example, the first row (Cell A1 to N1) contains the results in 14 VSP modes for the first day of measurement, the second row (Cell A2 to N2) contains the results in 14 VSP modes for the second day of measurement, and the third row (Cell A3 to N3) contains the results in 14 VSP modes for the third day of measurement.
The user is prompted to enter the number of input files. This is the flow of the MATLAB program for each input file: obtaining one second of measurement data; determining engine status for current second (Engine operation is predicted using the engine control rules summarized in Table 21.); calculating and determining VSP mode for current second (The 14 VSP modes are defined by Frey et al.\(^1\)); updating the sample size in the VSP mode for current second; if engine is determined as on for current second, updating the engine on sample size in the VSP mode for current second; and if there is next second of measurement data, going to the next second and following the flow, and if there is not, outputting the results.
This is the code:

```matlab
prompt = 'How many input files would you like to process? ';
x = input(prompt);
SampleSize = zeros(x,14);
PredictedOnSampleSize = zeros(x,14);
for i = 1:x
    num = xlsread(strcat('Input',num2str(i),'.xlsx'));
    VSS = num(:,1); ACC = num(:,2); RG = num(:,3);
    n = length(VSS);
    Predicted = zeros(n,1);
    VSP = zeros(n,1);
    for ii = 1:n
        VSP(ii) = VSS(ii)*0.44704*(1.1*ACC(ii)*0.44704+9.81*RG(ii)/100+0.132+0.000302*VSS(ii)*VSS(ii)*0.44704*0.44704);
    end
    for j = 1:n
        if VSS(j) <= 40
            if VSP(j) >= 4.58
                Predicted(j) = 1;
            end
        else
            Predicted(j) = 1;
        end
        if VSP(j) < -2
            SampleSize(i,1) = SampleSize(i,1) + 1;
            if Predicted(j) == 1
                PredictedOnSampleSize(i,1) = PredictedOnSampleSize(i,1) + 1;
            end
        elseif VSP(j) < 0
            SampleSize(i,2) = SampleSize(i,2) + 1;
            if Predicted(j) == 1
                PredictedOnSampleSize(i,2) = PredictedOnSampleSize(i,2) + 1;
        end
    end
end
```
elseif VSP(j) < 1
    SampleSize(i,3) = SampleSize(i,3) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,3) = PredictedOnSampleSize(i,3) + 1;
    end
elseif VSP(j) < 4
    SampleSize(i,4) = SampleSize(i,4) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,4) = PredictedOnSampleSize(i,4) + 1;
    end
elseif VSP(j) < 7
    SampleSize(i,5) = SampleSize(i,5) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,5) = PredictedOnSampleSize(i,5) + 1;
    end
elseif VSP(j) < 10
    SampleSize(i,6) = SampleSize(i,6) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,6) = PredictedOnSampleSize(i,6) + 1;
    end
elseif VSP(j) < 13
    SampleSize(i,7) = SampleSize(i,7) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,7) = PredictedOnSampleSize(i,7) + 1;
    end
elseif VSP(j) < 16
    SampleSize(i,8) = SampleSize(i,8) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,8) = PredictedOnSampleSize(i,8) + 1;
    end
elseif VSP(j) < 19
    SampleSize(i,9) = SampleSize(i,9) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,9) = PredictedOnSampleSize(i,9) + 1;
    end
elseif VSP(j) < 23
    SampleSize(i,10) = SampleSize(i,10) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,10) = PredictedOnSampleSize(i,10) + 1;
    end
elseif VSP(j) < 28
    SampleSize(i,11) = SampleSize(i,11) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,11) = PredictedOnSampleSize(i,11) + 1;
    end
elseif VSP(j) < 33
    SampleSize(i,12) = SampleSize(i,12) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,12) = PredictedOnSampleSize(i,12) + 1;
    end
elseif VSP(j) < 39
    SampleSize(i,13) = SampleSize(i,13) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,13) = PredictedOnSampleSize(i,13) + 1;
    end
else
    SampleSize(i,14) = SampleSize(i,14) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,14) = PredictedOnSampleSize(i,14) + 1;
    end
end
end

e-xlswrite('SampleSize.xlsx', SampleSize);
e-xlswrite('PredictedOnSampleSize.xlsx', PredictedOnSampleSize);

---

APPENDIX C  Duration and Travel Distance in Charge

Depleting Mode

A MATLAB program is developed to determine the duration and travel distance for the CD mode.

The program needs two parameter files, “TB_SOC_Test_Start.xlsx” and “TB_electricity_ER.xlsx”. The first row of the file, “TB_SOC_Test_Start.xlsx”, contains the initial TB SOC when PHEV starts operating for each day of measurement. For example, Cell A1 contains the initial TB SOC for the first day measurement, Cell B1 contains the initial TB SOC for the second day measurement, and Cell C1 contains the initial TB SOC for the third day measurement, etc. The first column (Cell A1 to A14) of the file, “TB_electricity_ER.xlsx”, contains the engine on TB electricity use rate for CD mode in 14 VSP modes, and the second column (Cell B1 to B14) of the file, “TB_electricity_ER.xlsx”, contains the engine off TB electricity use rate for CD mode in 14 VSP modes. Table A - 1 shows the TB electricity use rate during engine on and off for CD mode in each VSP mode.

TB electricity use rate is in terms of gasoline equivalent energy use rate (g/s) based on real-world measurement. For each day of measurement, the input file is named as “Input#.xlsx” (# = 1, 2, …, n. It signifies the number # input file.). For example, the input files should be
named as “Input1.xlsx” for the first day measurement, “Input2.xlsx” for the second day measurement, and “Input3.xlsx” for the third day measurement, etc. The first column of the file, “Input#.xlsx”, contains the second-by-second vehicle speed (mph); the second column of this file contains the second-by-second acceleration (mph/s); and the third column of this file contains the second-by-second road grade (%). Two excel files are produced as output files, “Duration.xlsx” and “Distance.xlsx”, which give the results of predicted duration (s) and travel distance (mile) in CD mode for each day of measurement. For example, Cell A1 contains the result for the first day measurement, Cell B1 contains the result for the second day measurement, and Cell C1 contains the result for the third day measurement, etc.

