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Hymotion Prius Conversion PHEV Demonstration Summary Report

M. Shirk

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Idaho National Laboratory

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Idaho Falls, Idaho 83415

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CONTENTS

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1. INTRODUCTION

Data detailing over 3.3 million miles of driving and over 70,000 charging events were recorded by onboard data loggers installed in 228 Toyota Prius vehicles that were converted to plug-in hybrid electric vehicles (PHEVs). The vehicles were converted through installation of A123 Systems' Hymotion™ Plug-In Conversion Module. As part of the Department of Energy's Advanced Vehicle Testing Activity, the Idaho National Laboratory worked in partnership with Hymotion to coordinate the on-road data collection activity among 70 fleets located throughout 23 states and Washington D.C. in the United States and throughout Canada and Finland. The majority of the vehicles were part of utility or municipal fleets, while others were rotated through private households as part of a study conducted by the University of California-Davis. The Idaho National Laboratory created and managed a server that contains second-by-second data for each driving and plug-in event. The data were collected for nearly 4 years, beginning in 2008. These data were used by the Idaho National Laboratory to create monthly reports for each participating fleet. Publicly available overview reports, detailing the operation of all vehicles, also were created monthly and posted on the Advanced Vehicle Testing Activity website. In addition to periodic reporting, deeper analysis of the driving and charging data was conducted and reported in a series of papers and fact sheets. Laboratory dynamometer and accelerated on-road testing were performed by Advanced Vehicle Testing Activity testing partners. This report briefly summarizes the key findings of the multi-year project and serves as a collection of the publications detailing the results of the tests and analyses performed.

2. BACKGROUND

The converted Prius vehicles, referred to as Hymotion Prius, were fitted with A123 Systems' Hymotion™ L5 Plug-In Conversion Module, which is a 5-DC kWh supplemental battery pack designed to integrate into the 2004 through 2009 model year Toyota Prius. The conversion vehicles are capable of limited electric operation under low-speed and load conditions, depending on ambient conditions and accessory usage. The plug-in pack is charged by plugging into a 120-V AC receptacle when the vehicle is parked. The electrical energy stored in the plug-in pack is depleted during driving (i.e., charge-depleting mode), until the pack is empty, at which time the pack switches off, returning the vehicle to standard hybrid operating mode (charge-sustaining mode).

The results of the baseline performance and accelerated testing are included in Appendix A, *PHEVAmerica Fact Sheet for Hymotion Prius with Generation II Battery Pack*, and Appendix B, *PHEV Accelerated Testing Results – May 2008*. These appendices detail the performance and fuel economy for both charge-depleting and charge-sustaining modes and show the relationship of trip distance, charging time, and route type on PHEV operation.

3. KEY FINDINGS

The performance of individual vehicles and the behavior of operators varied widely throughout the demonstration project. Several factors, including driving style of operators, ambient environmental conditions, accessory usage, and route type were found to significantly affect charge-depleting fuel economy. The overall fuel economy was heavily influenced by the proportion of mileage driven in charge-depleting mode, which was affected by the charging behavior of operators. The analysis of these factors on fuel economy is included in Appendix C, *Factors Affecting the Fuel Consumption of Plug-In Hybrid Electric Vehicles*. The resulting range of fuel economy can be demonstrated by the variability of fuel economy achieved by individual vehicles. The overall gasoline-only fuel economy of individual vehicles varied from a low of 26 miles per gallon (with 9 AC Wh per mile) to a high of 69 miles per gallon (with 87 AC Wh per mile) over the entire duration of data collection. The influence of undirected Hymotion Prius charging, by residences and commercial fleets, on electricity demand also was analyzed. The results are included in Appendix D, *Electricity Demand of PHEVs Operated by Private Households and Commercial Fleets: Effects of Driving and Charging Behavior*; Appendix E, *Charging and Driving Behavior Report for Hymotion Prius – Personal Use*; and Appendix F, *Charging and Driving Behavior Report for Hymotion Prius – Commercial Use*. The overall results of the Hymotion Prius demonstration are documented as three-page fact sheets and are included in Appendix G, *Fleet Summary Report for Hymotion Prius with V2Green Data Logger*, and Appendix H, *Fleet Summary Report for Hymotion Prius with Kvaser Data Logger*.

4. PETROLEUM REDUCTION ACHIEVED

To summarize the overall petroleum reduction realized by the fleet of conversion PHEVs, the mileage-weighted overall fuel economy, consisting of all miles driven and all fuel consumed, was compared to the charge-sustaining fuel economy observed over the course of the data collection project. The charge-sustaining operation of a Hymotion Prius is identical to that of a stock Prius of the same generation. Despite the addition of the plug-in pack mass, the fuel economy of a Hymotion Prius in charge-sustaining mode is nearly identical to that of a stock hybrid-electric vehicle Prius. Using these assumptions, an 11% overall reduction in fuel consumption was achieved by the PHEV Prius when compared to the charge-sustaining mode fuel economy. For the vehicles tested, this equates to 2.6 gallons of fuel saved per 1,000 miles driven. This fuel savings, realized through conversion to and operation as PHEVs, was offset by consumption of electricity from the grid. AC energy consumption was recorded by the vehicles equipped with the V2Green/GridPoint VCM data logger, which represents the majority of vehicles tested. This subset of vehicles consumed 151,331-AC kWh of energy from the electrical grid, which displaced 7,023 gallons of gasoline (using the assumptions stated above) over 2,899,288 miles of driving.

It is important to note that the results of the fleets studied do not represent an upper bound of fuel economy improvement for the technology or the system tested. The charge-depleting fuel economy of the entire fleet, 61 miles per gallon, reduced fuel consumption by 28% over the charge-sustaining fuel economy baseline. Although the fleet operated in charge-depleting mode for only a fraction of the total miles driven, the charge-depleting performance achieved is an indication of an upper bound of fuel economy for the vehicles tested, given the range of ambient conditions and fleet missions.

5. APPENDIXES

Appendix A, PHEVAmerica Fact Sheet for Hymotion Prius with Generation II Battery Pack

Appendix B, PHEV Accelerated Testing Results – May 2008

Appendix C, Factors Affecting the Fuel Consumption of Plug-In Hybrid Electric Vehicles

Appendix D, Electricity Demand of PHEVs Operated by Private Households and Commercial Fleets: Effects of Driving and Charging Behavior

Appendix E, Charging and Driving Behavior Report for Hymotion Prius – Personal Use

Appendix F, Charging and Driving Behavior Report for Hymotion Prius – Commercial Use

Appendix G, Fleet Summary Report for Hymotion Prius with V2Green Data Logger

Appendix H, Fleet Summary Report for Hymotion Prius with Kvaser Data Logger

Appendix A

PHEVAmerica Fact Sheet for Hymotion Prius with Generation II Battery Pack

PHEVAMERICA

U.S. DEPARTMENT OF ENERGY ADVANCED VEHICLE TESTING ACTIVITY

Base Vehicle Description

Make: Toyota
Model: Prius Year: 2007
VIN: JTDKB20U577558820
Number of Passengers: 5
Hybrid Configuration: Series/Parallel

2007 Hymotion Toyota Prius Plug-In Hybrid Generation II Battery Pack

VEHICLE SPECIFICATIONS

Weights
Design Curb Weight: 3037
Vehicle Test Weight: 3337 lbs
GVWR: 3795 lbs
GAWR F/R: 2335/2250
Distribution: 54.2%/45.8%
Payload: 758 lbs
Performance Goal: 400 lbs

Electric Drive System
Battery Manufacturer: A123
Battery Type: Li-Ion
Number of Cells: 616
Nominal Cell Voltage: 3.3V
Nominal System Voltage: 185V
Nominal Pack Energy: 4.7 kWh

Engine
Model: 1NZ-FXE
Output: 76 HP @ 5000 RPM
Configuration:
In-Line 4 Cylinder
Displacement: 1.5L
Fuel Tank Capacity: 11.9 gal
Fuel Types: Unleaded

Charge System:
Input Voltages: 120V
Required Breaker Current: 15-Amp
Charger Power Output: 1.2 kW
Charger Plug Type: NEMA 5-15
80% Charge Time: 4.4 Hrs
100% Charge Time: 5.5 Hrs

VEHICLE TEST RESULTS

Charge Depleting:
Acceleration 0-60 MPH
Time: 11.6 seconds
Acceleration 1/4 Mile
Time: 19.3 seconds
Maximum Speed: 78.9 MPH
Acceleration 1 Mile
Maximum Speed: 106.5 MPH

Charge Sustaining:
Acceleration 0-60 MPH
Time: 12.4 seconds
Acceleration 1/4 Mile
Time: 19.8 seconds
Maximum Speed: 76.7 MPH
Acceleration 1 Mile
Maximum Speed: 107.0 MPH

Brake Test @ 60 MPH
Distance Required: 153.0 ft

Fuel Economy with A/C Off[1]
Cold Start Charge Depleting[2]:
Fuel Economy: 155.2 MPG
AC kWh Consumed[7]: 0.204 kWh/mi
Charge Depleting[3]:
Average Fuel Economy: 170.3 MPG
AC kWh Consumed[7]: 0.201 kWh/mi
Charge Sustaining[4]:
Fuel Economy: 55.3 MPG

Fuel Economy with A/C On[1,5]
Cold Start Charge Depleting[2]:
Fuel Economy: 112.9 MPG
AC kWh Consumed[7]: 0.239 kWh/mi
Charge Depleting[3]:
Average Fuel Economy: 151.7 MPG
AC kWh Consumed[7]: 0.264 kWh/mi
Charge Sustaining[4]:
Fuel Economy: 43.4 MPG

