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DRAFT FOR REVIEW

Estimation of Emissions from Hybrid and Plug-In Hybrid Vehicles

TEXAS TRANSPORTATION INSTITUTE
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CHAPTER 1: INTRODUCTION

Overview

The purpose of this sub-task is to provide the Texas Department of Transportation (TxDOT) with a better understanding of battery charging/depletion, fuel economy and emissions reduction of plug-in hybrid electric vehicles (PHEVs) based on actual in-use test protocols. This task memorandum presents the work performed in Fiscal Year (FY) 2011 under Phase 2 of the task, and summarizes the findings from:

- Battery charge/depletion and cold start testing under controlled environment;
- In-use real world energy usage and driving characteristics data analysis; and
- In-use real world portable emissions measurement system (PEMS) emissions and fuel economy testing

PHEVs from the City of Houston's (CoH's) vehicle fleet, which are converted Toyota Priuses, are used for the testing.

PHEVs in the U.S. Market

In addition to regular hybrid electric vehicles (HEVs) which have become commonly available in the US, some models of PHEVs and even fully electric vehicles (such as the Nissan Leaf) have also been introduced into the market. In the U.S., there are currently two commercial PHEVs available- the Chevy Volt and the other is the Fisker Karma. Because Karmas' deliveries just began in the U.S. (in late July 2011),[1] not much information on the sales is known. For Volts, General Motors has sold 3,196 Volts through July 2011 since deliveries began in December 2010.[2] Although the gasoline-powered internal combustion engine (ICE) of a Chevy Volt provides some assistance at high speeds or performance improvement in some cases, the ICE mainly works to produce electricity to drive the electric motor for Volt's operations; i.e., emissions of the ICE are not directly related to the vehicle operations (or, driving). The the time that Texas Transportation Institute (TTI) researchers were locating PHEVs for testing, less than 500 Volts had been sold in the entire U.S., and, unfortunately, none of them were available for the testing.

There is another type of PHEV, so-called converted PHEVs. Until 2010 most PHEVs on the road in the U.S. are conversions of conventional hybrid electric vehicles, and the most prominent PHEVs are conversions of the 2004 or later Prius, which have added plug-in charging capabilities and more batteries to extend their electric-only range.[3] For a Prius, a motor and/or an ICE operates the vehicle depending on driving conditions; i.e., its emissions are directly related to the vehicle operations. Unfortunately, no official numbers of converted Priuses are available,

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[1] Plug In America. What's Coming When, http://www.pluginamerica.org/vehicle-tracker?make=All&drivetrain=PHEV&class=All&charger=All&cvrp=All&availability=All, accessed in August 2011.

[2] Wikipedia. Chevrolet Volt, http://en.wikipedia.org/wiki/Chevy_Volt, accessed in August 2011.

[3] Wikipedia. Plug-in hybrid, http://en.wikipedia.org/wiki/Plug-in_hybrid#cite_note-15, accessed in August 2011.

but some converted Priuses could be available for this study. For example, CoH possesses 15 converted Priuses; two of those were tested.

The expected market share of PHEVs and HEVs has been the topic of a few studies and research. For example, as mentioned in the Phase 1 report, Pike Research forecast that the U.S. would be the largest market for regular HEVs and PHEVs selling approximately 640,000 vehicles, and there would be a total of 1.7 million PHEVs on the world's roadways by 2015. These forecasts were made after analyzing the emerging PHEV market with a focus on business issues and demand drivers, technology issues such as the use of advanced batteries and the need for electric vehicle charging infrastructure, the effects of regulatory standards and government incentives around the world, and an in-depth assessment of major original equipment manufacturers' PHEV programs. [4] In a study of household PHEV trials using 67 converted Priuses, it was shown that there could be other factors, beyond just prices of PHEVs, affecting purchases of PHEVs, such as driving behavior, recharging adequacy, education on how PHEVs work and save money as well as how to incorporate environmental (or more generally, societal) costs and benefits into assessments, and the future.[5] Therefore, the market share could be varied depending on all of the factors previously mentioned.

FY2010 Work Performed

In FY2010, under Phase 1 of this task, TTI researchers provided a summary of previous research on emissions characteristics and test procedures of hybrid electric vehicles, including plug-in hybrids and a technical plan proposed for in-use testing. In the Phase 1 report, TTI performed a literature review to obtain such information on HEVs and PHEVs, and found that the potential effectiveness of PHEVs with respect to fuel economy and emissions reduction depends on many factors, and additional test procedures for PHEV fuel economy and emissions testing would be needed to capture the unique operating modes of PHEVs (the charge depletion [CD] mode and the transition mode between CD and charge sustaining [CS] modes). In addition, an in-use testing plan was developed to provide a better understanding of the uncertainties related to PHEV operations and to measure fuel consumption and emissions under real-world operational conditions. The proposed testing plan included testing under real world operations (i.e., in-use real world energy usage and driving characteristics data collection testing, and in-use real world PEMS emissions and fuel economy testing) as well as testing under environmentally controlled conditions (i.e., battery depletion and cold start testing).

In FY 2011, the testing was performed and the findings are reported here. This report consists of five chapters. This chapter (Chapter 1) provides a brief overview of both Phase 1 (FY2010) and

[4] Pike Research. Plug-in Hybrid Electric Vehicles – The Global Outlook for PHEVs: Business Issues, Technology Issues, Key Players, and Market Forecasts, http://www.pikeresearch.com/research/plug-in-hybrid-electric-vehicles. 2009.

[5] Kurani, K., J. Axsen, N. Caperello, J. Davies-Shawhyde, P. Dempster, M. Kempster, K. Nesbitt, and T. Stillwater. T. Plug-in Hybrid Electric Vehicle (PHEV) Demonstration and Consumer Education, Outreach, and Market Research Program: Volume II, UCD-ITS-RR-10-21, November 2010.

Phase 2 (FY2011) studies and current PHEV markets in the U.S. The remainder of this report describes the findings for operational characteristics of PHEVs (the converted PHEVs) tested for this study (Chapter 2) and methodologies of battery charge/depletion and cold start testing under a controlled environment, and of in-use real world fuel economy and emissions along with energy usage and driving characteristics testing (Chapter 3), and the testing results and discussions (Chapter 4). The last chapter (Chapter 5), presents the summary of the findings.

CHAPTER 2: OPERATIONAL CHARACTERISTICS OF PHEVS

TTI researchers investigated operational characteristics of PHEVs; for converted PHEVs and for commercial PHEVs. The findings are described in this chapter.

Operation Principles of Converted PHEVs

In principle, for a converted PHEV, a supplemental onboard electrical storage capacity (as a battery pack), which can be recharged at an electric outlet from regular household walls, is added on a HEV. This allows the HEV's pure electric drive to be used more often and for longer distances. This added capacity results in fuel efficiency gains and emissions reduction of carbon dioxide (CO_2) and other pollutants such as oxides of nitrogen (NO_x), carbon monoxide (CO), hydrocarbons (HC), and particulate matter (PM).

A regular HEV is powered by an ICE and an electric motor (usually powered by a battery). The electric motor is used for motive force at low speeds and supplemental force at high speeds. It provides power assistance to the engine output as needed. When starting off and driving at low speeds, the motor provides the primary motive force although the engine may start immediately if the HEV's battery state-of-charge (SOC) is low. When driving under normal conditions, the engine will start to drive the wheels and also to produce electricity to charge the HEV's battery. During full acceleration, the motor powered from the HEV battery will be supplemental to the engine. During deceleration or braking, energy from the spinning wheels is recovered and stored in the HEV's battery.

For a converted PHEV, a plug-in conversion module (PCM), including a battery pack, is installed on a HEV, and increases the electric capability of the HEV by supplementing the HEV's battery. For the operation/driving of the converted PHEV, power from the PHEV's battery will be consumed primarily. When the PHEV battery pack depletes, the PHEV's power system switches back to normal HEV operation/driving mode. The module does not receive any regenerative charge during driving. After the PHEV's battery is depleted, it is only recharged by being plugged in.

Operation Principles of Commercial PHEVs

As stated in an earlier section in this report, currently, there are two commercial PHEV models on the market in the U.S.; Chevy Volt and Fisker Karma. The Volt has an ICE and electric motors. Before the battery SOC drops below a pre-established threshold, the Volt operates by the motor. Then, the ICE starts, but acts primarily as a generator to power the motor. At certain loads and speeds, 30 to 70 mph (48 to 110 km/h), however, the engine may at times be engaged to assist the motor to propel the Volt.[2]

Similarly, the Karma is driven by a pair of electric motors powered by a battery pack or a generator spun by an ICE. The engine is mated with a generator to provide an electrical connection to the motors and also to recharge the batteries, and as such the electric motors are the only mechanical driving force connected to the wheels.[6]

[6] Wikipedia. Fisker Karma, http://en.wikipedia.org/wiki/Fisker_Karma, accessed in August 2011.