This is the flow of the MATLAB program for each input file: obtaining one second of measurement data; determining engine status for current second (Engine operation is predicted in terms of vehicle speed, road grade, and acceleration using the engine control rules summarized in Table 20.); calculating and determining VSP mode for current second (The 14 VSP modes are defined by Frey et al.\textsuperscript{1}); updating the total electricity energy left in the TB depending on engine status and VSP mode; and checking whether the total electricity energy left in the TB is less than or equal to 0 (If it is true, outputting the results, and if it is not, going to the next second and following the flow again.).
Table A - 1 The Traction Battery (TB) Electricity Use Rate During Engine On and Off for Charge Depleting (CD) Mode in Each Vehicle Specific Power (VSP) Mode

<table>
<thead>
<tr>
<th>VSP Mode</th>
<th>Engine On (g/s)</th>
<th>Engine Off (g/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.18</td>
<td>-0.34</td>
</tr>
<tr>
<td>2</td>
<td>-0.09</td>
<td>0.07</td>
</tr>
<tr>
<td>3</td>
<td>0.01</td>
<td>0.06</td>
</tr>
<tr>
<td>4</td>
<td>0.09</td>
<td>0.46</td>
</tr>
<tr>
<td>5</td>
<td>0.28</td>
<td>0.93</td>
</tr>
<tr>
<td>6</td>
<td>0.33</td>
<td>1.11</td>
</tr>
<tr>
<td>7</td>
<td>0.22</td>
<td>1.56</td>
</tr>
<tr>
<td>8</td>
<td>0.31</td>
<td>1.45</td>
</tr>
<tr>
<td>9</td>
<td>0.18</td>
<td>1.95</td>
</tr>
<tr>
<td>10</td>
<td>0.00</td>
<td>2.09</td>
</tr>
<tr>
<td>11</td>
<td>0.29</td>
<td>1.96</td>
</tr>
<tr>
<td>12</td>
<td>0.00</td>
<td>2.37</td>
</tr>
<tr>
<td>13</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>14</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>
This is the code:

```
Watt_hour_per_SOC = 54.7703111308352;
Gasoline_Heating_Value = 113602; % Btu/gallon
Gasoline_Density = 2791; % g/gallon
Electricity_Heat_Input = 10216.5079529135; % Btu/kWh
Gasoline_per_kWh = Electricity_Heat_Input/Gasoline_Heating_Value*Gasoline_Density; % g/kWh

TB_SOC_Test_Start = xlsread('TB_SOC_Test_Start.xlsx');
TB_SOC_Test_End = 23.4;

Total_Electricity_Energy = zeros(1,length(TB_SOC_Test_Start));
for m = 1:length(TB_SOC_Test_Start)
    Total_Electricity_Energy(m) = (TB_SOC_Test_Start(m) - TB_SOC_Test_End)*Watt_hour_per_SOC/1000*Gasoline_per_kWh;
end

electricityER = xlsread('TB_electricity_ER.xlsx');

Duration = zeros(1,length(TB_SOC_Test_Start));
Distance = zeros(1,length(TB_SOC_Test_Start));

for i = 1:length(TB_SOC_Test_Start)
    num = xlsread(strcat('Input',num2str(i),'.xlsx'));
    VSS = num(:,1); ACC = num(:,2); RG = num(:,3);
    n = length(VSS);
    Predicted = zeros(n,1);
    VSP = zeros(n,1);
    for ii = 1:n
        VSP(ii) = VSS(ii)*0.44704*(1.1*ACC(ii)*0.44704+9.81*RG(ii)/100+0.132+0.000302*VSS(ii)*VSS(ii)*0.44704*0.44704);
    end
    for j = 1:n
```
if VSS(j) <= 35
    if RG(j) >= 4.12
        Predicted(j) = 1;
    end
elseif VSS(j) <= 45
    if ACC(j) >= 2.5
        Predicted(j) = 1;
    end
elseif VSS(j) <= 55
    if RG(j) >= 1.97
        Predicted(j) = 1;
    end
elseif VSS(j) <= 60
    if RG(j) >= -0.34
        Predicted(j) = 1;
    end
else
    Predicted(j) = 1;
end

if Predicted(j) == 1
    if VSP(j) < -2
        Total_Electricity_Energy(i)=Total_Electricity_Energy(i)-electricityER(1,1);
    elseif VSP(j) < 0
        Total_Electricity_Energy(i)=Total_Electricity_Energy(i)-electricityER(2,1);
    elseif VSP(j) < 1
        Total_Electricity_Energy(i)=Total_Electricity_Energy(i)-electricityER(3,1);
    elseif VSP(j) < 4
        Total_Electricity_Energy(i)=Total_Electricity_Energy(i)-electricityER(4,1);
    elseif VSP(j) < 7
        Total_Electricity_Energy(i)=Total_Electricity_Energy(i)-electricityER(5,1);
    elseif VSP(j) < 10
        Total_Electricity_Energy(i)=Total_Electricity_Energy(i)-electricityER(6,1);
    elseif VSP(j) < 13
        Total_Electricity_Energy(i)=Total_Electricity_Energy(i)-electricityER(7,1);
    else
        Total_Electricity_Energy(i)=Total_Electricity_Energy(i)-electricityER(8,1);
    end
end
Total_Electricity_Energy(i)=Total_Electricity_Energy(i)-electricityER(8,1);
elseif VSP(j) < 19
  Total_Electricity_Energy(i)=Total_Electricity_Energy(i)-electricityER(9,1);
elseif VSP(j) < 23
  Total_Electricity_Energy(i)=Total_Electricity_Energy(i)-electricityER(10,1);
elseif VSP(j) < 28
  Total_Electricity_Energy(i)=Total_Electricity_Energy(i)-electricityER(11,1);
elseif VSP(j) < 33
  Total_Electricity_Energy(i)=Total_Electricity_Energy(i)-electricityER(12,1);
elseif VSP(j) < 39
  Total_Electricity_Energy(i)=Total_Electricity_Energy(i)-electricityER(13,1);
else
  Total_Electricity_Energy(i)=Total_Electricity_Energy(i)-electricityER(14,1);
end
else
  if VSP(j) < -2
    Total_Electricity_Energy(i)=Total_Electricity_Energy(i)-electricityER(1,2);
  elseif VSP(j) < 0
    Total_Electricity_Energy(i)=Total_Electricity_Energy(i)-electricityER(2,2);
  elseif VSP(j) < 1
    Total_Electricity_Energy(i)=Total_Electricity_Energy(i)-electricityER(3,2);
  elseif VSP(j) < 4
    Total_Electricity_Energy(i)=Total_Electricity_Energy(i)-electricityER(4,2);
  elseif VSP(j) < 7
    Total_Electricity_Energy(i)=Total_Electricity_Energy(i)-electricityER(5,2);
  elseif VSP(j) < 10
    Total_Electricity_Energy(i)=Total_Electricity_Energy(i)-electricityER(6,2);
  elseif VSP(j) < 13
    Total_Electricity_Energy(i)=Total_Electricity_Energy(i)-electricityER(7,2);
  elseif VSP(j) < 16
    Total_Electricity_Energy(i)=Total_Electricity_Energy(i)-electricityER(8,2);
  elseif VSP(j) < 19
    Total_Electricity_Energy(i)=Total_Electricity_Energy(i)-electricityER(9,2);
  elseif VSP(j) < 23
    Total_Electricity_Energy(i)=Total_Electricity_Energy(i)-electricityER(10,2);
  elseif VSP(j) < 28
    Total_Electricity_Energy(i)=Total_Electricity_Energy(i)-electricityER(11,2);
  else
    Total_Electricity_Energy(i)=Total_Electricity_Energy(i)-electricityER(12,2);
  end
end
Total_Electricity_Energy(i)=Total_Electricity_Energy(i)-electricityER(11,2);
elseif VSP(j) < 33
    Total_Electricity_Energy(i)=Total_Electricity_Energy(i)-electricityER(12,2);
elseif VSP(j) < 39
    Total_Electricity_Energy(i)=Total_Electricity_Energy(i)-electricityER(13,2);
else
    Total_Electricity_Energy(i)=Total_Electricity_Energy(i)-electricityER(14,2);
end
end

if Total_Electricity_Energy(i) <= 0
    Duration(i) = j;
    Distance(i) = sum(VSS(1:j))/3600;
    break;
end
end

xlswrite('Duration.xlsx', Duration);
xlswrite('Distance.xlsx', Distance);

APPENDIX D  Cycle Average Energy Use and Emission Rates in
Charge Depleting Mode

A MATLAB program is developed to estimate the cycle average energy use and emission rates in CD mode.