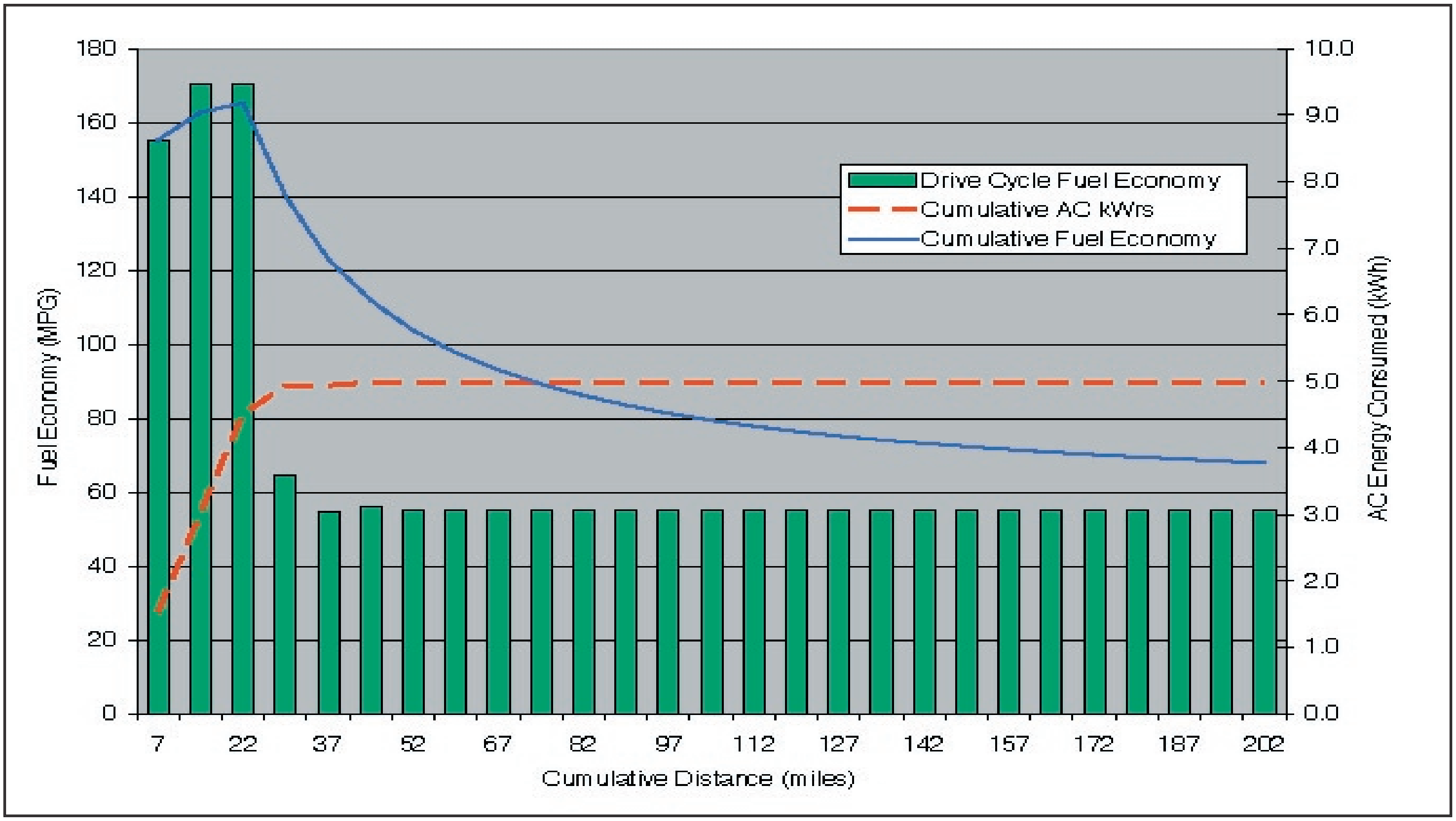
UDDS Fuel Economy[6]			HWFET Fuel Economy[6]		
Distance (miles)	Fuel Economy (mpg)	AC Energy Consumed (kWh)[7]	Distance (miles)	Fuel Economy (mpg)	AC Energy Consumed (kWh)[7]
10	157.8	2.03	10	92.0	1.57
20	164.4	4.03	20	102.3	3.10
40	119.0	4.95	40	91.3	4.66
60	97.6	4.98	60	79.0	4.66
80	87.0	4.98	80	73.0	4.66
100	80.7	4.98	100	69.5	4.66
200	68.0	4.98	200	62.4	4.66

TEST

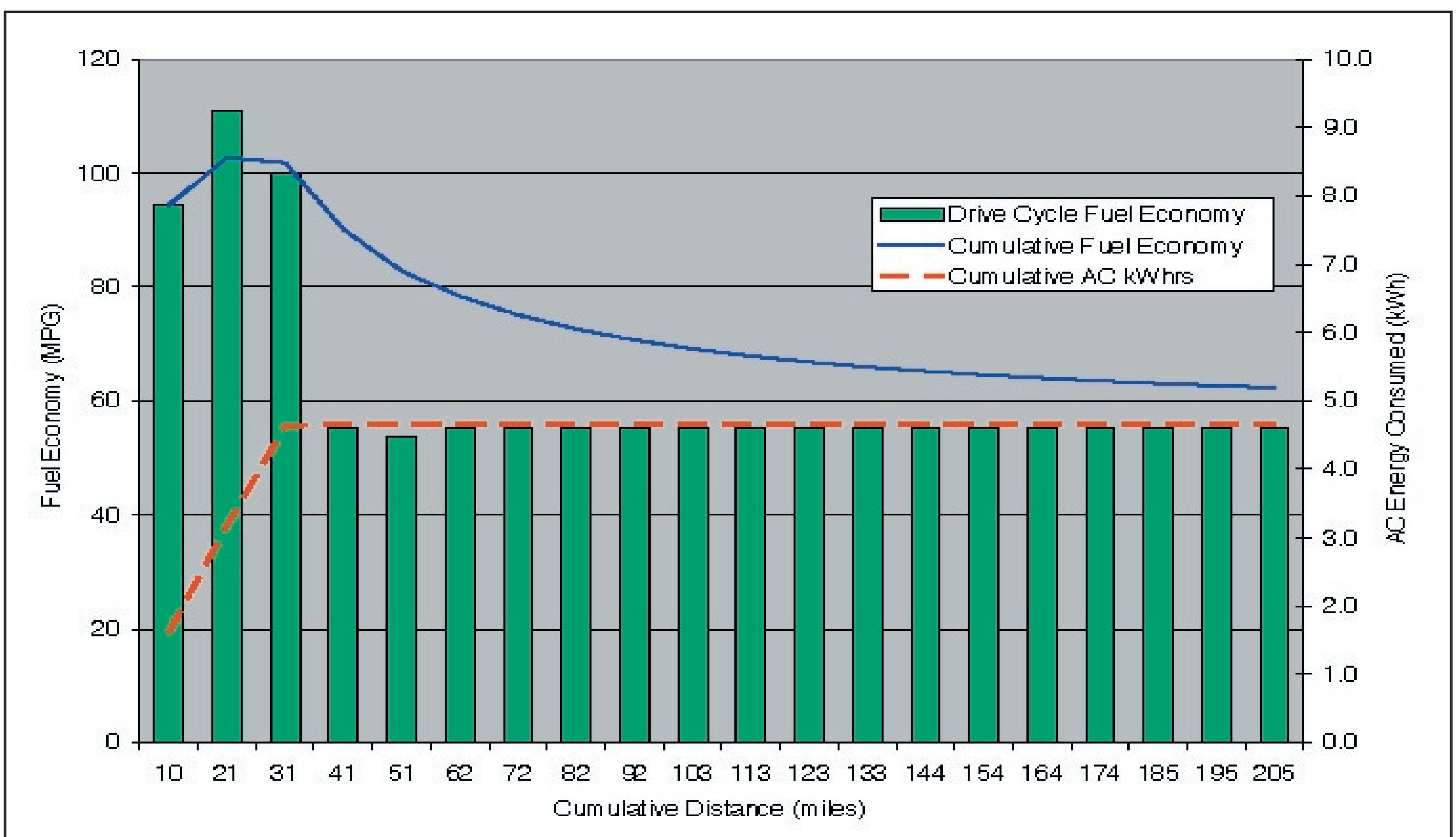
1. Cumulative fuel economy over EPA standard urban drive cycle.
2. Vehicle soaked at ambient temperature while off for a minimum of 12 hours prior to testing.
3. Average non-cold start charge depleting fuel economy.
4. Value determined from average charge sustaining fuel economy tests with appropriate energy correction calculations.
5. A/C on coldest setting with full blower power.
6. Calculated cumulative fuel economy values, includes cold start.
7. Cumulative AC energy based on measured charge efficiency.

This vehicle meets all HEV America Minimum Requirements listed on back of this sheet
Values in red indicate the Performance Goal was not met. All Power and Energy Values are DC unless otherwise specified.