CHAPTER 3: TEST METHODOLOGIES

Prior to conducting any testing of the converted PHEVs, owned and operated by CoH, Global Positioning System (GPS) units were deployed on five of CoH PHEVs to collect vehicle usage and operation data. The GPS data were collected during their normal operations. Examining the GPS data, two PHEVs were selected for the following tests:

- PHEV battery charging and depletion;
- Cold-start and idling emissions;
- In-use real world emissions; and
- In-use real world energy usage and driving characteristics.

The first two types of tests (battery and idling tests) were conducted under a controlled environment at TTI's environment and emissions research facility (EERF) in Bryan, TX. Then, the last two in-use real world tests (emissions and energy usage and driving characteristics tests) were conducted in the Houston area while the selected vehicles were performing their normal operations. Details of test protocol and test equipment as well as test vehicles are described in the following sections.

Test Vehicles

The two selected test vehicles were 2009 Toyota Priuses on which A123 Hymotion L5 PCMs were installed in November 2011 to convert them to PHEVs. Figure 1 shows one of the test vehicles and the conversion module installed on the vehicle. Specifications of the vehicle and the L5 PCM from the corresponding manufacturers are shown in Table 1 and Table 2.

(a)

(b)

Figure 1: Pictures of a Test Vehicle and a L5 PCM; (a) a test vehicle and (b) L5 PCM installed on the vehicle.

Table 1: Test Vehicle Specifications.

Manufacturer	Toyota
Model	Prius 1NZ-FXE
Model Year	2009
Engine Displacement	1.497 L
Maximum Motor Output	50 kW
Maximum Motor Torque	400 Nm
HEV Battery Type	Nickel-Metal Hydride
HEV Battery Overall Voltage	201.6 V
HEV Battery Capacity	1.3 kWh

Table 2: L5 PCM Specifications.

Manufacturer	A123 Systems, Inc.
Model	A123 Hymotion™ L5 Plug-In Conversion Module (designed for Toyota Prius, MY 2004 – 2009)
Weight	187 pounds
Charge Time	5.5 hours at 75 °F with 120V
Maximum Charging Current	10A
Operation/Charging Temperature	-20 °F to 140 °F
Battery Type	Nanophosphate™ lithium ion batteries
Battery Overall Voltage	187 V
Battery Capacity	5 kWh

After being charged, the PHEV will be driven by battery power of the L5 PCM at a low speed unless it needs extra power from the engine; for example, during the fast acceleration. Based on the manufacturer of the L5 PCM, the engine will automatically kick in when the speed reaches at 37 mph. At speeds of 37 mph or higher, the PHEV will be driven by the engine with assistance from L5 PCM as well as Prius' battery. After the L5 PCM battery is depleted, the PHEV will operate as a normal Prius. The Prius engine will start as driving speed increases above 15 to 20 mph.[7]

For in-use real world driving testing, emission and driving characteristic measuring instruments and other related equipment was installed on and/or placed on and in the test vehicles. The added weight was about 450 lb.

Test Equipment/Test Location

TTI Environmental and Emissions Research Facility

TTI's Environmental and Emissions Research Facility (EERF) is located at Texas A&M University's Riverside Campus (A&M RC) in Bryan, TX. The EERF includes an environmentally controlled test chamber with dimensions of 75 ft long × 23 ft wide × 22 ft high, in which both of the test vehicles were placed together for the battery and idling testing. The chamber can control both temperature and humidity. It also has a solar lighting array to simulate solar loading and fans to simulate wind chill effects. The chamber can control temperatures from -40°C to 55°C. Figure 2 shows a picture of the test chamber.

[7] Autoshop101. Hybrid11: Principles of Operation, http://www.autoshop101.com/forms/Hybrid11.pdf, accessed in August 2011.

Figure 2: TTI's EERF Test Chamber.

SEMTECH-DS

The SEMTECH-DS is a PEMS unit, which complies with the U.S. Environmental Protection Agency’s (EPA) Code of Federal Regulations (CFR) Title 40 Part 1065 (so-called, 40 CFR 1065) emissions testing and is used for emissions testing during the idling tests and in-use real world tests. It consists of a set of gas analyzers to measure gaseous emissions of NO_x (both nitrogen oxide [NO] and nitrogen dioxide [NO_2]), HC, CO, CO_2, and oxygen (O_2) in the exhaust. The SEMTECH-DS is used in conjunction with the SEMTECH electronic flow meter (EFM), which measures the vehicle exhaust flow rate. This allows for the calculation of exhaust mass emissions from all measured gasses. Figure 3 shows the SEMTECH-DS and EFM installed on a PHEV during the testing.

Figure 3: SEMTECH-DS and EFM.

Axion

The PEMS used to collect PM was the Axion system (Axion) manufactured by Clean Air Technologies International, Inc. The Axion consists of gas analyzers, a PM measurement system, an engine diagnostic scanner, a GPS, and an on-board computer. For this study only the PM measurement system was used. The PM measurement capability includes a laser light scattering detector and a sample conditioning system. The PM concentrations are converted to PM mass emissions using concentration rates measured by the Axion and the exhaust flow rates collected by the SEMTECH EFM. Figure 4 shows a picture of the Axion system installed on a test vehicle prior to testing. During the testing, most of measured PM concentration was under the detection limits. The measurement results are described in the result section in details.

Figure 4: Axion Unit.

IOSiX OBD-II Data Logger
The IOSiX data logger was used during the project to monitor the information being passed along the On-Board Diagnostics (OBD)-II system from the test vehicles. Figure 5 shows the picture of an IOSiX data logger. The data logger supports all existing OBD-II protocols as well as additional information from the L5 PCM including SOC. The data logger is fully configurable, allowing users to select which parameters are recorded, as well as the rate at which they are recorded. The data is saved to a microSD card, up to 2 GB in size. This allows for the storage of long term data collection without having to change the memory card. In addition to the data logging capability, the device also allows for a live data mode where the user can watch the data in real time.

Figure 5: IOSiX Data Logger.

Test Protocol

Battery Charge/Depletion Testing
The battery charge/depletion testing was conducted inside the EERF under the three different controlled test conditions shown in Table 3. At each test condition for each vehicle, the L5 PCM battery (PHEV battery from now on) was charged by being plugged into an electrical (120V) outlet inside the chamber. While being charged, SOC of the PHEV battery was monitored.

Table 3: Idle and Battery Depletion Testing Conditions.

Condition	Chamber Temperature Settings
1	86° F
2	68° F
3	23° F

After the PHEV battery was fully charged, battery depletion testing began. During the battery depletion testing, the SOC of the PHEV battery was also monitored. The battery depletion tests were conducted under different modes depending on test conditions:

- A/C mode: air conditioning (A/C) on with the maximum fan speed and re-circulation for test conditions 1 and 2;
- Heat mode: heater on with the maximum fan speed and re-circulation for test conditions 2 and 3; and
- Key-In mode: vehicle is on but without turning on A/C or heater for test condition 2 only.

After the vehicle was turned on, the engine automatically started and ran for about a minute or so (even when the PHEV was fully charged). Then, the PHEV battery SOC decreased as long as the PHEV remained on. When the PHEV battery was fully depleted (i.e., its SOC remained at the depleted level), the Prius battery pack (HEV battery) SOC began to decrease until it reached its minimum level. Then, the engine started again. During the time between when the first engine start at the beginning and the PHEV SOC decreased to the depleted level, PHEV battery depletion testing was conducted under the different test modes described previously. The test modes were switched from one to another during the entire test period. For each mode, SOC changes were monitored at least for one hour.

Cold-Start and Idling Emissions Testing

Cold-start and idling emissions testing was also conducted in the chamber. Prior to the testing, SEMTECH-DS and EFM, Axion, and other required equipment were installed on the test vehicle. After the PHEV battery was fully depleted, and, the HEV battery SOC reached at its minimum level, the emissions testing was conducted. Figure 6 shows both of the test vehicles inside the test chamber during the emissions testing.

Figure 6: Test Vehicles in Chamber for Battery and Idling Testing.

For a cold-start and idling emissions test, the PHEV was turned on and left on until stabilized idling emissions were observed. When the fully depleted PHEV was turned on, the engine started and remained on for a certain period of time with charging HEV the battery (not PHEV battery, though) until the SOC of the HEV battery reached its maximum level. Then, the engine turned off automatically. When the SOC of the HEV battery decreased to its minimum level again, the engine started again charging the HEV battery. These engine-on and off cycles repeated.