The program needs a parameter file, “ER.xlsx”. The 1st column (Cell A1 to A14) of the file, “ER.xlsx”, contains the energy use rate from electricity and gasoline for engine on in CD mode in 14 VSP modes, the 2nd column (Cell B1 to B14) contains the energy use rate from electricity for engine off in CD mode in 14 VSP modes, the 3rd column (Cell C1 to C14) of the file contains the CO₂ emission rate from electricity and gasoline for engine on in CD mode in 14 VSP modes, the 4th column (Cell D1 to D14) contains the CO₂ emission rate from electricity for engine off in CD mode in 14 VSP modes, the 5th column (Cell E1 to E14) of the file contains the CO emission rate from electricity and gasoline for engine on in CD mode in 14 VSP modes, the 6th column (Cell F1 to F14) contains the CO emission rate from electricity for engine off in CD mode in 14 VSP modes, the 7th column (Cell G1 to G14) of the file contains the HC emission rate from electricity and gasoline for engine on in CD mode in 14 VSP modes, the 8th column (Cell H1 to H14) contains the HC emission rate from electricity for engine off in CD mode in 14 VSP modes, the 9th column (Cell I1 to I14) of the
file contains the NO$_x$ emission rate from electricity and gasoline for engine on in CD mode in 14 VSP modes, the 10$^{th}$ column (Cell J1 to J14) contains the NO$_x$ emission rate from electricity for engine off in CD mode in 14 VSP modes, the 11$^{th}$ column (Cell K1 to K14) of the file contains the SO$_x$ emission rate from electricity and gasoline for engine on in CD mode in 14 VSP modes, the 12$^{th}$ column (Cell L1 to L14) contains the SO$_x$ emission rate from electricity for engine off in CD mode in 14 VSP modes, the 13$^{th}$ column (Cell M1 to M14) of the file contains the PM$_{2.5}$ emission rate from electricity and gasoline for engine on in CD mode in 14 VSP modes, the 14$^{th}$ column (Cell N1 to N14) contains the PM$_{2.5}$ emission rate from electricity for engine off in CD mode in 14 VSP modes, the 15$^{th}$ column (Cell O1 to O14) of the file contains the PM$_{10}$ emission rate from electricity and gasoline for engine on in CD mode in 14 VSP modes, and the 16$^{th}$ column (Cell P1 to P14) contains the PM$_{10}$ emission rate from electricity for engine off in CD mode in 14 VSP modes. Table A - 2 shows the energy use and emission rates during engine on and off for CD mode in each VSP mode. For each day of measurement, the input file is named as “Input#.xlsx” (# = 1, 2, ..., n. It signifies the number # input file.). For example, the input files should be named as “Input1.xlsx” for the first day measurement, “Input2.xlsx” for the second day measurement, and “Input3.xlsx” for the third day measurement, etc. The first column of the file, “Input#.xlsx”, contains the second-by-second vehicle speed (mph); the second column of this
file contains the second-by-second acceleration (mph/s); and the third column of this file contains the second-by-second road grade (%). Eight excel files are produced as output files, “PredictedEnergyER.xlsx”, “PredictedCO2ER.xlsx”, “PredictedCOER.xlsx”, “PredictedHCER.xlsx”, “PredictedNOxER.xlsx”, “PredictedSOxER.xlsx”, “Predictedpm25ER.xlsx”, and “PredictedPM10ER.xlsx”, which give the results of estimated cycle average energy use rate, and CO$_2$, CO, HC, NO$_x$, SO$_x$, PM$_{2.5}$, and PM$_{10}$ emission rates in CD mode for each day of measurement. For example, Cell A1 contains the result for the first day measurement, Cell A2 contains the result for the second day measurement, and Cell A3 contains the result for the third day measurement, etc.

The user is prompted to enter the number of input files. This is the flow of the MATLAB program for each input file: obtaining one second of measurement data; determining engine status for current second (Engine operation is predicted using the engine control rules summarized in Table 20.); calculating and determining VSP mode for current second (The 14 VSP modes are defined by Frey et al.$^1$); updating the sample size in the VSP mode for current second; if engine is determined as on for current second, updating the engine on sample size in the VSP mode for current second; and if there is next second of measurement data, going to the next second and following the flow, and if there is not, calculating the fraction of travel time for each VSP mode, the fraction of travel time for engine on in each
VSP mode, and the cycle average energy use and emission rates based on Equation (5), and outputting the results.
Table A - 2 The Energy Use and Emission Rates During Engine On and Off for Charge Depleting (CD) Mode in Each Vehicle Specific Power (VSP) Mode