Urban Driving Cumulative Fuel Economy at Range



Highway Driving Cumulative Fuel Economy at Range



This vehicle meets the following PHEVAmerica minimum requirements:

(1) Vehicles shall comply with Federal Motor Vehicle Safety Standards applicable on the date of manufacture and such compliance shall be certified by the manufacturer in accordance with 49 CFR 567. Suppliers shall provide a completed copy of Appendix A and Appendix B with their proposal, providing vehicle specifications and the method of compliance with each required section of 49 CFR 571. If certification includes exemption, the exemption number issued by the National Highway Transportation Safety Administration (NHTSA), the date of it's publication in the Federal Register and the page number(s) of the Federal Register acknowledging issuance of the exemption shall be provided along with Appendix B. Exemptions for any reason other than non-applicability shall not be allowed.
(2) Vehicles shall be certified under current California Air Resources Board (CARB) or Environmental Protection Agency (EPA) regulations.
(3) Suppliers shall supply Material Safety Data Sheets (MSDS) for all unique hazardous materials the vehicle is equipped with, including RESS batteries or capacitors, and auxiliary batteries.
(4) Suppliers shall provide recycling plans for batteries and other vehicle hazardous materials including how the plan has been implemented.
(5) All vehicles shall comply with the FCC requirements for unintentional emitted electromagnetic radiation, as identified in 47 CFR 15, Subpart B, "Unintentional Radiators."
(6) Vehicles shall have a minimum payload of at least 400 pounds.
(7) For conversions, OEM GVWR shall not be increased. For conversion vehicles, Suppliers shall specify the OEMs gross vehicle weight rating (GVWR).
(8) For conversions, OEM Gross Vehicle Axle Weight Ratings (GAWR) shall not be increased. Suppliers shall provide axle weights for the vehicle as delivered, and at full rated payload.
(9) Tires shall be subject to the following requirements:

- Tires provided with the vehicle shall be the standard tire offered by the HEV Supplier for the vehicle being proposed.
- Tires shall correspond to the requirements of the placard installed in accordance with 49 CFR 571.109, 110, 119 and 120, as applicable.
- Suppliers shall specify manufacturer, model and size of the standard tire.
- Tires sizes and in ation pressures shall be in accordance with the requirements of the placard.
- At no time shall the tire's in ation pressure exceed the maximum pressure imprinted upon that tire's sidewall.
- The tire shall be operable across the entire operation/load range of that vehicle.
- Replacement tires shall be commercially available to the end user in sufficient quantities to support the purchaser's needs.
- Tires provided as original equipment by the HEV manufacturer shall not have warranty restrictions in excess of those of the tire's manufacturer, unless the Supplier is the sole warrantor for the tires.
- If the vehicle may be equipped with more than one standard tire, this information shall be provided for each type/manufacturer of each standard tire.

(10) Seating capacity shall be a minimum of 1 driver and 1 passenger. Suppliers shall specify seating capacity (available seat belt positions) for their vehicle. For conversion vehicles, if the vehicle's seating capacity is changed from that specified by the OEM on their FMVSS placard, the seat(s) being added or abandoned shall be modified as required by 49 CFR 571.207, et al, and a new FMVSS placard installed as required by 49 CFR 567, 568 or 571, as applicable.
(11) For conversion vehicles, the OEM passenger space shall not be intruded upon by the Rechargeable Energy Storage System (RESS) or other conversion materials.
(12) The vehicle shall have a parking mechanism.
(13) The controller/inverter shall limit the minimum RESS battery discharge voltage to prevent degradation of battery life, and should limit the maximum regeneration voltage to prevent external gassing of the batteries.
(14) Vehicles shall comply with the requirements of 49 CFR 571.105.S5.2.1, or alternatively, 49 CFR 571.105.S5.2.2 for parking mechanisms.
(15) Vehicles shall be capable of completing rough road test (ETA-HTP-005) including (1) driving through standing water without damage and without battery to chassis leakage current exceeding 0.5 MIU per UL Standard 2202, and (2) standing for extended periods in extreme temperatures without damage to or failure of the vehicle or its systems.
Vehicle shall be capable of completing all AVTA tests without repairs exceeding a cumulative total of 72 hours.
(16) Vehicles shall be capable of completing two (2) Urban Dynamometer Driving Schedules (UDDS) followed by two (2) Highway Fuel Economy Driving Schedules in all charge depleting modes to obtain the fuel/energy efficiency. Testing will be conducted with the vehicle loaded to its design curb-weight plus 300 pounds.
(17) Suppliers should provide a detailed description of the RESS battery pack, battery pack voltage, number of battery modules and summary of previous performance tests. If different, customer available and battery available DOD ratings shall both be provided.
(18) Batteries shall comply with the requirements of SAE J1718.
Vehicles shall not auto-start the engine to charge the batteries while the vehicle is parked and the key switch is in the OFF position.
RESS batteries shall meet the requirements of NEC 625-29(c) or (d) for charging in enclosed spaces without a vent fan. The vehicle shall be labeled as not requiring ventilation for charging (or have the appropriate classification label from a UL-recognized Testing Laboratory).
(19) For vehicles with RESS system voltages of 48 volts and higher, batteries or capacitors and their enclosures shall be designed and constructed in a manner that complies with 49 CFR571.305. For vehicles with RESS system voltages below 48VDC, batteries or capacitors, and their enclosures, shall be designed and constructed in accordance with the requirements of SAE J1766. Further, irrespective of RESS system voltage, batteries or capacitors, and electrolyte will not intrude into the passenger compartment during or following FMVSS frontal barrier, rear barrier and side impact collisions, and rollover requirements of 49 CFR 571.301. Suppliers shall provide verification of conformance to this requirement.
(20) Concentrations of explosive gases in the battery box shall not be allowed to exceed 25% of the LEL (Lower Explosive Limit). Suppliers shall describe how battery boxes will be vented, to allow any battery gases to escape safely to atmosphere during and following normal or abnormal charging and operation of the vehicle. Battery gases shall not be allowed to enter the occupant compartment.
Batteries shall comply with the requirements of SAE J1718. and at a minimum shall meet the requirements of NEC 625-29(c) or (d) for charging in enclosed spaces without a vent fan.
(21) If a Supplier provides a vehicle with parallel battery packs, the Supplier shall provide detailed information on the equipment and charging algorithms required to prevent the parallel strings from becoming unbalanced.
(22) Flywheels and their enclosures shall be designed and constructed such that there is complete containment of the ywheel energy storage system during all modes of operation. Additionally, ywheels and their enclosures shall be designed and constructed such that there is complete containment of the ywheel energy storage system during or following frontal barrier, rear barrier and side impact collisions, and roll-over requirements of 49 CFR 571.301. Suppliers shall provide verification of conformance to this requirement.
(23) Vehicle suppliers shall provide the battery warranty provided including the procedures for making a warranty claim to the end user,
(24) If a Battery Management System is provided, the Supplier shall provide a description of the BMS operation.
(25) For vehicles using fuels other than gasoline, manufacturers shall indicate compliance with appropriate and applicable standards from SAE, NFPA, etc. [e.g., for vehicles using Compressed Natural Gas as fuel, manufacturers should indicate compliance with NFPA 52, "Compressed Natural Gas (CNG) Vehicular Fuel Systems Code," as well as 49 CFR 571.303 and 304.].
(26) Rechargeable Energy Storage Systems (RESS) shall be battery, capacitor, or electromechanical ywheel technology-based as defined in SAE J1711.
(27) Vehicles shall not contain exposed conductors, terminals, contact blocks devices of any type that create the potential for personnel to be exposed to 60 volts or greater (the distinction between low-voltage and high voltage, as specified in SAE J1127, J1128, et al.). Access to any high voltage components shall require the removal of at least one bolt, screw, or latch. Devices considered to be high voltage components shall be clearly marked as HIGH VOLTAGE. These markings should be installed at any point the voltage can be accessed by the end user. Additionally cable and wire marking shall consist of orange wire and/or orange sleeving as identified in SAE-J1127.
(28) For propulsion power systems with voltages greater than or equal to 48VDC, the system shall be isolated from the vehicle chassis such that leakage current does not exceed 0.5 MIU.
Charging circuits for RESS battery systems with voltages greater than or equal to 48VDC shall be isolated from the vehicle chassis such that ground current from the grounded chassis does not exceed 5 mA at any time the vehicle is connected to an off-board power supply.
(29) The automatic disconnect for the RESS batteries shall be capable of interrupting maximum rated controller/inverter current. The Supplier shall describe the automatic disconnect provided for the main propulsion batteries.
(30) The vehicle shall be prevented from being driven with the key turned on and the drive selector in the drive or reverse position while the vehicle's charge cord is attached. Additionally, the following interlocks shall be present:

- The controller shall not initially energize to move the vehicle with the gear selector in any position other than "PARK" or "NEUTRAL;"
- The start key shall be removable only when the "ignition switch" is in the "OFF" position, with the drive selector in "PARK;"
- With a pre-existing accelerator input, the controller shall not energize or excite such that the vehicle can move under its own power from this condition.

(31) The grid-connected charger shall be capable of recharging the RESS to a state of full charge from any possible state of discharge in less than 12 hours, at temperatures noted in Section 5.5, as applicable. The preferred recharge time should be less than eight (8) hours.

The charger shall be fully automatic, determining when "end of charge" conditions are met and transitioning into a mode that maintains the main propulsion battery at a full state of charge while not overcharging it, if continuously left on charge.
(32) The RESS charger shall be onboard the vehicle and shall use 120V or 208/240V single-phase 60-Hertz alternating current service, with an input voltage tolerance of ±10% of rated voltage. Input current for charges operating at 120 V shall be compatible with 15-ampere circuit breakers. Input current for chargers operating at 208V and 240V shall be compatible with 40-ampere circuit breakers.
Personnel protection systems shall be in accordance with the requirements of UL Standard 2202 and shall be determined based upon RESS charger input voltages. All personnel protection systems shall meet the requirements specified in the applicable sections of UL2231-1 and 2231-2.
(33) The RESS charger shall have a true power factor of 95 or greater and a harmonic current distortion of ≤20% (at rated load).
(34) Regardless of the charger used, the charger shall conform to the requirements of UL Standard 2202.
(35) Suppliers shall specify all optional equipment required to meet the requirements of this Vehicle Specification. The installation of options shall not relieve Suppliers of meeting other "shall requirements."
(36) Vehicles shall be accompanied by non-proprietary manuals for parts, service, operation and maintenance, interconnection wiring diagrams and schematics.

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Appendix B

PHEV Accelerated Testing Results – May 2008

PHEV Accelerated Testing Results – May 2008

Advanced Vehicle Testing Activity

2007 Hymotion Prius - Version I Battery

VIN # JTDK82OU577558820

Accelerated testing was completed in May 2008 and the final results can be found in the table to the right. The Hymotion Prius averaged 79.5 mpg over the 5,591 miles of testing (5,440-mile goal). Based on an electricity cost of 10 cents per kWh and a gasoline cost of $3.00 per gallon, the fuel cost was 1.18 cents per mile for electricity and 3.77 cents per mile for gasoline, for a total fuel cost of 4.95 cents per mile for the Hymotion Prius PHEV. The Prius HEVs tested by the AVTA averaged 44 mpg, so the conventional HEV Prius fuel cost would average 6.82 cents per mile.