Emissions during the first and continuous engine operations were measured. When the measured emissions during an engine operation were similar to those (especially, CO_2 emissions) during previous engine operations, the cold-start and idling emissions test ended. Then, after different soaking time (the time that the test vehicle was off), based on idling modes used in the MOtor Vehicle Emissions Simulator (MOVES) model,[8] the EPA's current regulatory emissions model, the next cold-start and idling emissions test was conducted. The tested soak time ID codes and their descriptions are listed in Table 4. There is another operation mode of soak time, OpmodeID code 107 for 360 minutes ≤ Soak Time < 720 minutes, which would need 6 hours waiting time. Because 360 minutes (or 6 hours) of waiting time for each vehicle for each test condition would delay the testing so long (at least 60 hours for soak time only), TTI researchers decided not to perform idling tests with the Opmode 107.

[8] EPA. Modeling and Inventories: MOVES, http://www.epa.gov/otaq/models/moves/index.htm, accessed in August 2011.

Table 4: Operating Mode for Start and Extended Idle Processes.

OpmodeID Code	Operating Mode Description
101	Soak Time < 6 minutes
102	6 minutes ≤ Soak Time < 30 minutes
103	30 minutes ≤ Soak Time < 60 minutes
104	60 minutes ≤ Soak Time < 90 minutes
105	90 minutes ≤ Soak Time < 120 minutes
106	120 minutes ≤ Soak Time < 360 minutes
108*	720 minutes ≤ Soak Time

* OpmodeID 108 is so-called a cold-start.

For each vehicle, a set of cold-start and idling emissions tests, with different soak time for test condition 1 (86 °F), was conducted under the A/C mode only while another set of tests for test condition 3 (23 °F) was conducted under Heat mode only. For test condition 2 (68 °F), three sets of tests were conducted for each vehicle under all three modes, key-in, A/C, and Heat modes; one set of test for each mode.

In-Use Real World Emissions and Fuel Consumption Testing

Fuel consumption and emissions testing of the test PHEVs were conducted while they were in-use during their real world normal operations. Pictures taken during the testing are shown in Figure 7. Prior to the testing, SEMTECH-DS, SEMTECH-EFM, Axion, and other required equipment were installed on the test PHEV, warmed-up, and calibrated as necessary.

Figure 7: Pictures of a Test Vehicle during the In-Use Real World Testing.

During the testing, CoH employees drove the test PHEVs for their normal operations in the Houston area for a total of four days. During the in-use real world testing, TTI researchers followed the PHEVs closely and checked the raw data of fuel consumption and emissions measured and the status of SEMTECH-DS wirelessly.

The vehicle (CoH ID #) 40012 was tested for the first two days. Then, all of the equipment was dismantled from the PHEV and transported to and installed on the other vehicle 39980. The vehicle 33980 was tested for the following two days. During the testing, PHEVs were operated by their engine and/or battery (PHEV and/or HEV battery) power.

In-Use Real World Vehicle Driving Characteristics Testing

The real world driving characteristics testing was conducted at the same time during the fuel consumption and emissions testing described previously. While fuel consumption and emissions data were collected, driving characteristics data such as vehicle speed, engine speed, and PHEV battery SOC were also collected by using a GPS unit and data loggers. Using the driving characteristics data, the fine-scale disaggregate driving characteristic measure, vehicle specific power (VSP), was identified among different driving conditions.

The VSP is a combined measure of instantaneous speed, acceleration, road grade, and road load. After it is normalized by mass, operating mode bins are determined from VSP and instantaneous speeds. Table 5 shows the MOVES' operating mode bins, which represent ranges of vehicle speeds and VSP. There are 23 operating bins for estimating running emissions while vehicles are moving or idling at hot-stabilized conditions as shown in Table 5. A vehicle operating over a test trip, which is considered for a PHEV operation moving from a location (after starting the vehicle) to a destination (then, turning off the vehicle), spends different times in different bins depending on the operation.

Table 5: MOVES Operating Mode Bin Definitions for Running Emissions.

Braking (Bin 0)			
Idle (Bin 1)			
	Instantaneous Speed (mph)		
Instantaneous VSP (kW/tonne)	**0-25**	**25-50**	**> 50**
< 0	Bin 11	Bin 21	
0 to 3	Bin 12	Bin 22	
3 to 6	Bin 13	Bin 23	
6 to 9	Bin 14	Bin 24	
9 to 12	Bin 15	Bin 25	
12 and greater	Bin 16		
12 to 18		Bin 27	Bin 37
18 to 24		Bin 28	Bin 38
24 to 30		Bin 29	Bin 39
30 and greater		Bin 30	Bin 40
6 to 12			Bin 35
< 6			Bin 33

The VSP, defined as "power per unit mass of the source," is calculated by the following equation:[9]

$$VSP = \frac{A \times u + B \times u^2 + C \times u^3 + M \times u \times a}{M}$$

Where:

- A = is a rolling resistance term;
- u = is instantaneous speed of vehicle;
- B = is rotating resistance term;
- C = is a drag term
- M = is the vehicle's mass; and
- a = is instantaneous acceleration of vehicle.

The VSP accounts for the forces a vehicle must overcome when operating on the road, including acceleration, road grade, tire rolling resistance, and aerodynamic drag. For example, fast accelerations or driving up a steep hill would have a higher VSP bin rather than coasting downhill. Therefore, VSP represents vehicle driving characteristics in fine scales.

[9] EPA. Motor Vehicle Emission Simulator Highway Vehicle Implementation (MOVES-HVI) Demonstration Version: Software Design and Reference Manual – Draft, 420-P-07-001, February 2007.

CHAPTER 4: TEST RESULTS AND DISCUSSIONS

TTI researchers performed battery charge/depletion testing, cold start and idling emissions testing, in-use real world energy usage and driving characteristics testing, and in-use real world emissions testing with using two converted PHEVs. The test results are presented and discussed in the following sections.

Battery Charge/Depletion Testing

The purpose of the proposed battery charge/depletion testing was to examine battery charge/depletion rates in terms of ambient conditions, i.e., temperature conditions as described in the previous chapter. Also, battery depletion tests under different modes were conducted. Table 6 shows battery charging rates and time.

Table 6: PHEV Battery Charging Rates and Time.

	Battery charging rates (SOC%/hr)			Battery fully-charging time (hr)*		
Condition (°F)	23	68	86	23	68	86
33980	17.6	17.7	16.5	5.1	5.1	5.5
40012	17.4	17.6	16.1	5.2	5.1	5.6

* The charging time is based on charging the PHEV battery from 10% (i.e., depleted) of SOC level to 100%.

Based on the test results shown in Table 6, PHEV battery charging rates of were similar for both test vehicles. For each vehicle, as shown in Table 6, the charging rate at 86 °F was lower than those at lower temperatures of 68 and 23 °F, which are close to each other. Consequently, charging time at 86 °F takes about 10% longer than time at colder temperature of 68 and 23 °F. The charging time of 5.5 hr (for vehicle 33980) and 5.6 hr (for vehicle 40012) matches with the time specified by the manufacturer, about 5.5 hr at 75 °F shown in Table 2.

Table 7 shows PHEV battery depletion rates (as battery SOC changes per hour; SOC[%]/hr) and time at three different temperature conditions under different test modes. For both vehicles, the PHEV batteries depleted slower during the Key-In mode than during the A/C or Heat modes, both of which have higher loads on the vehicle operations requiring more power from the PHEV battery. Consequently, depletion time during the Key-In mode was longer than that during the A/C or Heat mode.

Table 7: PHEV Battery Depletion Rates and Time.

		Battery depletion rates (SOC[%]/hr)			Battery fully-depletion time (hr)*		
Depletion Mode	Condition (°F)	23	68	86	23	68	86
Key-In	33980	8.5	7.9	4.8	10.6	11.4	18.8
	40012	8.0	7.7	4.3	11.3	11.7	20.9
A/C	33980	N/A**	18.5	18.9	N/A**	4.9	4.8
	40012	N/A**	21.8	21.8	N/A**	4.1	4.1
Heat	33980	23.8	11.6	N/A**	3.8	7.8	N/A**
	40012	21.4	21.2	N/A**	4.2	4.2	N/A**

* The charging time is based on charging the PHEV battery from 10% of SOC level to 100%.
** N/A: Not Applicable.

Comparing both vehicles, the battery depletion results were similar, except that the depletion rate of vehicle 33980 during the Heat mode at 68 °F, which was about a half of that of the 40012 vehicle during the same mode at the same temperature for unknown reasons. Battery charge/depletion tests were performed only once for each vehicle for each temperature condition due to limited time and budget; all three depletion modes were tested for each vehicle for each temperature condition. More tests may identify a possible reason or reasons of the exceptional observation.