<table>
<thead>
<tr>
<th>VSP Mode</th>
<th>Energy Use</th>
<th>CO₂</th>
<th>CO</th>
<th>HC</th>
<th>NOₓ</th>
<th>SOₓ</th>
<th>PM₂.₅</th>
<th>PM₁₀</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g/s</td>
<td>g/s</td>
<td>mg/s</td>
<td>mg/s</td>
<td>mg/s</td>
<td>mg/s</td>
<td>mg/s</td>
<td>mg/s</td>
</tr>
<tr>
<td>On</td>
<td>Off</td>
<td>On</td>
<td>Off</td>
<td>On</td>
<td>Off</td>
<td>On</td>
<td>Off</td>
<td>On</td>
</tr>
<tr>
<td>1</td>
<td>0.24</td>
<td>-0.34</td>
<td>1.42</td>
<td>0.19</td>
<td>1.33</td>
<td>0.11</td>
<td>0.72</td>
<td>0.02</td>
</tr>
<tr>
<td>2</td>
<td>0.34</td>
<td>0.07</td>
<td>1.25</td>
<td>0.39</td>
<td>1.67</td>
<td>0.22</td>
<td>0.51</td>
<td>0.04</td>
</tr>
<tr>
<td>3</td>
<td>0.46</td>
<td>0.06</td>
<td>1.33</td>
<td>0.11</td>
<td>3.68</td>
<td>0.06</td>
<td>0.99</td>
<td>0.01</td>
</tr>
<tr>
<td>4</td>
<td>0.60</td>
<td>0.46</td>
<td>1.73</td>
<td>0.72</td>
<td>1.28</td>
<td>0.40</td>
<td>0.61</td>
<td>0.08</td>
</tr>
<tr>
<td>5</td>
<td>1.12</td>
<td>0.93</td>
<td>2.69</td>
<td>1.60</td>
<td>1.75</td>
<td>0.90</td>
<td>1.27</td>
<td>0.17</td>
</tr>
<tr>
<td>6</td>
<td>1.42</td>
<td>1.11</td>
<td>3.74</td>
<td>1.87</td>
<td>1.92</td>
<td>1.05</td>
<td>1.34</td>
<td>0.20</td>
</tr>
<tr>
<td>7</td>
<td>1.65</td>
<td>1.56</td>
<td>4.48</td>
<td>2.67</td>
<td>2.14</td>
<td>1.49</td>
<td>1.66</td>
<td>0.28</td>
</tr>
<tr>
<td>8</td>
<td>1.81</td>
<td>1.45</td>
<td>4.99</td>
<td>2.80</td>
<td>2.29</td>
<td>1.56</td>
<td>2.28</td>
<td>0.30</td>
</tr>
<tr>
<td>9</td>
<td>1.93</td>
<td>1.95</td>
<td>5.43</td>
<td>3.70</td>
<td>3.45</td>
<td>2.07</td>
<td>2.42</td>
<td>0.39</td>
</tr>
<tr>
<td>10</td>
<td>1.89</td>
<td>2.09</td>
<td>5.47</td>
<td>3.89</td>
<td>2.66</td>
<td>2.18</td>
<td>2.23</td>
<td>0.41</td>
</tr>
<tr>
<td>11</td>
<td>2.31</td>
<td>1.96</td>
<td>5.84</td>
<td>4.13</td>
<td>2.52</td>
<td>2.31</td>
<td>3.03</td>
<td>0.44</td>
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<tr>
<td>12</td>
<td>2.51</td>
<td>2.37</td>
<td>7.25</td>
<td>5.01</td>
<td>2.22</td>
<td>2.80</td>
<td>7.94</td>
<td>0.53</td>
</tr>
<tr>
<td>13</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>14</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

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This is the code:

```matlab
prompt = 'How many input files would you like to process? ';
x = input(prompt);
SampleSize = zeros(x,14);
PredictedOnSampleSize = zeros(x,14);
for i = 1:x
    num = xlsread(strcat('Input',num2str(i),'.xlsx'));
    VSS = num(:,1); ACC = num(:,2); RG = num(:,3);
    n = length(VSS);
    Predicted = zeros(n,1);
    VSP = zeros(n,1);
    for ii = 1:n
        VSP(ii) = VSS(ii)*0.44704*(1.1*ACC(ii)*0.44704+9.81*RG(ii)/100+0.132+0.000302*VSS(ii)*VSS(ii)*0.44704*0.44704);
    end
    for j = 1:n
        if VSS(j) <= 35
            if RG(j) >= 4.12
                Predicted(j) = 1;
            end
        elseif VSS(j) <= 45
            if ACC(j) >= 2.5
                Predicted(j) = 1;
            end
        elseif VSS(j) <= 55
            if RG(j) >= 1.97
                Predicted(j) = 1;
            end
        elseif VSS(j) <= 60
            if RG(j) >= -0.34
                Predicted(j) = 1;
            end
        else
            Predicted(j) = 0;
        end
    end
end
```
Predicted(j) = 1;
end

if VSP(j) < -2
    SampleSize(i,1) = SampleSize(i,1) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,1) = PredictedOnSampleSize(i,1) + 1;
    end
elseif VSP(j) < 0
    SampleSize(i,2) = SampleSize(i,2) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,2) = PredictedOnSampleSize(i,2) + 1;
    end
elseif VSP(j) < 1
    SampleSize(i,3) = SampleSize(i,3) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,3) = PredictedOnSampleSize(i,3) + 1;
    end
elseif VSP(j) < 4
    SampleSize(i,4) = SampleSize(i,4) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,4) = PredictedOnSampleSize(i,4) + 1;
    end
elseif VSP(j) < 7
    SampleSize(i,5) = SampleSize(i,5) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,5) = PredictedOnSampleSize(i,5) + 1;
    end
elseif VSP(j) < 10
    SampleSize(i,6) = SampleSize(i,6) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,6) = PredictedOnSampleSize(i,6) + 1;
    end
elseif VSP(j) < 13
    SampleSize(i,7) = SampleSize(i,7) + 1;
    if Predicted(j) == 1
PredictedOnSampleSize(i,7) = PredictedOnSampleSize(i,7) + 1;
end
elseif VSP(j) < 16
    SampleSize(i,8) = SampleSize(i,8) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,8) = PredictedOnSampleSize(i,8) + 1;
    end
elseif VSP(j) < 19
    SampleSize(i,9) = SampleSize(i,9) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,9) = PredictedOnSampleSize(i,9) + 1;
    end
elseif VSP(j) < 23
    SampleSize(i,10) = SampleSize(i,10) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,10) = PredictedOnSampleSize(i,10) + 1;
    end
elseif VSP(j) < 28
    SampleSize(i,11) = SampleSize(i,11) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,11) = PredictedOnSampleSize(i,11) + 1;
    end
elseif VSP(j) < 33
    SampleSize(i,12) = SampleSize(i,12) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,12) = PredictedOnSampleSize(i,12) + 1;
    end
elseif VSP(j) < 39
    SampleSize(i,13) = SampleSize(i,13) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,13) = PredictedOnSampleSize(i,13) + 1;
    end
else
    SampleSize(i,14) = SampleSize(i,14) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,14) = PredictedOnSampleSize(i,14) + 1;
ER = xlsread('ER.xlsx');

FractionOfTravelTime = zeros(x,14);  
FractionOfPredictedOnTravelTime = zeros(x,14);  
PredictedEnergyER = zeros(x,1);  
PredictedCO2ER = zeros(x,1);  
PredictedCOER = zeros(x,1);  
PredictedHCER = zeros(x,1);  
PredictedNOxER = zeros(x,1);  
PredictedSOxER = zeros(x,1);  
PredictedPM25ER = zeros(x,1);  
PredictedPM10ER = zeros(x,1);  