If the Hymotion Prius PHEV were operated for 100,000 miles at 79.5 mpg, it would use 1,258 gallons of gasoline while the HEV Prius would use 2,273 gallons of gasoline over 100,000 miles at 44 mpg – 81% more gasoline than the Hymotion PHEV Prius.

This testing also documented over 100+ mpg testing results when the Hymotion PHEV Prius vehicle is driven in urban applications, so depending how this vehicle is operated, actual petroleum savings can be much greater.

Hymotion Prius – Accelerated Testing

Cycle	Urban	Highway	Charge	Reps	Total	Electricity	Gasoline	
(mi)	(10 mi)	(10 mi)	(hr)	(N)	(mi)	kWh	Gals	MPG
10	1	0	4	60	600	136.33	4.81	127.2
20	1	1	8	30	600	122.02	5.37	115.9
40	4	0	12	15	600	84.10	6.05	101.1
40	2	2	12	15	600	87.22	5.78	106.9
40	0	4	12	15	600	79.82	8.54	73.1
60	2	4	12	10	600	55.33	8.98	68.9
80	2	6	12	8	640	43.99	11.36	58.3
100	2	8	12	6	600	35.98	8.43	73.2
200	2	18	12	3	600	15.0	11.02	54.8
Total	2340	3100	1404	167	5,440	Weighted Average		79.5

Each total distance slightly greater than 600 and 640 miles. HEV version = 44 mpg

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Appendix C
Factors Affecting the Fuel Consumption of Plug-In Hybrid Electric Vehicles

EVS-25 Shenzhen, China, Nov. 5-9, 2010
The 25th World Battery, Hybrid and Fuel Cell Electric Vehicle Symposium & Exhibition

Factors Affecting the Fuel Consumption of Plug-In Hybrid Electric Vehicles

Richard 'Barney' Carlson, Matthew G. Shirk, and Benjamin M. Geller

Energy Storage and Transportation Systems Department, Idaho National Laboratory
2525 N. Fremont Ave., Idaho Falls, ID 83401, USA
E-mail: richard.carlson@inl.gov

Abstract— Plug-in hybrid electric vehicles (PHEVs) have proven to significantly reduce petroleum consumption when compared to conventional internal combustion engine vehicles by utilizing onboard electrical energy storage for propulsion. Through extensive testing of PHEVs, analysis has shown that fuel consumption of PHEVs is more significantly affected than conventional vehicles by the driver's inputs, as well as by the environmental inputs around the vehicle. Six primary factors have been identified that significantly affect fuel consumption and electrical energy consumption of PHEVs. In this paper, these primary factors are analyzed from the on-road driving and charging data of the Hymotion Prius PHEV. The data consist of 1.8 million miles of driving and charging from over 200 PHEVs in 23 states, Canada, and Finland.

The Idaho National Laboratory tests PHEVs as part of its conduct of the U.S. Department of Energy's Advanced Vehicle Testing Activity. The Advanced Vehicle Testing Activity is part of the U.S. Department of Energy's Vehicle Technology Program. In collaboration with its more than 90 PHEV testing partners, Idaho National Laboratory has collected data on 12 different PHEV models (as distinguished by battery manufacturer), while conducting fleet, track, and dynamometer testing for the U.S. Department of Energy's Advanced Vehicle Testing Activity.[1]

Keywords— PHEV, Fuel Consumption, On-Road, Testing

1. Introduction

The U.S. Department of Energy's Advanced Vehicle Testing Activity, in collaboration with 80 testing partners throughout the United States, Canada, and Finland, has collected data from over 1.8 million miles of plug-in hybrid electric vehicle (PHEV) driving and charging events.[1] A map of the testing partner locations is shown in Figure 1. Analysis of this extensive data, performed by the Idaho National Laboratory, has identified six primary factors that significantly impact fuel consumption and electrical energy consumption of PHEVs. For this paper, the six primary factors are analyzed for the Hymotion Prius PHEV and the results of the analysis are discussed.

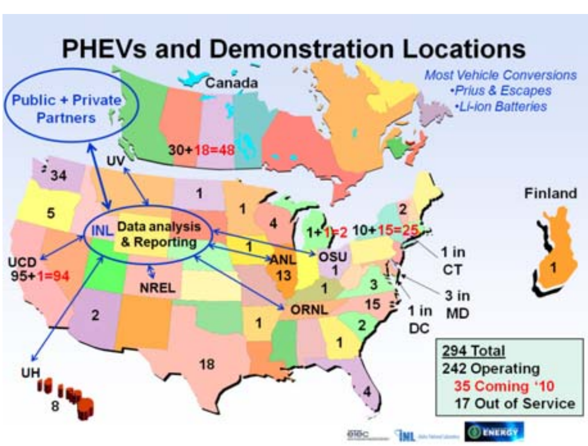

Figure 1: Locations of collaborative PHEV demonstration and test partners.

2. Vehicle Description

The analysis for this paper was performed on data obtained from the Hymotion Prius PHEVs operating in the demonstration fleet discussed previously. The Hymotion Prius PHEV uses A123 Systems' Hymotion L5 PCM (plug-in conversion module), which is a 5 DC kWh supplemental battery pack that is designed to fully integrate into a 2004 through 2009 Toyota Prius.[2] With the additional onboard battery capacity of the Hymotion L5 PCM, charge depleting operation is used in an effort to significantly reduce petroleum consumption. Figure 2 shows a picture of one of over 200 Hymotion Prius PHEVs used as part of the collaborative fleet data collection activity.

Figure 2: Hymotion Prius PHEV conversion with integrated A123 Systems' Hymotion L5 PCM.

3. Six Primary Factors

Six primary factors have been identified that significantly impact PHEV fuel consumption and electrical energy consumption. These six factors are listed below. Some of the factors are unique to PHEVs while others are common for all types of vehicles.

3.1 Usable Electrical Energy

Usable electrical energy is dictated by battery capacity, rate of depletion, and state of charge at the beginning of each trip. With less electrical energy available for use, the powertrain must use more petroleum to generate the demanded power output. With minimal usable electrical energy, a PHEV operates similarly to a hybrid electric vehicle (HEV).

3.2 Vehicle Accessory Utilization

Air conditioner systems and defroster systems are capable of consuming a significant amount of additional energy that does not contribute to the propulsion of the vehicle.

3.3 Ambient Temperature

The ambient temperature can reduce the efficiency of many powertrain components by significantly increasing fluid viscosity. For vehicles that utilize battery energy storage systems (ESS), the temperature can greatly affect the power output capability of the ESS, thus reducing its system effectiveness. In cold ambient temperatures, the need for cabin heat to warm the driver and passengers increases the time of engine operation, increasing fuel consumption.

3.4 Engine Startup/Warm up

Engine startup/warm up includes control strategies to improve cold start emissions and control routines to quickly supply cabin heat. These control strategies, while necessary for emissions control and consumer acceptance, increase fuel demand.

3.5 Route Type

Route type includes city and highway driving that can affect fuel consumption because the route can involve stop and go driving or ascending and descending steep grades.

3.6 Driver Aggressiveness

Driver aggressiveness impacts fuel consumption of nearly all vehicles; however, the impact is greater for high-efficiency powertrains such as HEVs and PHEVs.

Because many of the impact factors are independent from the other factors, it is highly possible for multiple factors to simultaneously impact fuel and electrical consumption. To accurately determine the extent of the impact for each factor, each factor must be isolated from the other impact factors. To accomplish this, fleet data are analyzed for the specific factor during periods of operation when the other five factors are within a set of nominal conditions and the sample size is greater than fifty trips. The nominal conditions are shown in Table 1. Because of random driver and environmental conditions that are present, normal distributions of data can be assumed with average values representing a majority of the respective recorded data.

Table 1: Nominal conditions of primary factors used for PHEV fleet data analysis.

Primary Factors	Nominal Conditions
Usable Electrical Energy	Trip entirely in charge depleting or in charge sustaining mode
Vehicle Accessory Utilization	No accessories on
Ambient Temperature	15 to 30°C
Engine Startup / Warm up	Initial engine temperature >50°C and trip duration > 0.2 hours
Route Type	Urban driving
Driver Aggressiveness	Less than 20% of time of the drive greater than 40% pedal position
Driver Aggressiveness	Less than 20% of time of the drive greater than 40% pedal position

4. Usable Electrical Energy

For vehicle propulsion, the amount of wheel energy is determined by the road loads on the vehicle. To create the necessary wheel energy, the powertrain, which can be comprised of a wide variety of configurations, is required to generate the required power to satisfy the desired wheel energy. For PHEVs, the powertrain uses fuel and electrical energy to produce the required output power. Because of current technology constraints of onboard ESS, the available electrical energy for use by PHEVs is much less than the available fuel energy available onboard the vehicle. For a given powertrain energy requirement, increased contribution from the onboard electrical energy storage system lessens the amount of fuel demanded to fulfill the driving requirement.

For the Hymotion Prius PHEV, the ESS enables charge depleting operation in which fuel consumption is reduced as shown in Figure 3 by displacing fuel energy with electrical energy. But charge depleting operation is only possible if there is energy available for use in the ESS from prior recharging. The energy storage system is recharged from off-board electrical energy. If the energy storage system is not fully charged prior to a trip, fuel consumption will be increased due to decreased usable electrical energy, as shown in Figure 3. At high initial states of charge, sufficient electrical energy is available to displace a large portion of the fuel consumed; however, at decreasing initial states of charge, the fuel displacement benefit is reduced.

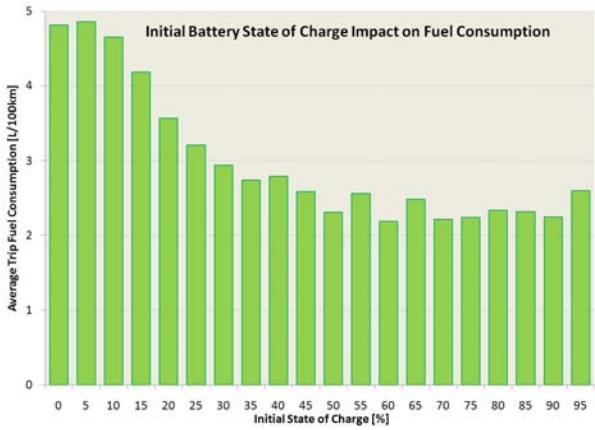

Figure 3: Fuel consumption impact dependant on ESS initial SOC.