Compared during the Key-In mode, battery depletion rates decreased as temperature conditions increased. However, the differences between 68 °F and 86 °F (about a 40% decrease) are much greater than those between 23 °F and 68 °F (about 5%) for unknown reasons. More tests with more temperature conditions may necessary to elucidate the reasons.

Compared during the A/C mode, depletion rates of each vehicle were similar regardless of temperature conditions. The depletion rates of the 33980 vehicle were about 15% lower than those of the 40012 vehicle during the A/C mode. For the Heat mode, depletion rates of the 40012 vehicle were similar regardless of temperature conditions, but those of the 33980 vehicle were not because of the exceptional observed rate of 11.6 %/hr, which is only about a half compared to the other temperature condition, as described earlier in this section. At 23 °F, the depletion rate of the 33980 vehicle during the Heat mode is about 10% higher than that of the 40012 vehicle for unknown reasons. More tests with more vehicles and test modes and conditions along with information of power usage/consumption of air conditioning and heater systems of the vehicles would identify and/or elucidate the differences.

Cold-Start and Idling Testing

The purpose of the cold start and idling testing was to examine cold start and idling emissions impacts of PHEVs after the PHEV batteries are depleted; i.e., examination of the benefits of fuel savings and emissions reduction for cold-start and idling testing for the converted PHEV having charged PHEV battery. As discussed in the previous section, after the PHEV is fully charged, it does not require any fuel consumption nor produce any emissions for more than 10 hours of idling (i.e., Key-In mode) or at least 3.8 hours of idling with providing heat or A/C (i.e., Heat or A/C mode) except for about one minute of cold (or, first) stat idling, which is the default setup of the PHEV.

Cold start and idling tests were conducted at three different conditions with different soak times as described in the previous chapter. At 68 °F, the testing was conducted for all of test modes, Key-In, A/C, and Heat modes, while the testing at 23 °F was for Heat mode only, and the testing at 86 °F was for A/C only. During the tests, the engine was turned on and off repeatedly depending on SOC of HEV battery and loads, i.e., operations of A/C or heating systems. When the test vehicle was turned on, initially the engine started and remained on for operations of A/C or heating system (depending on the test mode) or others including electronic displays of fuel gauge, odometer, battery SOC on screens of the test vehicle (for all modes) and for charging the HEV battery until SOC of the HEV battery reached at its maximum CS level. Then, the engine was turned off by itself, and the HEV battery took over the operations until the HEV battery reached at its minimum CS level. Then, the engine was turned on automatically. These cycles were repeated during the cold stat and idling tests. The intervals for engine on-off cycles and the duration when the engine was on each time varied depending on test modes, conditions, and vehicles.

Figure 8 shows observed emissions rates of CO_2 and NO_x (with respect to time on x-axis) for cold start and idling testing of vehicle 33980 at the temperature conditions of 86 °F for A/C mode. As shown in Figure 8, its emissions (or so-called an emissions peak) were observed while the engine was running. The duration of each observed emissions peak and an interval between a peak and its next peak vary. In Figure 8, the first peak shows the cold start emissions. Then, some transient emissions peaks follow. Emissions peaks beginning at around 11:15 (shown in Figure 8) appeared similar to each other in emissions rates as well as durations of and intervals between peaks. These (so-called stabilized) peaks were mainly considered to examine the emissions benefits.

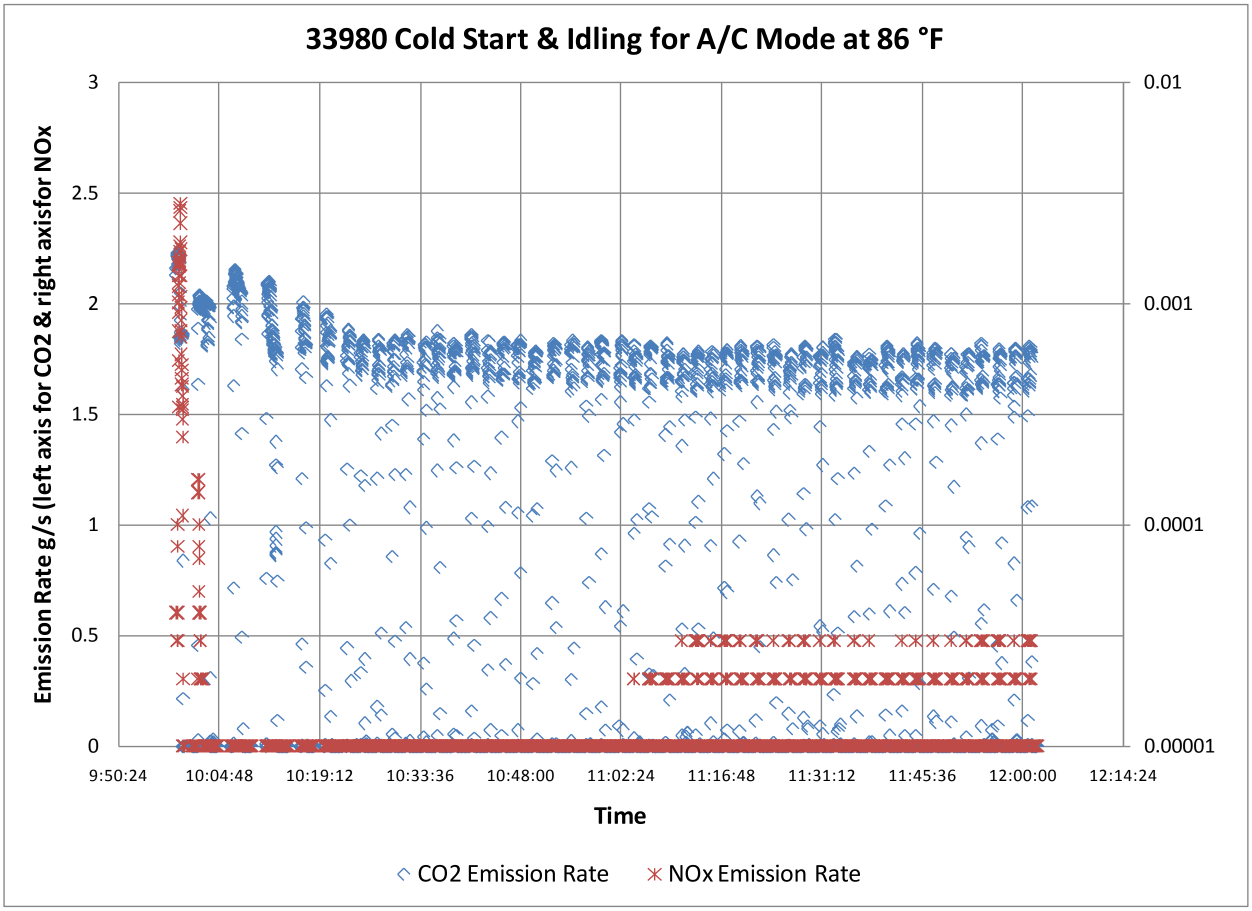

Figure 8: Cold Start and Idling Testing Results for the 33980 Vehicle at 86 °F for the A/C Mode.

For a cold start and idling test, as shown in Figure 8, a pattern of the first (cold) start emissions peak, transition peaks, and, then, stabilized peaks was observed. The observed differences among different tests were intervals between peaks, durations and the magnitudes of the peaks depending on the test conditions and modes.

Test results of the first peak (first idling) and the stabilized peaks (stabilized idling) on average for all conditions and modes for both vehicles are summarized in Table 8. In addition to fuel consumption rates and emissions rates of CO_2, NO_x, CO, and HC, durations of and intervals between emission peaks are also shown in Table 8. For PM, no results were shown in Table 8 because measured PM concentrations during the cold start and idling testing were below the detection limit. It should be noted that fuel consumption and emissions rates for the first idling, which lasted only for a few minutes, were shown as hourly rates to compare to those of stabilized idling. The hourly idling time shown in Table 8 was calculated by multiplying the duration of an emissions peak by the number of emissions peaks per hour.

Table 8: Cold Start and Idling Emissions Results at 68°F.