DaySampleSize = sum(SampleSize,2);

for k = 1:x
    for m = 1:14
        FractionOfTravelTime(k,m) = SampleSize(k,m)/DaySampleSize(k);  
        if SampleSize(k,m) ~= 0  
            FractionOfPredictedOnTravelTime(k,m) = PredictedOnSampleSize(k,m)/SampleSize(k,m);  
        end
        PredictedEnergyER(k) = PredictedEnergyER(k) + FractionOfTravelTime(k,m) *  
            (ER(m,1)*FractionOfPredictedOnTravelTime(k,m) + ER(m,2)*(1-FractionOfPredictedOnTravelTime(k,m)));  
        PredictedCO2ER(k) = PredictedCO2ER(k) + FractionOfTravelTime(k,m) *  
            (ER(m,3)*FractionOfPredictedOnTravelTime(k,m) + ER(m,4)*(1-FractionOfPredictedOnTravelTime(k,m)));  
        PredictedCOER(k) = PredictedCOER(k) + FractionOfTravelTime(k,m) *  
            (ER(m,5)*FractionOfPredictedOnTravelTime(k,m) + ER(m,6)*(1-FractionOfPredictedOnTravelTime(k,m)));  
        PredictedHCER(k) = PredictedHCER(k) + FractionOfTravelTime(k,m) *  
            (ER(m,7)*FractionOfPredictedOnTravelTime(k,m) + ER(m,8)*(1-FractionOfPredictedOnTravelTime(k,m)));  
        PredictedNOxER(k) = PredictedNOxER(k) + FractionOfTravelTime(k,m) *  
            (ER(m,9)*FractionOfPredictedOnTravelTime(k,m) + ER(m,10)*(1-FractionOfPredictedOnTravelTime(k,m)));  
    end
end
PredictedSOxER(k) = PredictedSOxER(k) + FractionOfTravelTime(k,m) * (ER(m,11)*FractionOfPredictedOnTravelTime(k,m)+ER(m,12)*(1-FractionOfPredictedOnTravelTime(k,m)));

PredictedPM25ER(k) = PredictedPM25ER(k) + FractionOfTravelTime(k,m) * (ER(m,13)*FractionOfPredictedOnTravelTime(k,m)+ER(m,14)*(1-FractionOfPredictedOnTravelTime(k,m)));

PredictedPM10ER(k) = PredictedPM10ER(k) + FractionOfTravelTime(k,m) * (ER(m,15)*FractionOfPredictedOnTravelTime(k,m)+ER(m,16)*(1-FractionOfPredictedOnTravelTime(k,m)));

end
end

xlswrite('PredictedEnergyER.xlsx', PredictedEnergyER);
xlswrite('PredictedCO2ER.xlsx', PredictedCO2ER);
xlswrite('PredictedCOER.xlsx', PredictedCOER);
xlswrite('PredictedHCER.xlsx', PredictedHCER);
xlswrite('PredictedNOxER.xlsx', PredictedNOxER);
xlswrite('PredictedSOxER.xlsx', PredictedSOxER);
xlswrite('PredictedPM25ER.xlsx', PredictedPM25ER);
xlswrite('PredictedPM10ER.xlsx', PredictedPM10ER);

APPENDIX E  Cycle Average Energy Use and Emission Rates in
Charge Sustaining Mode

A MATLAB program is developed to estimate the cycle average energy use and emission
rates in CS mode.

The program needs a parameter file, “ER.xlsx”. The 1st column (Cell A1 to A14) of the file,
“ER.xlsx”, contains the energy use rate from gasoline for engine on in CS mode in 14 VSP
modes, the 2nd column (Cell B1 to B14) of the file contains the CO₂ emission rate from
gasoline for engine on in CS mode in 14 VSP modes, the 3rd column (Cell C1 to C14) of the
file contains the CO emission rate from gasoline for engine on in CS mode in 14 VSP modes,
the 4th column (Cell D1 to D14) of the file contains the HC emission rate from gasoline for
engine on in CS mode in 14 VSP modes, the 5th column (Cell E1 to E14) of the file contains
the NOₓ emission rate from gasoline for engine on in CS mode in 14 VSP modes, the 6th
column (Cell F1 to F14) of the file contains the SOₓ emission rate from gasoline for engine
on in CS mode in 14 VSP modes, the 7th column (Cell G1 to G14) of the file contains the
PM₂₅ emission rate from gasoline for engine on in CS mode in 14 VSP modes, and the 8th
column (Cell H1 to H14) of the file contains the PM₁₀ emission rate from gasoline for engine
on in CS mode in 14 VSP modes. Table A - 3 shows the energy use and emission rates
during engine on for CS mode in each VSP mode. For each day of measurement, the input file is named as “Input#.xlsx” (# = 1, 2, …, n. It signifies the number # input file.). For example, the input files should be named as “Input1.xlsx” for the first day measurement, “Input2.xlsx” for the second day measurement, and “Input3.xlsx” for the third day measurement, etc. The first column of the file, “Input#.xlsx”, contains the second-by-second vehicle speed (mph); the second column of this file contains the second-by-second acceleration (mph/s); and the third column of this file contains the second-by-second road grade (%). Eight excel files are produced as output files, “PredictedEnergyER.xlsx”, “PredictedCO2ER.xlsx”, “PredictedCOER.xlsx”, “PredictedHCER.xlsx”, “PredictedNOxER.xlsx”, “PredictedSOxER.xlsx”, “Predictedpm25ER.xlsx”, and “PredictedPM10ER.xlsx”, which give the results of estimated cycle average energy use rate, and CO₂, CO, HC, NOₓ, SOₓ, PM_{2.5}, and PM_{10} emission rates in CS mode for each day of measurement. For example, Cell A1 contains the result for the first day measurement, Cell A2 contains the result for the second day measurement, and Cell A3 contains the result for the third day measurement, etc.

The user is prompted to enter the number of input files. This is the flow of the MATLAB program for each input file: obtaining one second of measurement data; determining engine status for current second (Engine operation is predicted using the engine control rules
summarized in Table 21); calculating and determining VSP mode for current second (The 14 VSP modes are defined by Frey et al.\textsuperscript{1}); updating the sample size in the VSP mode for current second; if engine is determined as on for current second, updating the engine on sample size in the VSP mode for current second; and if there is next second of measurement data, going to the next second and following the flow, and if there is not, calculating the fraction of travel time for each VSP mode, the fraction of travel time for engine on in each VSP mode, and the cycle average energy use and emission rates based on Equation (6), and outputting the results.
Table A - 3 The Energy Use and Emission Rates During Engine On for Charge Sustaining (CS) Mode in Each Vehicle Specific Power (VSP) Mode