5. Vehicle Accessory Utilization

In the Hymotion Prius PHEV, air conditioner operation is the primary accessory that impacts fuel consumption and electrical energy consumption. The air conditioner compressor is driven by a high voltage electric motor (same as in the Toyota Prius) and is operated during cabin cooling and windshield defroster operation. Figure 4 shows the relative number of driving trips in which the air conditioner compressor was operating across a range of ambient temperatures. For example, nearly all driving trips (about 90%) above 30°C ambient temperature utilized the air conditioner, whereas trips below 0°C had very low utilization of the air conditioner (about 0%). Figure 4 also shows the groupings of driving trips that utilized the air conditioner for windshield defrost and cabin air cooling. The utilization decreases for cabin air cooling as the ambient air temperature decreases from 30°C; however, windshield defroster utilization peaks just below 10°C with a utilization range from 0 to 15°C ambient temperature.

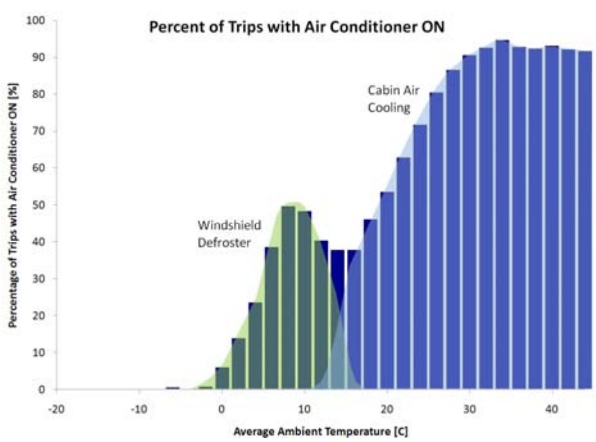

Figure 4: Percent of trips with air conditioner operation at various ambient temperatures.

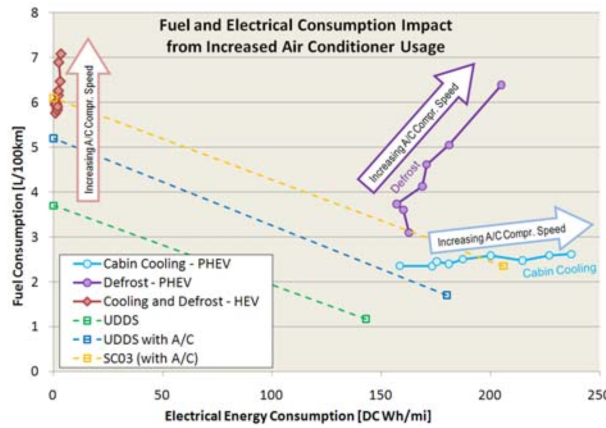

Figure 5: Fuel and electrical energy consumption impact of increasing compressor speed.[3]

Air conditioner compressor speed is closely related to the power draw from the air conditioner system. Compressor speed is available from the data collected on the Hymotion Prius PHEV fleet operation, whereas air conditioner system power draw is not available. Therefore, air conditioner compressor speed will be the metric used for comparison to determine the impact of air conditioner utilization throughout this analysis. Figure 5 shows the impact of increased air conditioner compressor speed on fuel consumption and electrical energy consumption. During charge depleting operation, with the air conditioner operating for cabin air cooling, electrical energy consumption significantly increases as fuel consumption slightly increases. This seems logical because the air conditioner compressor is driven by a high-voltage electric motor and, as electrical load increases on the energy storage system, electrical energy consumption also increases. When air conditioner operation is required for operation of the windshield defroster, both fuel consumption and electrical energy consumption significantly increase. This is due to increased engine operation during defroster operation relative to cabin cooling air conditioner operation. Because the defrost operation is primarily utilized between 0 and 15°C ambient temperature, two primary impact factors are concurrently effecting fuel consumption. As for charge sustaining operation, fuel consumption increases as compressor speed increases because all loads ultimately are powered from fuel energy. For comparison, Figure 5 shows the results of three chassis dynamometer tests of the Hymotion Prius PHEV.[3] With increasing cabin cooling load (from UDDS to UDDS with A/C to SC03), electrical energy consumption significantly increases and fuel consumption slightly increases.

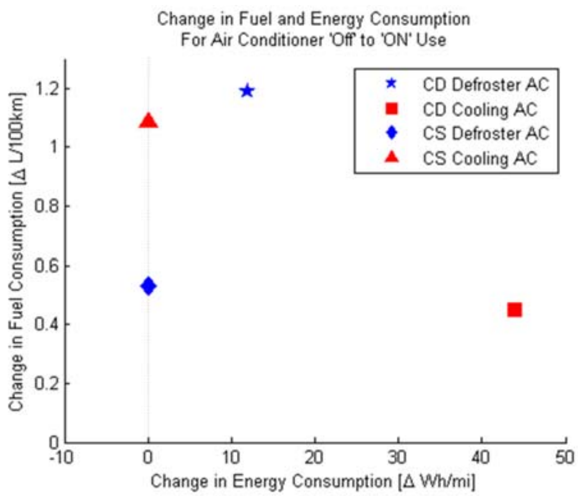

Figure 6: Average fuel and electrical consumption as impacted by use of the air conditioner for defroster and cooling purposes.

A comparison of air conditioner operation for cabin cooling and windshield defrost for both charge depleting and charge sustaining operation is shown in Figure 6. The points on the figure show the change in fuel and electrical consumption for air conditioner operation compared with no operation. The averages for each data set over the available temperature ranges are shown in Figure 6. Because the windshield defroster is only used at lower ambient temperatures, trips with an average ambient temperature below 15°C are presented as “Defroster AC.” Similarly cabin cooling air conditioner operation is only used for higher ambient temperatures; therefore, trips above 15°C are presented as “Cooling AC.” From the analysis, an increase in fuel consumption is observed for all instances of air conditioner operation regardless of vehicle mode (charge depleting or charge sustaining) or air conditioner operation type (cabin cooling or defrost). For variation in air conditioner operation type (defrost and cabin cooling), Figure 6 shows cabin cooling has the greatest impact on fuel consumption in charge sustaining operation, whereas defrost has the largest impact on fuel consumption in charge depleting operation. This effect is caused by an engine-on command for charge depleting defroster operation. For cabin cooling air conditioner operation, electrical power is required because the air conditioner compressor is driven by a high-voltage electric motor. For charge depleting operation, cabin cooling air conditioning operation uses more electrical energy from the energy storage system. For charge sustaining operation of the cabin cooling air conditioning, the additional energy requirement ultimately comes from additional fuel consumption because, by definition, the battery system has no net energy output during charge sustaining-operation.

Figure 7 shows the average air conditioner compressor speed for each driving trip in which the air conditioner system is used with respect to ambient temperature. Above 15°C, the average compressor speed for each trip exponentially increases with respect to ambient temperature. This is due to increased cooling load requirements at high ambient temperature to keep the passenger compartment cool. Below 15°C, compressor operation is for windshield defroster operation, and the average compressor speed is typically 1,000 RPM. This shows that windshield defroster operation requires a reduced and more consistent amount of power for proper operation across the operating temperature range.

Also shown in Figure 7 is the total occurrence (number of trips) for each average compressor speed for a given ambient temperature as indicated by color. Note the high occurrence, shown in dark red, of windshield defrost operation between 5 and 15°C, and contrast that with the low occurrence (shown in green and blue) of high speed compressor operation at high ambient temperatures (30°C). This means that even though the there is a large percentage of trips at high ambient temperature that use the air conditioner system (shown in Figure 4), the occurrence of those trips is rather low compared to the typical operation of the vehicle (shown in Figure 7).

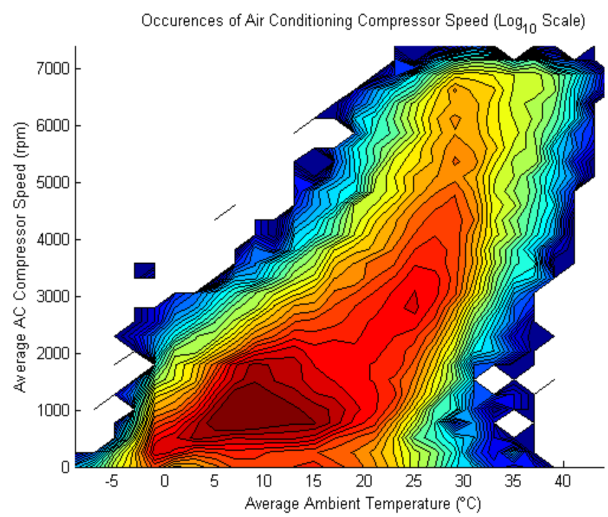

Figure 7: Percent of trips with air conditioner operation at various ambient temperatures.

6. Ambient Temperature

The ambient temperature in which a vehicle is driven impacts fuel consumption of nearly all vehicles due to changes in viscosity of lubrication fluids for the powertrain and driveline and operational changes (e.g., transmission shift schedule and engine idle speed) for improved drivability. For PHEVs, the ambient temperature has similar and additional impacts, including increased engine operating time to provide cabin air heat at low ambient temperatures and reduced battery performance at very high ambient temperatures. Figure 8 shows fuel consumption of the Hymotion Prius PHEV fleet over a wide temperature range in charge depleting and charge sustaining operation. Note the increase in fuel consumption in extremely low ambient temperature and high ambient temperature. This trend of increased fuel consumption tracks with the percentage of electric only operation as shown in Figure 9. At low ambient temperatures, the engine operates more to provide cabin air heat for passengers and longer engine warm up times are required.