		Vehicle # 33980						Vehicle # 40012					
Idling Condition		86°F	68°F	68°F	68°F	23°F	Average	86°F	68°F	68°F	68°F	23°F	Average
Idling Mode		A/C	A/C	Key-In	Heat	Heat		A/C	A/C	Key-In	Heat	Heat	
First Idling	Fuel (gal/h)	0.75	0.82	0.82	0.44	0.49	0.66	0.65	0.76	0.78	0.69	0.64	0.70
	CO_2 (kg/h)	6.77	7.44	7.33	4.01	4.50	6.0	5.87	6.89	7.09	6.27	5.88	6.4
	NO_x (g/h)	0.52	0.09	0.41	0.08	0.72	0.36	0.02	0.05	0.26	0.32	1.05	0.34
	CO (g/h)	2.57	7.74	33.02	2.61	5.57	10.30	5.53	22.14	12.83	9.82	2.87	10.64
	HC (g/h)	2.29	4.57	13.44	0.95	1.38	4.53	0.92	6.42	6.55	3.18	1.29	3.67
	Duration (s)	102	68	61	413	294	188	120	58	44	129	219	114
Stabilized Idling	Fuel (gal/h)	0.66	0.69	0.64	0.49	0.47	0.59	0.61	0.65	0.68	0.52	0.56	0.604
	CO_2 (kg/h)	5.97	6.29	5.77	4.50	4.27	5.36	5.55	5.90	6.05	4.71	5.12	5.47
	NO_x (g/h)	0.09	0.11	0.12	0.15	0.13	0.12	0.00	0.10	3.03	0.29	0.07	0.70
	CO (g/h)	1.92	7.46	9.14	3.67	0.96	4.63	1.10	4.62	26.49	4.22	1.76	7.64
	HC (g/h)	0.91	0.89	26.31	0.14	0.39	5.73	0.08	0.30	22.21	0.33	2.32	5.05
	Duration (s)	47	46	42	56	64	51	62	63	131	18	53	65.4
	Interval (min)	4.0	4.0	12.8	1.7	3.3	5.2	4.7	4.5	40.1	1.5	4.5	11.1
	Hourly Idling Time (min)	11.7	11.4	3.3	33.3	19.2	15.8	13.2	13.9	3.3	12.1	11.7	10.8

For the first idling test, fuel consumption rates for the A/C and Key-In modes, which were similar to each other, were higher (53 – 86%) than those for the Heat mode for the 33980 vehicle while the former were similar to or slightly higher than the latter for the 40012 vehicle; -6 – 22%. However, for stabilized idling, fuel consumption rates for the A/C and Key-In modes, which were similar to each other, were higher than those for the Heat mode for both vehicles; 31 – 47% higher for the 33980 vehicle and 9 – 31% higher for the 40012 vehicle. On average, fuel consumption rates for the first idling test were slightly higher than those for stabilized idling; 13% higher for the 33980 vehicle and 17% higher for the 40012 vehicle. Comparing both vehicles, fuel consumption rates of the 40012 vehicle were, on average, similar to those of the 33980 vehicle. CO_2 emissions results were essentially the same.

For NO_x emissions, the average NO_x emission rates of the 33980 vehicle during the stabilized idling were very low (only a few tenths grams of NO_x hourly as shown in Table 8) and similar to each other regardless of the test conditions and modes. These results are similar to those of the 40012 vehicle except the NO_x emissions rate of 3.03 g for the Key-In mode at 68 °F. TTI researchers speculate that, compared to those of all other conditions/modes (a few minutes) for the 40012 vehicle and of all other conditions (again a few minutes) as well as the Key-In mode (13 minutes) for the 33980 vehicle, the longer interval between each emissions peak (40 minutes) as shown in Table 8 made the NO_x catalyst of the 40012 vehicle for the condition/mode ineffective. That is, the engine was not turned on often (once every 40 minutes) so that the NO_x catalyst could not be warmed up to the operational temperature.

Similar results were found for other pollutants, CO and HC. For the 40012 vehicle, average stabilized CO and HC emissions rates for the Key-In mode were also much higher than those for other modes/conditions as shown in Table 8; more than 4.7 times higher for CO and more than 9.6 times higher for HC. Additionally, CO and HC emissions rates for the 33980 vehicle in the Key-In mode were higher than those for other modes/conditions as shown in Table 8. More tests monitoring the catalyst temperature can elucidate the relationship between emissions of these pollutants and catalyst temperature with respect to engine operation frequencies and intervals.

For the first idling test, the emissions rates, averages of first emissions with different soak times for the same test condition/mode, which is described in the previous chapter, show mixed results in Table 8. For each test condition/mode for each vehicle, the first idling emissions test for each soak time was measured only once due to the limited budget and time. Then, the first idling test emissions with different soak times (for Opmode 101, 102, 103, 104, 105, 106, and 108 as described in the previous chapter) were averaged for the same test condition/mode for each vehicle and presented in Table 8. The single emissions measurement for each soak time could cause uncertainty on the measured emissions. In addition, except for the OpmodeID 108, the test vehicle should be fully warmed-up prior to soak time, but, the test vehicle might not have fully warm-up in some cases, which would increase CO and HC emissions and change NO_x emissions.

For idling tests of regular vehicles, in general, the cold start/first idling emissions peak when the vehicle is turned on. Then, the emissions stabilize with time as the vehicle/engine is warmed.

The vehicle runs during the entire time for the test condition until it is turned off to be soaked for the next idle test with different a soak time. However, for this study, the test vehicle was turned on and off automatically depending on loads for the test condition/mode and the SOC of the HEV battery, which is the nature of HEV operations. The on-off cycles would probably not allow the test vehicle to be fully warmed up. For HEV (or depleted PHEV) idle testing, it should be considered. After an idling test with a soak time ends, a little bit of driving to warm up the test vehicle before starting soak for the next idling test would resolve the issue. For this study, that approach could not be practiced due to the limited budget and time.

Due to the vehicle on-off cycles, the actual idling time of the test vehicles varied. As shown in Table 8, for both vehicles, the actual idling time per an hour of idling test time (idle time per hour) for the Key-In mode, which had the least loads compared to the A/C and Heat modes, was the shortest, 3.3 minutes. For the 40012 vehicle, the idle time per hour for all other modes was similar; a less than 15 minutes (11.7 – 13.9 minutes). For the 33980 vehicle, the A/C modes had shorter idle times (11.7 and 11.4 minutes) than the Heat modes, and the Heat mode idle time at 68 °F (33.3 min) was longer than the Heat mode idle time at 23 °F (19.2).

For overall fuel consumption and emissions, based on the testing results, charged PHEVs can save, on average, about 0.6 gallons of fuel and reduce about 5.4 kg of CO_2, 0.4 g of NO_x, 6.4g of CO and 5.4g of HC for one hour of idling over regular HEVs (or depleted PHEVs).

In-Use Real World Energy Usage and Driving Characteristics Testing

As mentioned in the previous chapter, energy usage and driving characteristics data were collected during the normal operations of the test PHEVs. For the 33890 vehicle, the data were collected during six different trips in two days. Using the driving characteristics data, i.e., second-by-second vehicle operation data, VSP was calculated, and all of the operation data were identified in 23 different MOVES operation mode bins described in the previous chapter. The numbers of observed operation data in the corresponding bins (as ratios of bins over the entire observations) are shown in Figure 9.