<table>
<thead>
<tr>
<th>VSP Mode</th>
<th>Energy Use</th>
<th>CO₂</th>
<th>CO</th>
<th>HC</th>
<th>NOₓ</th>
<th>SOₓ</th>
<th>PM₂.₅</th>
<th>PM₁₀</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g/s</td>
<td>g/s</td>
<td>mg/s</td>
<td>mg/s</td>
<td>mg/s</td>
<td>mg/s</td>
<td>mg/s</td>
<td>mg/s</td>
</tr>
<tr>
<td>1</td>
<td>0.46</td>
<td>1.34</td>
<td>0.59</td>
<td>0.48</td>
<td>0.78</td>
<td>0.62</td>
<td>0.05</td>
<td>0.08</td>
</tr>
<tr>
<td>2</td>
<td>0.64</td>
<td>1.84</td>
<td>0.79</td>
<td>0.66</td>
<td>1.08</td>
<td>0.85</td>
<td>0.07</td>
<td>0.10</td>
</tr>
<tr>
<td>3</td>
<td>0.56</td>
<td>1.62</td>
<td>1.59</td>
<td>0.67</td>
<td>0.98</td>
<td>0.75</td>
<td>0.06</td>
<td>0.09</td>
</tr>
<tr>
<td>4</td>
<td>0.76</td>
<td>2.18</td>
<td>0.83</td>
<td>0.78</td>
<td>1.31</td>
<td>1.01</td>
<td>0.09</td>
<td>0.12</td>
</tr>
<tr>
<td>5</td>
<td>0.90</td>
<td>2.62</td>
<td>0.99</td>
<td>0.94</td>
<td>1.57</td>
<td>1.20</td>
<td>0.10</td>
<td>0.15</td>
</tr>
<tr>
<td>6</td>
<td>1.09</td>
<td>3.14</td>
<td>1.28</td>
<td>1.12</td>
<td>1.87</td>
<td>1.44</td>
<td>0.13</td>
<td>0.18</td>
</tr>
<tr>
<td>7</td>
<td>1.28</td>
<td>3.70</td>
<td>1.29</td>
<td>1.32</td>
<td>2.18</td>
<td>1.70</td>
<td>0.15</td>
<td>0.21</td>
</tr>
<tr>
<td>8</td>
<td>1.44</td>
<td>4.17</td>
<td>1.43</td>
<td>1.49</td>
<td>2.46</td>
<td>1.92</td>
<td>0.17</td>
<td>0.24</td>
</tr>
<tr>
<td>9</td>
<td>1.57</td>
<td>4.55</td>
<td>1.56</td>
<td>1.62</td>
<td>2.67</td>
<td>2.09</td>
<td>0.18</td>
<td>0.26</td>
</tr>
<tr>
<td>10</td>
<td>1.65</td>
<td>4.78</td>
<td>1.78</td>
<td>1.72</td>
<td>2.81</td>
<td>2.20</td>
<td>0.19</td>
<td>0.27</td>
</tr>
<tr>
<td>11</td>
<td>1.83</td>
<td>5.29</td>
<td>1.93</td>
<td>1.89</td>
<td>3.08</td>
<td>2.44</td>
<td>0.21</td>
<td>0.30</td>
</tr>
<tr>
<td>12</td>
<td>2.04</td>
<td>5.89</td>
<td>1.91</td>
<td>2.10</td>
<td>3.41</td>
<td>2.71</td>
<td>0.23</td>
<td>0.33</td>
</tr>
<tr>
<td>13</td>
<td>2.24</td>
<td>6.47</td>
<td>2.24</td>
<td>2.31</td>
<td>3.74</td>
<td>2.98</td>
<td>0.26</td>
<td>0.36</td>
</tr>
<tr>
<td>14</td>
<td>2.56</td>
<td>7.40</td>
<td>2.02</td>
<td>2.58</td>
<td>4.27</td>
<td>3.41</td>
<td>0.30</td>
<td>0.42</td>
</tr>
</tbody>
</table>
This is the code:

```matlab
prompt = 'How many input files would you like to process? ';
x = input(prompt);
SampleSize = zeros(x,14);
PredictedOnSampleSize = zeros(x,14);
for i = 1:x
    num = xlsread(strcat('Input',num2str(i),'.xlsx'));
    VSS = num(:,1); ACC = num(:,2); RG = num(:,3);
    n = length(VSS);
    Predicted = zeros(n,1);
    VSP = zeros(n,1);
    for ii = 1:n
        VSP(ii) = VSS(ii)*0.44704*(1.1*ACC(ii)*0.44704+9.81*RG(ii)/100+0.132+0.000302*VSS(ii)*VSS(ii)*0.44704*0.44704);
    end
    for j = 1:n
        if VSS(j) <= 40
            if VSP(j) >= 4.58
                Predicted(j) = 1;
            end
        else
            Predicted(j) = 1;
        end
    end
if VSP(j) < -2
    SampleSize(i,1) = SampleSize(i,1) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,1) = PredictedOnSampleSize(i,1) + 1;
    end
elseif VSP(j) < 0
    SampleSize(i,2) = SampleSize(i,2) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,2) = PredictedOnSampleSize(i,2) + 1;
    end
```
end

elseif VSP(j) < 1
    SampleSize(i,3) = SampleSize(i,3) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,3) = PredictedOnSampleSize(i,3) + 1;
    end
elseif VSP(j) < 4
    SampleSize(i,4) = SampleSize(i,4) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,4) = PredictedOnSampleSize(i,4) + 1;
    end
elseif VSP(j) < 7
    SampleSize(i,5) = SampleSize(i,5) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,5) = PredictedOnSampleSize(i,5) + 1;
    end
elseif VSP(j) < 10
    SampleSize(i,6) = SampleSize(i,6) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,6) = PredictedOnSampleSize(i,6) + 1;
    end
elseif VSP(j) < 13
    SampleSize(i,7) = SampleSize(i,7) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,7) = PredictedOnSampleSize(i,7) + 1;
    end
elseif VSP(j) < 16
    SampleSize(i,8) = SampleSize(i,8) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,8) = PredictedOnSampleSize(i,8) + 1;
    end
elseif VSP(j) < 19
    SampleSize(i,9) = SampleSize(i,9) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,9) = PredictedOnSampleSize(i,9) + 1;
    end
elseif VSP(j) < 23
    SampleSize(i,10) = SampleSize(i,10) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,10) = PredictedOnSampleSize(i,10) + 1;
    end
elseif VSP(j) < 28
    SampleSize(i,11) = SampleSize(i,11) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,11) = PredictedOnSampleSize(i,11) + 1;
    end
elseif VSP(j) < 33
    SampleSize(i,12) = SampleSize(i,12) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,12) = PredictedOnSampleSize(i,12) + 1;
    end
elseif VSP(j) < 39
    SampleSize(i,13) = SampleSize(i,13) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,13) = PredictedOnSampleSize(i,13) + 1;
    end
else
    SampleSize(i,14) = SampleSize(i,14) + 1;
    if Predicted(j) == 1
        PredictedOnSampleSize(i,14) = PredictedOnSampleSize(i,14) + 1;
    end
end
end
end

ER = xlsread('ER.xlsx');

FractionOfTravelTime = zeros(x,14);
FractionOfPredictedOnTravelTime = zeros(x,14);
PredictedEnergyER = zeros(x,1);
PredictedCO2ER = zeros(x,1);
PredictedCOER = zeros(x,1);
PredictedHCER = zeros(x,1);
PredictedNOxER = zeros(x,1);
PredictedSOxER = zeros(x,1);
PredictedPM25ER = zeros(x,1);
PredictedPM10ER = zeros(x,1);