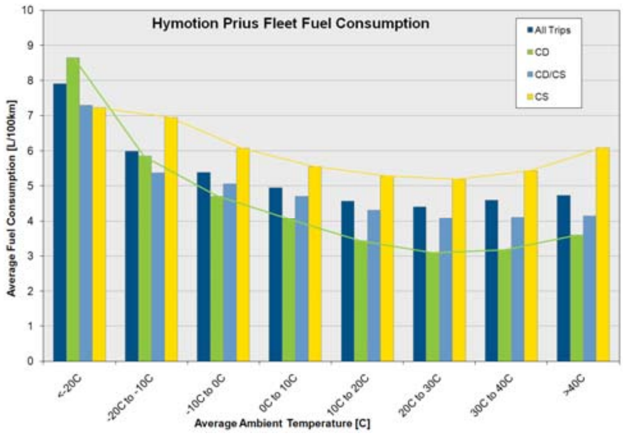

Figure 8: Fuel consumption impact of ambient temperatures.

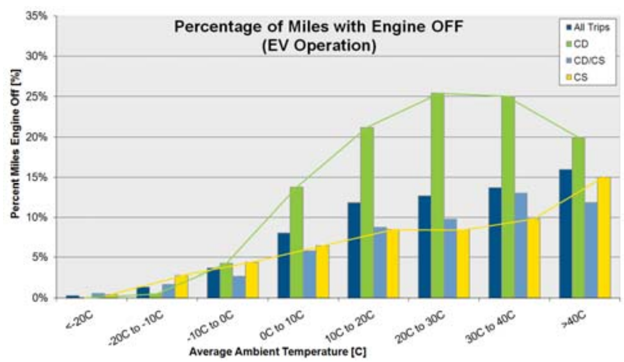

Figure 9: Electric Only operation with respect to ambient temperatures.

7. Engine Startup

At initial startup, increased fuel and electrical energy consumption occurs due to engine warm up in the Hymotion Prius PHEV. During engine warm up, different engine control strategies are used to ensure tailpipe emissions' compliance and smooth operation; however, as a result, more fuel is consumed to warm the engine. This also results in less power output from the engine during this warm up state; therefore, more electrical energy is required to meet the driver's demand. For trips with higher initial engine temperature, this increased fuel and electrical energy consumption is reduced as seen in Figure 10. The warm up period is rather brief (2 to 4 minutes); longer trips show less overall impact to fuel and electrical energy consumption due to a significant portion of driving occurring after the warm up period. As trip duration increases, the overall impact of engine warm up time to fuel and electrical energy consumption is diminished (Figure 10).

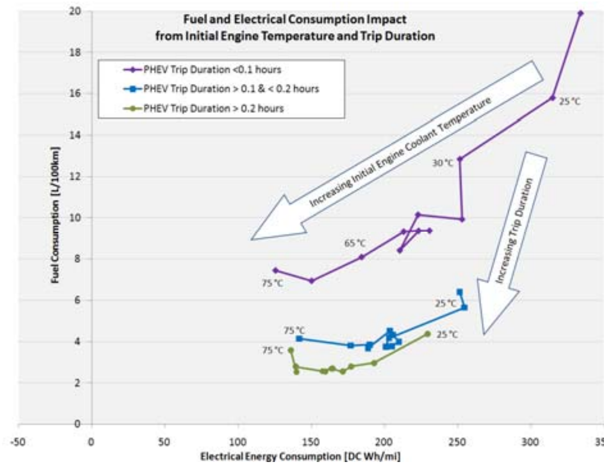

Figure 10: Fuel and electrical energy consumption impact by initial engine coolant temperature and trip duration.

Fuel flow and fuel consumption for two trips with different initial and final trip temperatures over similar trip routes is shown in Figures 11 and 12. As the engine coolant temperature during the trip increases, the fuel volume used during the trip is reduced. It can be seen by comparing Figures 11 and 12 that the colder the initial engine temperature, the longer it takes for the engine to warm up, thus increasing the fuel flow and total volume consumed. Also of importance to note is trips starting at especially cold temperatures (such as the below freezing trip in Figure 11) have an increased fuel consumption rate even during low demand driving conditions. As the engine coolant temperature increases, the engine operation and fuel flow becomes more dependent on driver demand. This reduction with increasing engine coolant temperature is the same effect shown in Figure 10 where longer trips have lower average fuel consumption

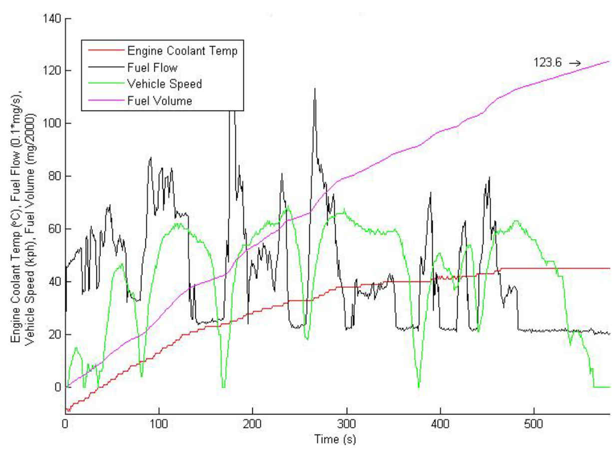

Figure 11: Driving data from a trip with initial engine coolant temperature of -8°C.

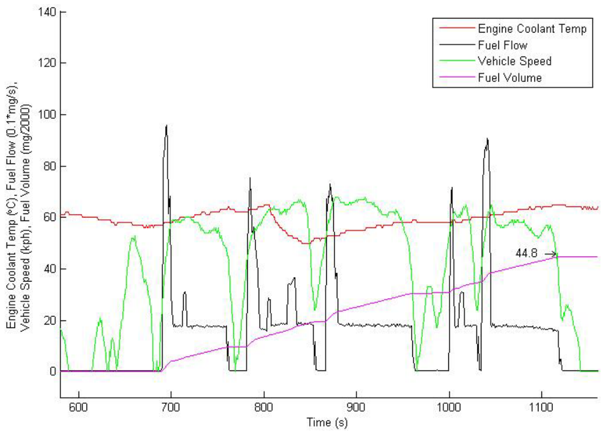

Figure 12: Driving data from a trip with initial engine coolant temperature of 61°C.

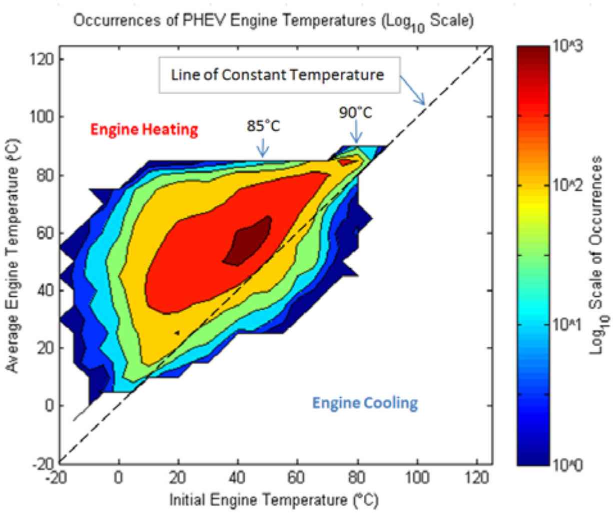

Figure 13: Number of occurrences of initial and average engine temperature during charge depleting operation.

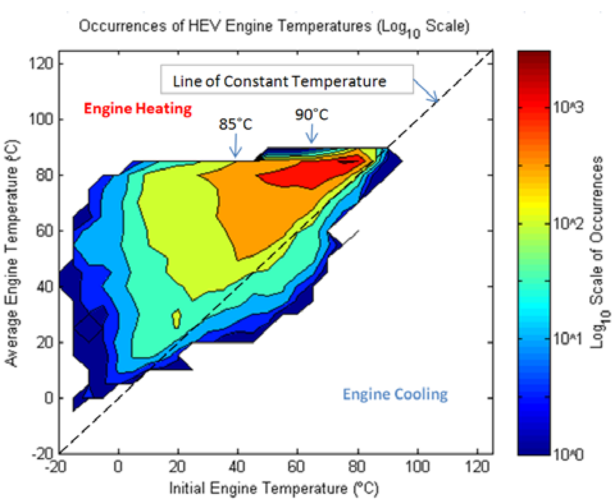

Figure 14: Number of occurrences of initial and average engine temperature during charge sustaining operation.

Figures 13 and 14 show the number of occurrences of initial and average engine temperatures for charge depleting and charge sustaining operation respectively. The engine operates within different coolant temperature ranges depending on vehicle operating mode. During charge sustaining operation, the engine is required to operate more often and at higher load, which increases the average operating temperature because all propulsion energy ultimately comes from fuel energy. For trips starting in charge sustaining mode, many are preceded by charge depleting trips in which the engine approaches typical operating temperature. In contrast, it is less likely that a charge depleting trip was preceded by a significant driving event; therefore, charge depleting trips typically begin with much lower initial engine coolant temperature. The occurrences of initial and average engine temperatures lead to an understanding that, on average, vehicles operated in charge sustaining mode operate at more fuel-efficient engine temperatures more often than vehicles operated in charge depleting mode. However, these effects are usually negated by electrical energy offsets to the total energy consumption by depletion of the battery during charge depleting operation. Additionally, in Figures 13 and 14, it is shown that the typical peak operating temperature is about 85°C, but for trips with a high initial temperature, the engine can reach about 90°C. The "Engine Heating" and "Engine Cooling" divisions of Figures 13 and 14 represent trips where the initial engine temperature is lower and higher than the average engine temperature, respectively. Engine cooling occurs when the engine is off for a significant amount of time during the trip such that the engine coolant temperature decreases over the duration of the trip.