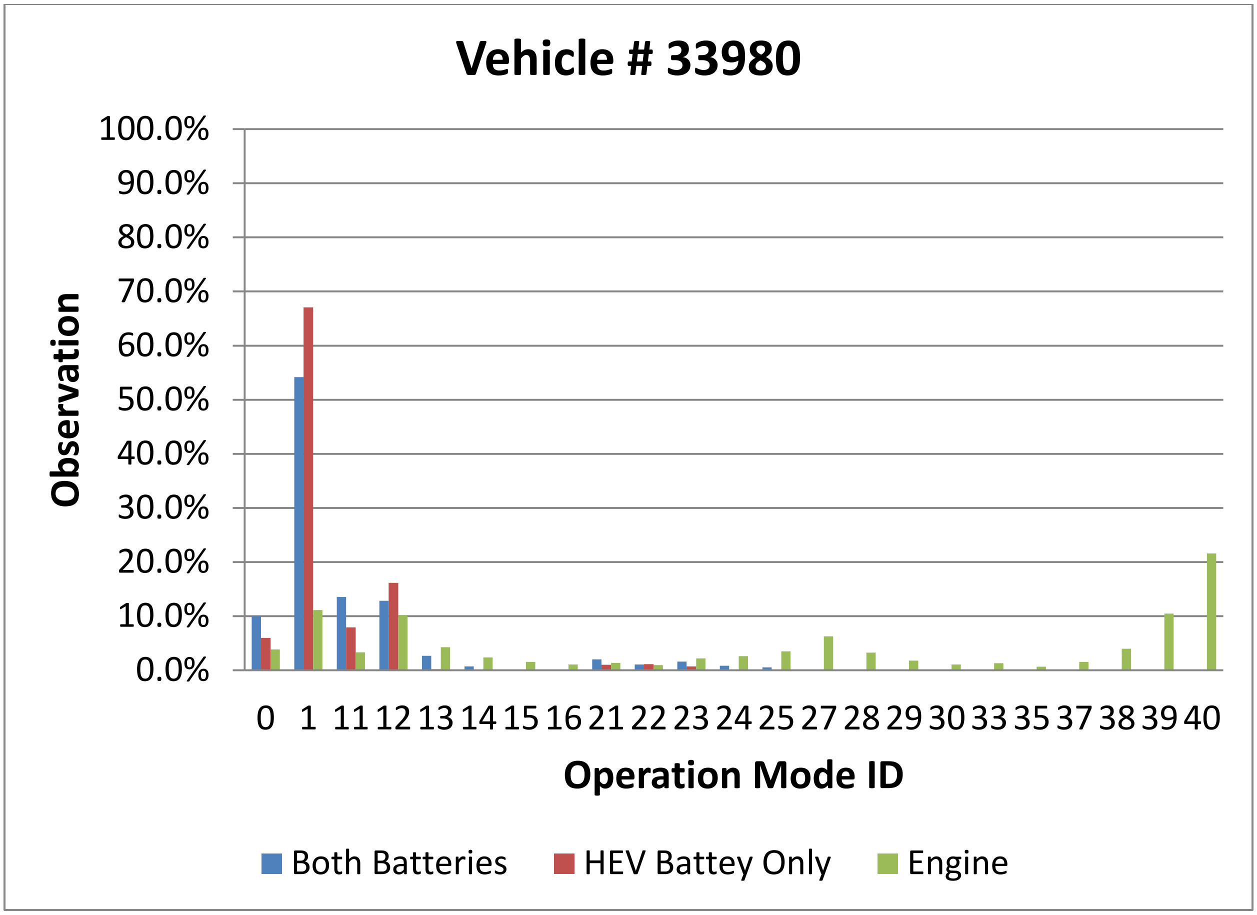

Figure 9: A Vehicle Operation Distribution in MOVES Operation Mode Bins for the 33980 Vehicle.

As shown in Figure 9 and explained in the previous chapters, vehicle operations by PHEV as well as HEV batteries (shown as Both Batteries in Figure 9) were not observed in operation mode bins of 27 or higher, which represent higher power operations (for example, fast acceleration) at speeds of 25 – 50 mph and operations at speeds of 50 mph or higher, while vehicle operations by the engine power were observed in all of the operation mode bins. For vehicle operations by the HEV battery (i.e., after the PHEV battery was fully depleted), the observed operations were mainly shown in bins 0, 1, 11, and 12 representing braking, idling, and low power operations at speeds of 0 – 25 mph.

For the 40012 vehicle, similar trends were observed during five different trips in two days as shown in Figure 10. Vehicle operations by both batteries were not observed in operation mode bins of 16, which represents the highest power operation at speeds of 0 – 25 mph, as well as 27 or higher, representing again higher power operations at speeds of 25 – 50 mph and operations at speeds of 50 mph or higher, while vehicle operations by the engine power were observed in all of the operation mode bins. For vehicle operations from the HEV battery, same as the results of the

33980 vehicle, the observed operations were mainly shown in bins 0, 1, 11, and 12 representing braking, idling, and low power operations at speeds of 0 – 25 mph.

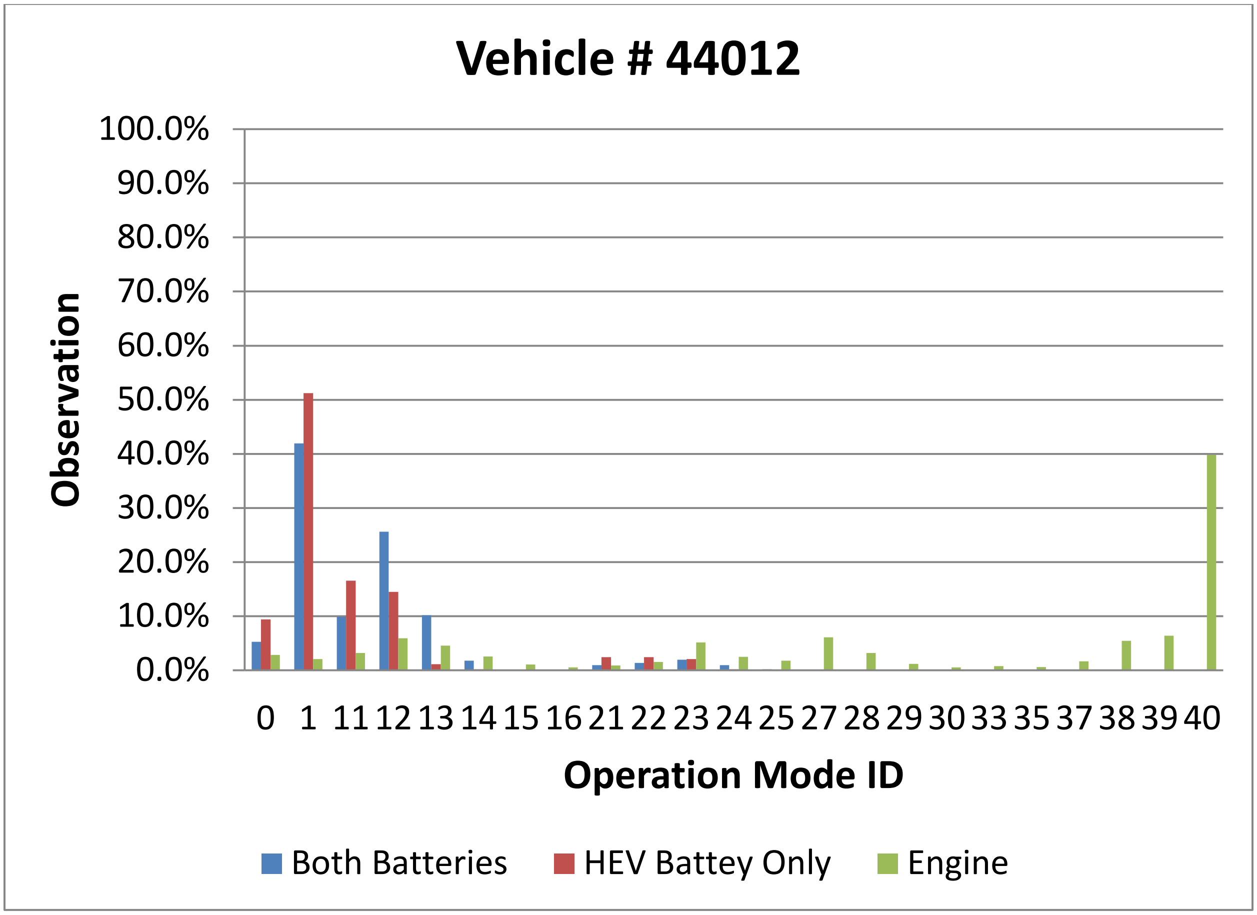

Figure 10: A Vehicle Operation Distribution in MOVES Operation Mode Bins for the 40012 Vehicle.

In addition, using the driving characteristic data collected during the six trips, vehicle miles travelled (VMT), the PHEV SOC change (by subtracting the SOC at the end of the trip from the SOC at the beginning of the trip), and energy usage (E; calculated by multiplying the SOC change by energy capacity of the PHEV battery, 5kWh) were obtained and/or calculated. The obtained and/or calculated values for the 33980 vehicle are summarized in Table 9 along with brief description of the trips.

Table 9: Energy Usage and Driving Characteristic Results for the 33980 Vehicle.

	Trip #						
	1	2	3	4	5	6	Overall
VMT (mi)	16.7	10.2	9.1	1.7	8.7	3.8	50.2
SOC change (%)	58.5	25	30.5	10	31.5	10.5	166
PHEV Battery E (kWh/mi)	0.18	0.12	0.17	0.29	0.18	0.14	0.17
Trip Characteristics	C&H†	C&H†	C&H†	City*	C&H†	C&H†	

† Mix of city and highway driving.
** City driving with driving speeds not exceeding 50 mph.

As shown in Table 9 and Figure 11, the overall E over all six trips was 0.17 kWh/mi. Figure 11 shows PHEV battery E of vehicle 33980 and 40012, on average, for trips of city driving (City), trips of mix of city and highway driving (City & Highway), and overall trips (Overall). Because the PHEV battery E is greater during low-speed driving (with the motor driven mainly from the PHEV battery) than high-speed driving (with the engine and some assistance from the PHEV battery), the PHEV battery E during the city driving with speeds less than 50 mph (0.29 kWh/mi for Trip 4) was higher than those during the mix of city and highway driving (from 0.12 to 0.18 kWh/mi for Trips 1, 2, 3, 5, and 6). After the source of the electricity used for charging the PHEV battery is identified (for example, coal-fired power plant in Ohio), the corresponding emissions values can be obtained.