DaySampleSize = sum(SampleSize,2);

for k = 1:x
    for m = 1:14
        FractionOfTravelTime(k,m) = SampleSize(k,m)/DaySampleSize(k);
        if SampleSize(k,m) ~= 0
            FractionOfPredictedOnTravelTime(k,m) = PredictedOnSampleSize(k,m)/SampleSize(k,m);
        end
        PredictedEnergyER(k) = PredictedEnergyER(k) + FractionOfTravelTime(k,m) * ER(m,1)*FractionOfPredictedOnTravelTime(k,m);
        PredictedCO2ER(k) = PredictedCO2ER(k) + FractionOfTravelTime(k,m) * ER(m,2)*FractionOfPredictedOnTravelTime(k,m);
        PredictedCOER(k) = PredictedCOER(k) + FractionOfTravelTime(k,m) * ER(m,3)*FractionOfPredictedOnTravelTime(k,m);
        PredictedHCER(k) = PredictedHCER(k) + FractionOfTravelTime(k,m) * ER(m,4)*FractionOfPredictedOnTravelTime(k,m);
        PredictedNOxER(k) = PredictedNOxER(k) + FractionOfTravelTime(k,m) * ER(m,5)*FractionOfPredictedOnTravelTime(k,m);
        PredictedSOxER(k) = PredictedSOxER(k) + FractionOfTravelTime(k,m) * ER(m,6)*FractionOfPredictedOnTravelTime(k,m);
        PredictedPM25ER(k) = PredictedPM25ER(k) + FractionOfTravelTime(k,m) * ER(m,7)*FractionOfPredictedOnTravelTime(k,m);
        PredictedPM10ER(k) = PredictedPM10ER(k) + FractionOfTravelTime(k,m) * ER(m,8)*FractionOfPredictedOnTravelTime(k,m);
    end
end

xlswrite('PredictedEnergyER.xlsx', PredictedEnergyER);
xlswrite('PredictedCO2ER.xlsx', PredictedCO2ER);
xlswrite('PredictedCOER.xlsx', PredictedCOER);
APPENDIX F  Second-by-Second Tailpipe CO\textsubscript{2} Emission Rate in Charge Depleting Mode

A MATLAB program is developed to estimate the second-by-second tailpipe CO\textsubscript{2} emission rates in CD mode.

The program needs a parameter file, “co2\_ER.xlsx”. The first column (Cell A1 to A14) of the file, “co2\_ER.xlsx”, contains the tailpipe CO\textsubscript{2} emission rate for engine on in CD mode in 14 VSP modes. Table A - 4 shows the direct tailpipe CO\textsubscript{2} emission rate during engine on for CD mode in each VSP mode. For each day of measurement, the input file is named as “Input#.xlsx” (# = 1, 2, …, n. It signifies the number # input file.). For example, the input files should be named as “Input1.xlsx” for the first day measurement, “Input2.xlsx” for the second day measurement, and “Input3.xlsx” for the third day measurement, etc. The first column of the file, “Input#.xlsx”, contains the second-by-second vehicle speed (mph); the second column of this file contains the second-by-second acceleration (mph/s); and the third column of this file contains the second-by-second road grade (%). The number of output files is the same as the number of input files. The output files are named as “PredictedCO2_#.xlsx” (# = 1, 2, …, n. It signifies the number # output file.). For example, the output files should be named as “PredictedCO2_1.xlsx” for the predicted second-by-
second tailpipe CO2 emission rates for the first day measurement, “PredictedCO2_2.xlsx” for the predicted second-by-second tailpipe CO2 emission rates for the second day measurement, and “PredictedCO2_3.xlsx” for the predicted second-by-second tailpipe CO2 emission rates for the third day measurement, etc. The first column of the output files contains the second-by-second tailpipe CO2 emission rates in the order of time. For example, Cell A1 contains the result of predicted 1\textsuperscript{st} second of tailpipe CO2 emission rate, Cell A2 contains the result of predicted 2\textsuperscript{nd} second of tailpipe CO2 emission rate, and Cell A3 contains the result of predicted 3\textsuperscript{rd} second of tailpipe CO2 emission rate, etc.

The user is prompted to enter the number of input files. This is the flow of the MATLAB program for each input file: obtaining one second of measurement data; determining engine status for current second (Engine operation is predicted using the engine control rules summarized in Table 20.); calculating and determining VSP mode for current second (The 14 VSP modes are defined by Frey et al.\textsuperscript{1}); if engine is determined as on for current second, updating the tailpipe CO2 emission rate depending on the VSP mode for current second; and if there is next second of measurement data, going to the next second and following the flow, and if there is not, outputting the results.
<table>
<thead>
<tr>
<th>VSP Mode</th>
<th>Direct Tailpipe CO₂ Emission Rate (g/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.03</td>
</tr>
<tr>
<td>2</td>
<td>1.06</td>
</tr>
<tr>
<td>3</td>
<td>1.09</td>
</tr>
<tr>
<td>4</td>
<td>1.24</td>
</tr>
<tr>
<td>5</td>
<td>2.06</td>
</tr>
<tr>
<td>6</td>
<td>2.65</td>
</tr>
<tr>
<td>7</td>
<td>3.50</td>
</tr>
<tr>
<td>8</td>
<td>3.67</td>
</tr>
<tr>
<td>9</td>
<td>4.28</td>
</tr>
<tr>
<td>10</td>
<td>4.63</td>
</tr>
<tr>
<td>11</td>
<td>4.94</td>
</tr>
<tr>
<td>12</td>
<td>6.13</td>
</tr>
<tr>
<td>13</td>
<td>--</td>
</tr>
<tr>
<td>14</td>
<td>--</td>
</tr>
</tbody>
</table>
This is the code:

```matlab
prompt = 'How many input files would you like to process? ';
x = input(prompt);

CO2ER = xlsread('co2_ER.xlsx');

for i = 1:x
    num = xlsread(strcat('Input',num2str(i),'.xlsx'));
    VSS = num(:,1); ACC = num(:,2); RG = num(:,3);
    n = length(VSS);
    Predicted = zeros(n,1);
    PredictedCO2 = zeros(n,1);
    VSP = zeros(n,1);
    for ii = 1:n
        VSP(ii) = 
            VSS(ii)*0.44704*(1.1*ACC(ii)*0.44704+9.81*RG(ii)/100+0.132+0.000302*VSS(ii)*VSS(ii)*0.44704*(1.1*ACC(ii)*0.44704+9.81*RG(ii)/100+0.132+0.000302*VSS(ii)*VSS(ii)*0.44704*0.44704);
    end
    for j = 1:n
        if VSS(j) <= 35
            if RG(j) >= 4.12
                Predicted(j) = 1;
            end
        elseif VSS(j) <= 45
            if ACC(j) >= 2.5
                Predicted(j) = 1;
            end
        elseif VSS(j) <= 55
            if RG(j) >= 1.97
                Predicted(j) = 1;
            end
        elseif VSS(j) <= 60
            if RG(j) >= -0.34
                Predicted(j) = 1;
            end
```
else
    Predicted(j) = 1;
end