8. Route Type

The characteristics of the route driven also impact the overall fuel and electrical energy consumption of the Hymotion Prius PHEV. Driving in stop-and-go traffic in an urban environment or cruising at high speed on a freeway will result in different fuel and electrical consumption. Mountainous driving up and down steep grades also can have a significant impact. A few parameters that are used to aid in characterization of the route type are average vehicle speed, vehicle stops per distance traveled, and percent idle time (percent of trip time when vehicle speed is zero). A strong correlation between average vehicle speed and stops per kilometer for this PHEV fleet data is shown in Figure 15. Highway driving on freeways consists of high average vehicle speeds and a low number of stops per distance traveled. Urban driving consists of a moderate number of stops per distance traveled and lower average vehicle speeds. Delivery route-type driving has a very high number of stops per distance traveled, and very low average vehicle speeds. For comparison, dynamometer drive cycle route characteristics are shown on Figure 15.[3]

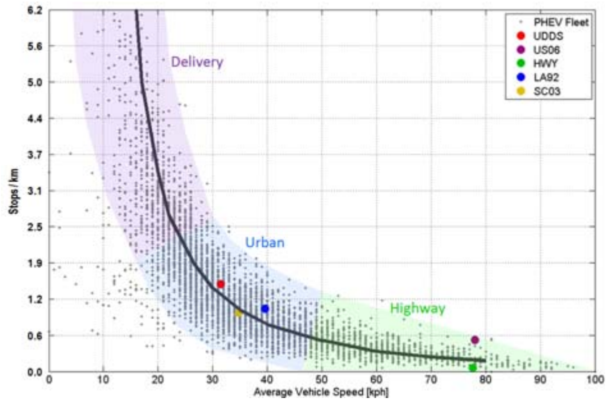

Figure 15: Relationship between average vehicle speed and stops per mile for the fleet

For the Hymotion Prius PHEV, the impact of the driving route characteristics changes near a 35-kph average vehicle speed and 1.2 stops per kilometer as shown in Figure 16. At average vehicle speeds lower than 35 kph, the fuel and electrical energy consumption decrease dramatically with increasing average vehicle speed. This trend is due to less stop and go driving, which results in the powertrain operating in regions of higher efficiency. Above average vehicle speeds of 35 kph, the fuel consumption increases while electrical energy consumption decreases with increasing average vehicle speed. This trend results from an increasing percentage of the wheel energy being delivered by fuel energy.

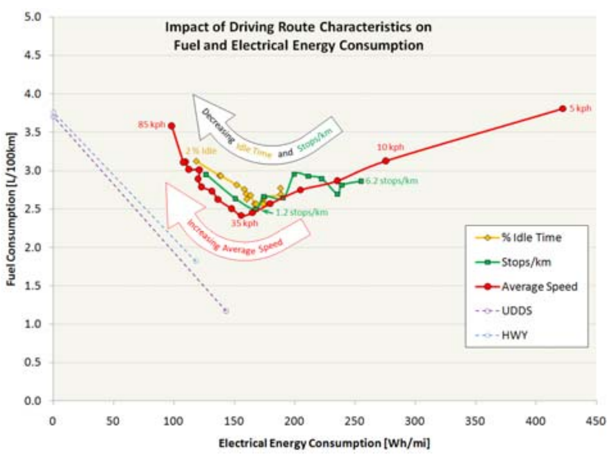

Figure 16 – Impact of average speed, idle time, and stops per mile of fuel and electrical energy consumption.[2]

The route characteristics of stops per mile and percent idle time track with a similar effect as average vehicle speed. This is due to the nature of typical driving. As average vehicle speed increases, the number of stops and total time stopped decreases. For comparison with the fleet data results, two dynamometer drive cycle results are shown in Figure 16 for the Hymotion Prius PHEV over the UDDS and the HWFET (HWY) cycles. Fuel consumption increases while the electrical energy consumption decreases when comparing the UDDS to the HWFET cycle. This is due to the increase in average vehicle speed from 32 kph to 78 kph, and the decrease in stops per mile from 1.5 to 0.06 for the UDDS and the HWFET respectively.

9. Driver Aggressiveness

Because of the power limitations of the electric drive components in the Prius powertrain, the internal combustion engine will add tractive power when road load exceeds the electric drive component power limitations. Relative driver torque request was measured by recording the accelerator pedal position throughout the driving trips. The aggressiveness factor presented here is the percent of time the accelerator pedal is depressed greater than 40% of full pedal range of travel. Early testing of the Hymotion Prius PHEV revealed that at low speeds, accelerator pedal positions greater than about 40% would cause the engine to turn on in charge depleting mode. Figure 17 shows the trend of increased fuel consumption and decreased electrical energy consumption for trips with increasing aggressiveness for a given range of average trip speed. Each point presented is the average electrical energy and fuel consumption of all trips within the given trip aggressiveness and average speed ranges.

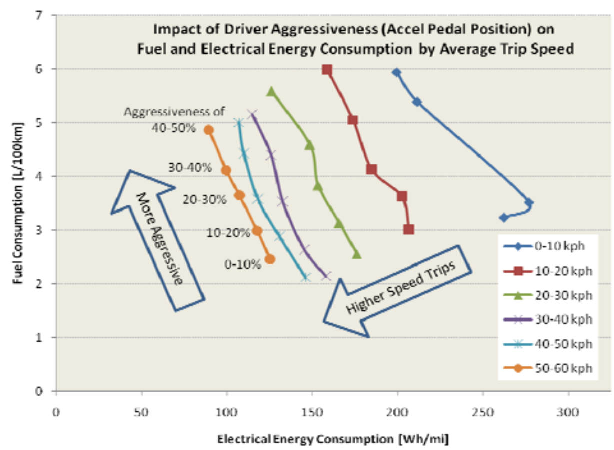

Figure 17 – Effects of driver aggressiveness on fuel and electrical energy consumption.

Driver aggressiveness is composed of characteristics involving vehicle acceleration and vehicle speed. Therefore aggressiveness has some elements that are synergistic with the driving route, specifically trip average speed. For a fixed aggressiveness range, the trend of higher speed trips having decreased fuel consumption and electrical energy consumption below 35 kph is shown in Figure 17. Above 35 kph, the trend changes to increased fuel consumption and decreased electrical energy consumption for increasing vehicle speed. This is the same trend shown in Figure 16. For a fixed-speed range, the trend is for higher fuel consumption with increasing aggressiveness due to more engine operation and higher engine torque request. While the fuel consumption increases, electrical energy consumption decreases due to the increased engine operation fulfilling a larger percent of the torque request.

10. Summary

Six primary factors that impact the fuel consumption and electrical energy consumption of PHEVs were identified from the analysis of 1.8 million miles of PHEV driving and charging data from the Hymotion Prius PHEVs. The six factors include available electrical energy, driver aggressiveness, route type, engine start-up, ambient temperature, and accessory utilization.

Through analysis of these six primary impact factors, it was determined that driving at moderate speeds (about 35 kph) in an urban environment without the air conditioner, in a non-aggressive manner, at ambient temperature near 25°C, and after plugging in the vehicle often will result in very low fuel consumption. Because very few drivers actually drive in this manner, continued advances in powertrain technology, energy storage system technologies, and vehicle architectures are needed to continue improvements in petroleum displacement.

11. Acknowledgments

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13. Author

Richard 'Barney' Carlson
Idaho National Laboratory,
2351 N Boulevard
Idaho Falls, ID 83415, USA
richard.carlson@inl.gov
http://avt.inl.gov
Mr. Carlson is a vehicle test engineer in the Energy Storage and Transportation Systems department at INL

Matthew Shirk
Idaho National Laboratory,
2351 N Boulevard
Idaho Falls, ID 83415, USA
matthew.shirk@inl.gov
http://avt.inl.gov
Mr. Shirk is a vehicle test engineer in the Energy Storage and Transportation Systems department at INL

Benjamin Geller
Idaho National Laboratory,
2351 N Boulevard
Idaho Falls, ID 83415, USA
benjamin.geller@inl.gov
http://avt.inl.gov
Mr. Geller is a is a mechanical engineering graduate student intern from Colorado State University working as a vehicle test engineer in the Energy Storage and Transportation Systems department at INL

14. Disclaimer

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Appendix D
Electricity Demand of PHEVs Operated by Private Households and Commercial Fleets: Effects of Driving and Charging Behavior

Electricity Demand of PHEVs Operated by Private Households and Commercial Fleets: Effects of Driving and Charging Behavior

John Smart[1], Jamie Davies[2], Matthew Shirk[1], Casey Quinn[1], and Kenneth S. Kurani[2]

[1]Idaho National Laboratory, Energy Storage and Transportation Systems Department,
2351 N Boulevard, Idaho Falls, ID 83415, USA
john.smart@inl.gov, matthew.shirk@inl.gov, casey.quinn@inl.gov

[2]Institute of Transportation Studies, University of California, Davis,
One Shields Avenue, Davis, California, CA 95658, USA
jdavies@ucdavis.edu, knkurani@ucdavis.edu

Abstract – The U.S. Department of Energy's Advanced Vehicle Testing Activity – conducted by the Idaho National Laboratory for the U.S. Department of Energy's Vehicle Technologies Program – in partnership with the University of California, Davis's Institute for Transportation Studies, has collected data from a fleet of plug-in hybrid electric vehicle (PHEV) conversions, placed into diverse operating environments, to quantify the petroleum displacement potential of early PHEV models. This demonstration also provided an opportunity to assess the impact of PHEVs on the electric grid based on observed, rather than simulated, vehicle driving and charging behavior. This paper presents the electricity demand of PHEVs operating in undirected, real-world conditions.

For personal-use vehicles on weekdays, peak power demand to charge the PHEVs and the period of greatest variability in demand across weekdays occurred during an evening peak that started around 4:00 p.m. and rose until 10:00 p.m. On weekends, peak demand also occurred at 10:00 p.m., but at lower magnitude than on weekdays because fewer vehicles were plugged-in and those that were typically had a higher battery state of charge. For the commercial-use group, peak demand occurred between 2:00 and 7:00 p.m. on weekdays, varying with the day of the week, and around 10:00 p.m. on the weekend. Weekend demand was significantly less than weekday demand. Driving and charging behaviors are examined for both commercial-use and personal-use vehicles. Underlying reasons for charging behavior, based on interviews and survey responses, are also presented.