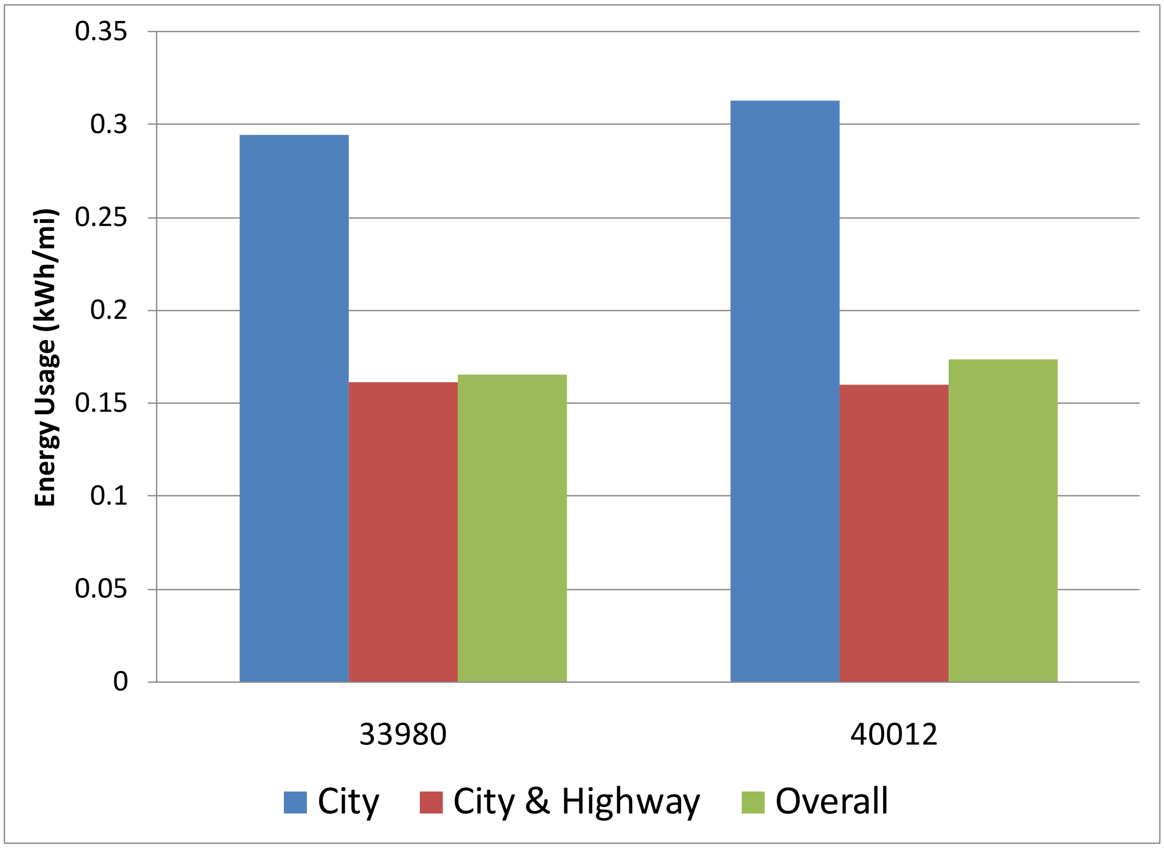

Figure 11: PHEV Battery Energy Usage.

Similar results for the 40012 vehicle were observed. For the 40012 vehicle, among the five different trips, the Trip 3 was taken after the PHEV battery had been depleted. The VMT, PHEV SOC change, and E values during the other four trips (Trip 1, 2, 4, and 5) are summarized in Table 10 along with brief description of the trips as well.

Table 10: Energy Usage and Driving Characteristic Results for the 44012 Vehicle.

	Trip #				
	1	2	4	5	Overall
VMT (mi)	19.7	0.4	14.1	2.8	37.1
SOC change (%)	72.5	4.5	35.5	15.5	128
PHEV Battery E (kWh/mi)	0.18	0.56	0.13	0.28	0.17
Trip Characteristics	C&H†	City**	C&H†	City**	

† Mix of city and highway driving.
*City driving with driving speeds not exceeding 25 mph.
** City driving with driving speeds not exceeding 50 mph.

Based on the test results, the overall E for all four trips for the 40012 vehicle was 0.17 kWh/mi, the same as the result as the 33980 vehicle. Similar to results for the 33980vehicle, the PHEV battery E for the 40012 vehicle during the city driving test with speeds less than 50 mph (0.28 kWh/mi for Trip 5) was higher than those during the mix of city and highway driving (0.18 of Trip 1 and 0.13 kWh/mi for Trip 4). For Trip 2, during the city driving test with speeds even less than 25 mph, the PHEV battery E was the highest, 0.56 kWh/mi.

In-Use Real World PEMS Emissions and Fuel Economy Testing

While performing in-use real world testing of the PHEVs in their normal operations, fuel consumption and emissions data were also collected in addition to the driving characteristic and E data. The measured second-by-second fuel consumption data (gallons of fuel consumed per second) were converted to fuel economy (VMT for each gallon of fuel; mpg). The fuel economy results for the 33980 vehicle are shown in Table 11 for comparisons between operation during the PHEV mode and the HEV only mode.

Table 11: Fuel Economy Results for the 33980 Vehicle.

	Both (PHEV and HEV) Batteries							HEV Battery Only			
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Overall	Trip 1	Trip 2	Trip 6	Overall
VMT (mi)	16.7	10.2	9.1	1.7	8.7	3.8	50.2	1.4	12.4	4.5	18.3
SOC change (%)	58.5	25	30.5	10	31.5	10.5	166				
MPG	26.4	42.8	48.7	64.1	44.3	44.1	36.8	19.2	29.4	34.7	29.3
Trip Characteristics	C&H†	C&H†	C&H†	City*	C&H†	C&H†		City*	C&H†	C&H†	

† Mix of city and highway driving.
*City driving with driving speeds not exceeding 50 mph.

Fuel economy (as mpg) depends on driving conditions. For example, fuel economy for Trip 1 with assistance from both batteries (26.4 mpg) was lower than that for Trip 6 with only the HEV's battery pack (34.7 mpg) as shown in Table 11. Comparing two short city driving conditions, the one with both batteries (1.74 miles; Trip 4) and the other one with the HEV battery only (1.39; Trip 1), the fuel economy for the former (64.1) was more than three times greater than that for the latter (19.2). In general, fuel economy with assistance from both batteries was greater than that with the HEV battery only. For the same trip, the fuel economy with two batteries was always greater than that with the HEV battery only; 26.4 vs. 19.2 for Trip 1, 42.8 vs. 29.4 for Trip 2, and 44.1 vs. 34.7 for Trip 6. For overall trips, the fuel economy with assistance from two batteries (36.8) was also greater than that with the HEV's battery only (29.3) as shown in Table 11.

The fuel economy test results for the 40012 vehicle are shown in Table 12 to compare results obtained during the PHEV mode to those during the HEV only mode. Fuel economy results for the 40012 vehicle showed similar trends to those for the 33980 vehicle. Again, fuel economy depends on driving conditions; for example, fuel economy for Trip 1 with assistance from both batteries (33.2 mpg) was lower than that for Trip 4 with only the HEV battery (40.6 mpg) as shown in Table 12. Comparing short city driving conditions, the trip with both batteries (2.76 miles; Trip 5) and the other trip with the HEV battery only (2.68; Trip 4), the fuel economy for the former (42.0) was greater than that for the latter (40.6). For the shortest trip (only 0.39 miles; Trip 2 with both batteries) having very slow city driving conditions (all of the speeds driven for the trip were less than 25 mph), fuel economy was the highest, 123.4 mph. In general, the fuel economy with assistance from two batteries was again greater than that with the HEV battery only. For the same trip, fuel economy with two batteries was always greater than that with the HEV battery only; 123.4 vs. 34.9 for Trip 2, 58.3 vs. 40.6 for Trip 4, and 42.0 vs. 32.7 for Trip 5. For overall trips, the fuel economy with assistance from two batteries (40.9) was also greater than that with the HEV battery only (32.3) as shown in Table 12. Compared to the 33980 vehicle, fuel economy of the 40012 vehicle was greater in general; overall fuel economy of 40.9 for the 40012 vehicle vs. 36.8 for the 33980 vehicle with both batteries and 32.3 for the 40012 vehicle vs. 29.3 for the 33980 vehicle with the HEV's only, respectively, as shown in Table 11 and 12.