if Predicted(j) == 1
    if VSP(j) < -2
        PredictedCO2(j) = CO2ER(1);
    elseif VSP(j) < 0
        PredictedCO2(j) = CO2ER(2);
    elseif VSP(j) < 1
        PredictedCO2(j) = CO2ER(3);
    elseif VSP(j) < 4
        PredictedCO2(j) = CO2ER(4);
    elseif VSP(j) < 7
        PredictedCO2(j) = CO2ER(5);
    elseif VSP(j) < 10
        PredictedCO2(j) = CO2ER(6);
    elseif VSP(j) < 13
        PredictedCO2(j) = CO2ER(7);
    elseif VSP(j) < 16
        PredictedCO2(j) = CO2ER(8);
    elseif VSP(j) < 19
        PredictedCO2(j) = CO2ER(9);
    elseif VSP(j) < 23
        PredictedCO2(j) = CO2ER(10);
    elseif VSP(j) < 28
        PredictedCO2(j) = CO2ER(11);
    elseif VSP(j) < 33
        PredictedCO2(j) = CO2ER(12);
    elseif VSP(j) < 39
        PredictedCO2(j) = CO2ER(13);
    else
        PredictedCO2(j) = CO2ER(14);
    end
end
end

xlswrite(strcat('PredictedCO2_',num2str(i),'.xlsx'), PredictedCO2);
end

APPENDIX G  Second-by-Second Tailpipe CO₂ Emission Rate in Charge Sustaining Mode

A MATLAB program is developed to estimate the second-by-second tailpipe CO₂ emission rates in CS mode.

The program needs a parameter file, “co2_ER.xlsx”. The first column (Cell A1 to A14) of the file, “co2_ER.xlsx”, contains the tailpipe CO₂ emission rate for engine on in CS mode in 14 VSP modes. Table A - 5 shows the direct tailpipe CO₂ emission rate during engine on for CS mode in each VSP mode. For each day of measurement, the input file is named as “Input#.xlsx” (# = 1, 2, …, n. It signifies the number # input file.). For example, the input files should be named as “Input1.xlsx” for the first day measurement, “Input2.xlsx” for the second day measurement, and “Input3.xlsx” for the third day measurement, etc. The first column of the file, “Input#.xlsx”, contains the second-by-second vehicle speed (mph); the second column of this file contains the second-by-second acceleration (mph/s); and the third column of this file contains the second-by-second road grade (%). The number of output files is the same as the number of input files. The output files are named as “PredictedCO2_#.xlsx” (# = 1, 2, …, n. It signifies the number # output file.). For example, the output files should be named as “PredictedCO2_1.xlsx” for the predicted second-by-
second tailpipe CO₂ emission rates for the first day measurement, “PredictedCO2_2.xlsx” for the predicted second-by-second tailpipe CO₂ emission rates for the second day measurement, and “PredictedCO2_3.xlsx” for the predicted second-by-second tailpipe CO₂ emission rates for the third day measurement, etc. The first column of the output files contains the second-by-second tailpipe CO₂ emission rates in the order of time. For example, Cell A1 contains the result of predicted 1st second of tailpipe CO₂ emission rate, Cell A2 contains the result of predicted 2nd second of tailpipe CO₂ emission rate, and Cell A3 contains the result of predicted 3rd second of tailpipe CO₂ emission rate, etc.

The user is prompted to enter the number of input files. This is the flow of the MATLAB program for each input file: obtaining one second of measurement data; determining engine status for current second (Engine operation is predicted using the engine control rules summarized in Table 21.); calculating and determining VSP mode for current second (The 14 VSP modes are defined by Frey et al.¹); if engine is determined as on for current second, updating the tailpipe CO₂ emission rate depending on the VSP mode for current second; and if there is next second of measurement data, going to the next second and following the flow, and if there is not, outputting the results.
Table A - 5 The Direct Tailpipe CO₂ Emission Rate During Engine On for Charge Sustaining (CS) Mode in Each Vehicle Specific Power (VSP) Mode

<table>
<thead>
<tr>
<th>VSP Mode</th>
<th>Direct Tailpipe CO₂ Emission Rate (g/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.13</td>
</tr>
<tr>
<td>2</td>
<td>1.56</td>
</tr>
<tr>
<td>3</td>
<td>1.37</td>
</tr>
<tr>
<td>4</td>
<td>1.85</td>
</tr>
<tr>
<td>5</td>
<td>2.21</td>
</tr>
<tr>
<td>6</td>
<td>2.65</td>
</tr>
<tr>
<td>7</td>
<td>3.13</td>
</tr>
<tr>
<td>8</td>
<td>3.53</td>
</tr>
<tr>
<td>9</td>
<td>3.85</td>
</tr>
<tr>
<td>10</td>
<td>4.04</td>
</tr>
<tr>
<td>11</td>
<td>4.48</td>
</tr>
<tr>
<td>12</td>
<td>4.98</td>
</tr>
<tr>
<td>13</td>
<td>5.47</td>
</tr>
<tr>
<td>14</td>
<td>6.26</td>
</tr>
</tbody>
</table>
This is the code:

```
prompt = 'How many input files would you like to process? ';  
x = input(prompt);  

CO2ER = xlsread('co2_ER.xlsx');  

for i = 1:x  
    num = xlsread(strcat('Input',num2str(i),'.xlsx'));  
    VSS = num(:,1); ACC = num(:,2); RG = num(:,3);  
    n = length(VSS);  
    Predicted = zeros(n,1);  
    PredictedCO2 = zeros(n,1);  
    VSP = zeros(n,1);  
    for ii = 1:n  
        VSP(ii) = VSS(ii)*0.44704*(1.1*ACC(ii)*0.44704+9.81*RG(ii)/100+0.132+0.000302*VSS(ii)*VSS(ii)*0.44704*0.44704);  
    end  
    for j = 1:n  
        if VSS(j) <= 40  
            if VSP(j) >= 4.58  
                Predicted(j) = 1;  
            end  
            else  
                Predicted(j) = 1;  
        end  
    end  
    if Predicted(j) == 1  
        if VSP(j) < -2  
            PredictedCO2(j) = CO2ER(1);  
        elseif VSP(j) < 0  
            PredictedCO2(j) = CO2ER(2);  
        elseif VSP(j) < 1  
            PredictedCO2(j) = CO2ER(3);  
```
elseif VSP(j) < 4
    PredictedCO2(j) = CO2ER(4);
elseif VSP(j) < 7
    PredictedCO2(j) = CO2ER(5);
elseif VSP(j) < 10
    PredictedCO2(j) = CO2ER(6);
elseif VSP(j) < 13
    PredictedCO2(j) = CO2ER(7);
elseif VSP(j) < 16
    PredictedCO2(j) = CO2ER(8);
elseif VSP(j) < 19
    PredictedCO2(j) = CO2ER(9);
elseif VSP(j) < 23
    PredictedCO2(j) = CO2ER(10);
elseif VSP(j) < 28
    PredictedCO2(j) = CO2ER(11);
elseif VSP(j) < 33
    PredictedCO2(j) = CO2ER(12);
elseif VSP(j) < 39
    PredictedCO2(j) = CO2ER(13);
else
    PredictedCO2(j) = CO2ER(14);
end

end

xlswrite(strcat('PredictedCO2_\_','num2str(i),\_','xlsx'), PredictedCO2);
end