Table 12: Fuel Economy Results for the 40012 Vehicle.

	Both (PHEV and HEV) Batteries					HEV Battery Only				
	Trip 1	Trip 2	Trip 4	Trip 5	Overall	Trip 2	Trip 3	Trip 4	Trip 5	Overall
VMT (mi)	19.7	0.4	14.1	2.8	37.1	16.4	53.4	2.7	7.2	79.7
SOC change (%)	72.5	4.5	35.5	15.5	128					
MPG	33.2	123.4	58.3	42.0	40.9	34.9	31.3	40.6	32.7	32.3
Trip Characteristics	C&H†	City*	C&H†	City**		C&H†	C&H***	City**	City**	

† Mix of city and highway driving.
*City driving with driving speeds not exceeding 25 mph.
** City driving with driving speeds not exceeding 50 mph.
*** Mostly highway driving; 93% of operations belong to MOVES operation mode bin 40 representing the highest power operation at speeds greater than 50 mph.

In addition to fuel consumption data, emissions data were also collected during the in-use real world testing during the PHEV normal operations. The emissions results are shown in Table 13. During the testing, PM was also measured. However, most of measured concentrations except those during the Trip 1were below the detection limit. For the Trip 1 with assistance from both batteries for the 33980 vehicle, the measured PM emissions rate was only 0.005 g/mi. It should also be noted that no HC emissions data were available due to malfunctioning of the hydrocarbon measuring instrument. However, CO data may represent HC data similarly because CO and HC emissions from gasoline vehicles generally show similar trends.

Table 13: Emissions Results (Overall Emissions Rates).

	Emissions Rate (g/mi) for the Overall Trips					
	Vehicle 33980			Vehicle 40012		
	CO_2	CO	NOx	CO_2	CO	NOx
Both Batteries (PHEV Mode)	248	0.183	0.048	223	0.286	0.053
HEV Battery only (HEV Mode)	312	0.131	0.056	282	0.153	0.132
Emission Reduction	**21%**	**-40%**	**13%**	**21%**	**-87%**	**60%**

Emissions rates of CO_2, CO, and NO_x for both vehicles are compared between the PHEV mode and HEV mode and shown in Table 10. As shown in Table 13, emission rates of CO_2 and NO_x during the PHEV mode were lower than those during the HEV mode for both vehicles as expected. Consequently, based on the test results of the trips, PHEV mode operations (i.e., the converted Priuses) reduced CO_2 emissions by 21% for both vehicles and NO_x by 13% for the 33980 vehicle and 60% for the 40012 vehicle, respectively, compared with the HEV mode operations (i.e., regular Priuses.) For CO, however, emissions rates during the PHEV mode operations were higher than the HEV emissions. This is because the cold start and idling emissions are solely ascribed to PHEV mode operations.

Because the HEV mode operations of a converted Prius followed the PHEV mode operations, all of the cold start idling emissions belong to the PHEV mode operations although, for a regular Prius, such cold start idling emissions belong to the HEV operations. Consequently, the PHEV mode idling emissions (in MOVES operating mode bin 1) were about 7.5 times higher for the 33980 vehicle and 19.6 times for the 40012 vehicle compared to HEV mode idling emissions. For fair comparisons, TTI researchers compared hot and stabilized emissions results from only MOVES operating mode bin 11and 12, in which most of the PHEV and HEV operation data were observed compared with any other bins except idling.

For bin 11, PHEV mode CO emissions were only about 1/3 of those from the HEV mode; 33% for the 33980 vehicle and 31% for the 40012 vehicle, respectively. That is, converted Priuses reduced CO emissions by 67% and 74%, respectively, based on the test results of the 33980 vehicle and the 40012 vehicle. For bin 12, PHEV mode CO emissions were only about 1/4 for the 33980 vehicle (26%) and about 1/5 (18%) for the 40012 vehicle of those from the HEV mode, respectively; that is, 74% and 82% reduction, respectively.

Operating mode bin comparisons can provide more details results and discussions than overall trip comparisons. However, due to the limited time and budget, little or no data were available for certain bins. For example, for operating mode bins 16, 29, 30, 33, and 35, less than 10 emissions data were observed for each bin. More tests can provide more data, so that, consequently, more detailed comparisons/discussions between PHEV and HEV emissions could be performed.

CHAPTER 5: CONCLUSIONS

In this task, two converted PHEVs were tested for battery charge/depletion, cold start and idling, in-use real world driving characteristics and energy usage, and in-use real world fuel consumption and emissions testing. The driving characteristics, energy usage, fuel consumption and emissions tests were conducted during the normal operation of the vehicles, and the battery charge/depletion tests and cold start and idling tests were conducted under environmentally controlled conditions inside TTI's environmental chamber test facility.

The key findings from these tests are summarized below:

Battery Charging/Depletion Testing

- PHEV battery charging rates were similar for both test vehicles. The charging time (from 10% [i.e., depleted] of SOC level to 100%) at 86 °F was about 10% longer than those at lower temperatures of 68 and 23 °F, which was similar to each other (about 5.1 hours).
- Overall, battery depletion rates were found to increase when A/C or heat was turned on. A general trend of battery depletion rates decreasing as ambient temperature conditions increased was also observed. However, there were differences between trends for the two test vehicles in terms of battery performance under A/C or heat modes. These mixed results can be clarified with further testing of vehicles under different test modes along with information of power usage/consumption of air conditioning and heater systems of the vehicles.

Cold Start/Idling Testing

- The depleted PHEV cold start and idling emissions showed the pattern of first (cold) start emissions peak, transition peaks, and, then, stabilized peaks for each test condition/mode. For initial/startup idling and for stabilized idling, the overall observation for both vehicles was that fuel consumption rates for the A/C and Key-In modes were similar to each other, and higher than those for the Heat mode. There were slight variations in the extent of these differences among different vehicles. The CO_2 emissions results were essentially the same as the fuel consumption results. The NO_x and CO emissions rates varied due to the repeated on-off cycles, which might have not raised the temperature of the emissions reduction catalysts to the effective level. In general, the higher emissions rates were observed for the longer intervals between emissions peaks. More tests with monitoring the catalyst temperature can elucidate the emissions with respect to engine operation frequencies and intervals. The measured PM emissions were below the detection limit.
- Based on the overall cold start and idling test results, it is estimated that a charged PHEV (where the engine would not idle) can save, on average, about 0.6 gallons of fuel and reduce about 5.4 kg of CO_2, 0.4 g of NO_x, 6.4g of CO and 5.4g of HC for one hour of idling over a depleted PHEV (or regular HEV).

In-Use/Real-World Testing

- PHEV driving characteristics were identified based on collected GPS data and fit into VSP-based MOVES operation mode bins. Overall, it was observed that the PHEV battery did not operate during the higher power operations (for example, fast acceleration) at speeds between 25 mph and 50 mph, and did not operate at speeds of 50 mph or higher. Vehicle operations by the HEV battery (i.e., after the PHEV battery was fully depleted), was observed mainly during the braking, idling, and low-power operations at speeds between 0 mph and 25 mph.
- The overall measured PHEV energy usage was 0.17 kWh/mi for both vehicles. For the 33980 vehicle, the usage was in a range of 0.12 – 0.29 kWh/mi depending on the test trip characteristics, city or highway driving. For the 40012 vehicle, the usage was in a range of 0.13 – 0.56 kWh/mi. The usage was higher for city driving than highway driving.
- For real world driving tests, fuel economy (as mpg) depended on the driving conditions. In general, fuel economy during the PHEV mode was greater than that during the HEV mode. For overall trips, fuel economy during the PHEV modes was 36.8 for the 33980 vehicle and 40.9 mpg for the 40012 vehicle while fuel economy during the HEV modes was 29.3 for the 33980 vehicle and 32.3 mpg for the 40012 vehicle.
- During the real world driving testing, PM emissions results were observed for only one trip, and were very low (0.005 g/mi). Due to the malfunctioning of the HC instrument, HC emissions data were not available. Overall, PHEV mode operations reduced CO_2 emissions by 21% for both vehicles and NO_x by 13% for the 33980 vehicle and 60% for the 40012 vehicle, respectively, compared with HEV mode operations. For CO emissions, compared during the main operations (operating mode bin 11 and 12), PHEV mode operations produced approximately 70% or less emissions. Due to time and budget constraints, such operating mode bin comparisons could not be performed for all of the pollutants for all bins, and could be a potential area for future investigation.