Keywords—"Plug-in Hybrid Electric Vehicle (PHEV) charging," "Electric grid impact"

1. Introduction

Through the U.S. Department of Energy's Advanced Vehicle Testing Activity (AVTA), the Idaho National Laboratory (INL) has led an international plug-in hybrid electric vehicle (PHEV) demonstration and data collection project. The AVTA is part of the U.S. Department of Energy's Vehicle Technologies Program. Since 2007, INL has collected data from 294 PHEVs – the majority of them being aftermarket conversions of hybrid electric vehicles – in undirected, real-world operation. From these data, INL has documented the vehicles' gasoline and electricity consumption and the vehicle operators' driving and charging behavior. This demonstration provided the opportunity to quantify the petroleum displacement potential of PHEV conversions and to observe, rather than simulate, the impact of PHEV charging on the electric grid.

PHEVs in this demonstration were driven by commercial fleets and private households. The vehicles operated by private households were part of a PHEV demonstration and research project at the University of California, Davis's

Institute for Transportation Studies (ITS-Davis). ITS-Davis placed Toyota Priuses that were converted to PHEV operation in households in northern California. Households received a PHEV for four to six weeks. They were instructed to substitute the PHEV conversion for one of their existing vehicles. Households were neither encouraged to, nor discouraged from, charging the vehicles. This allowed ITS-Davis to study how people reacted to PHEV technology and how they used their vehicles. INL assisted the University of California Davis with data collection from the vehicles; these data are included in the overall AVTA vehicle data pool.

The purpose of this paper is to document the impact of PHEV charging on the electric grid that was observed in this demonstration, comparing the private household and commercial fleet vehicles. Grid impact is quantified in terms of when the vehicles were plugged into the electric grid and their aggregate electricity demand. Vehicle usage also is described, highlighting the wide variation of driving and charging behavior seen within and across the different vehicle use groups. To date, others have studied PHEV grid impact using computer simulations of PHEVs and the grid that were derived from travel studies of conventional vehicles and assumed charging behavior [1–3]. This paper provides grid impact results based on actual vehicle usage to facilitate further development of vehicle-grid models and energy policies.

2. PHEV Fleet Description

The AVTA PHEV fleet was comprised of over 290 aftermarket PHEV conversions from various conversion companies that were based on the Ford Escape Hybrid and Toyota Prius production hybrid electric vehicles. Fleet vehicles were owned by over 90 organizations, operating in 26 U.S. states, three Canadian provinces, and Finland [4]. Vehicle usage across the fleet varied widely, but can be characterized as either commercial or personal use. Each vehicle was equipped with an onboard data logger, which recorded time history data during driving and charging.

This paper addresses the results of Hymotion Prius conversion PHEVs that were equipped with data loggers from Gridpoint (formerly V2Green). Conclusions are made based on electronic data collected by data loggers and interviews of household and commercial fleet drivers.

The Hymotion Prius has a 5–kWh, lithium-ion supplemental battery pack that is charged by plugging into the electric grid. All charging of these vehicles was “uncontrolled,” meaning charging was not purposefully delayed or otherwise directed from the grid side. Also, all charging was done at the Level 1 charge rate (up to 120 V AC/12 A).

The Hymotion Prius data set was separated into commercial-use and personal-use groups (the latter being the ITS-Davis vehicles). For this paper, all analyses of the personal-use group were performed on data that came from the last week of vehicle operation by 67 households through March 2010. For the commercial-use group, charging and driving behavior was analyzed using a data set that included all commercial-use vehicle operation that occurred from January through December 2009. Results of these analyses are given in Section 5. To increase computational efficiency, a smaller data set was used for commercial-use vehicle grid impact analysis, which is shown in Section 4. This smaller data set included charging events that were performed during six randomly sampled weeks between January and December, 2009 by 67 random vehicles in each week.

Table 1 summarizes the number of vehicles (for the personal-use group this number is synonymous with households), number of trips, charging events, and driving distance accumulated by both vehicle groups.

Table 1: PHEV vehicle groups.

Use Group	Personal[1]	Commercial[2]
Number of Vehicles	67	153
Number of Trips	2,245	66,443
Distance Driven (mi)	19,168	634,784
Number Charging Events	531	14,363

1. Count of personal "vehicles" is the number of distinct households. Counts of personal trips, distance, and charging events are based on one week each from each household.
2. Counts of commercial trips, distance, and charging events are based on each commercial vehicles' total time in service during 2009.

3. Vehicle Energy Consumption and Charge Depleting Operation

As a dual-fuel vehicle, the Hymotion Prius consumes energy for propulsion from both gasoline and electricity. When the supplemental plug-in battery pack is charged, the vehicle operates in charge depleting (CD) operation, typically drawing a higher proportion of propulsion energy from electricity. When the plug-in pack reaches its minimum state of charge, the vehicle operates in charge sustaining (CS) mode. Tables 2 and 3 show the gasoline consumption, electricity consumption, and proportion of operation in CD and CS modes for the personal-use and commercial-use groups, respectively.

Table 2: Personal-use group (one week) energy consumption and operating mode.

Operating Mode	CD	CS	Com-bined
Gasoline Consumption (mpg)	66	44	53
Electricity Consumption (Wh/mi)	176	0	86
Percent of Distance Driven (%)	49	51	100

Table 3: Commercial-use group (total 2009) energy consumption and operating mode.

Operating Mode	CD	CS	Com-bined
Gasoline Consumption (mpg)	63	43	48
Electricity Consumption (Wh/mi)	183	0	56
Percent of Distance Driven (%)	31	69	100

Other publications have elaborated on operation of the Hymotion and the factors that influence its fuel consumption [5, 6]. However, this paper focuses on the effect of vehicle charging on the electric grid.

4. Grid Impact

The impact of PHEV charging on the electric grid that was observed in this demonstration is quantified in terms of the percent of vehicles plugged into the electric grid and their aggregate electricity demand versus time of day and day of the week.

The percent of vehicles plugged into the electric grid is a measure of when vehicles were physically plugged into an electrical outlet, regardless of how much power the vehicles were drawing from the grid. The vehicles could be at any state of charge or even finished charging. Electricity demand refers to the aggregate load shape that would be seen by a single hypothetical electric utility serving all these PHEVs. Figures 1 through 4 contain these distributions for the personal-use and commercial-use groups.

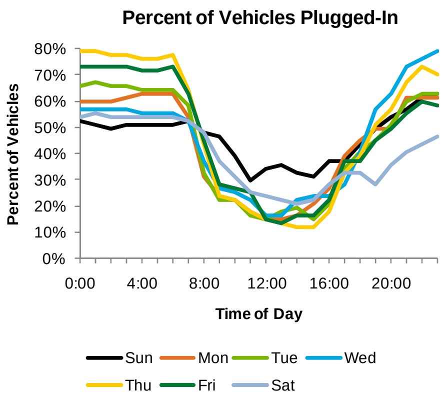

Figure 1: Percent of personal-use vehicles plugged-in.

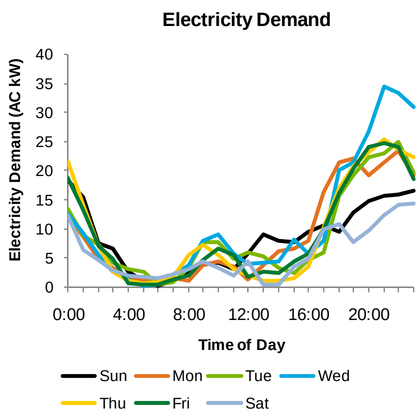

Figure 2: Electricity demand of personal-use vehicles.

For the personal-use group (Figures 1 and 2), all charging events recorded during each household's last week of PHEV use were included in the distributions. Charging from all 67 households was assumed to take place within a single calendar week. Electricity demand for both use groups is shown as the sum of power demand from all vehicles in each data set.

Most personal-use drivers commuted to and from work on weekdays. Therefore, the percent of vehicles plugged-in steadily decreased and electricity demand dropped between 6:00 and 9:00 a.m. as drivers unplugged to drive to work. Daytime electricity demand among personal-use PHEVs can be attributed to a small number of vehicle drivers who plugged in at work and the retired individuals, homemakers, and telecommuters who were usually at home during the day. As commuters returned from work, the percent of vehicles plugged-in steadily increased throughout the evening and peaked from midnight to 6:00 a.m. Electricity demand peak saw a similarly steady rise, but peaked between 9:00 and 10:00 p.m.

Peak power to charge a Hymotion Prius typcially varied between 1.0 to 1.4 AC kW. However, in aggregate, peak demand per vehicle was considerably less. For example, the percent of possible power drawn per vehicle on Wednesday at 9:00 p.m. – the period of absolute peak aggregate demand – was 37% (assuming a 1.4-kW maximum power demand per vehicle). This was due to the variation in starting times of individual charging events throughout the day and night. At any given time, some vehicles drew full power, while others were plugged-in but had completed charging and consumed little power.

Figures 1 and 2 show variation in charging behavior between the days of the week. The most noticeable differences are seen between weekdays and weekend days. The percent of vehicles plugged-in on the weekend was lower at night and higher during the day than on weekdays. The exception is Sunday evening, which aligns with weekday nights. This was because fewer vehicles were driven on the weekend; therefore, they were left plugged-in more often. Total electricity demand was lower on the weekend for this same reason. Section 5.2 quantifies weekday and weekend driving behavior.

The trends in Figures 1 and 2 also reflect weekend travel routines of some of the households (i.e., often taking overnight trips and not plugging in the vehicles until returning home later in the day on Sunday [7]). Also, note the reduced charging demand and percent of vehicles plugged-in during Monday morning. This may mean that drivers perceived less of a need to charge the vehicle, perhaps knowing that the vehicle was fully charged to start the week.

Figures 3 and 4 show the grid impact of the commercial-use vehicles.

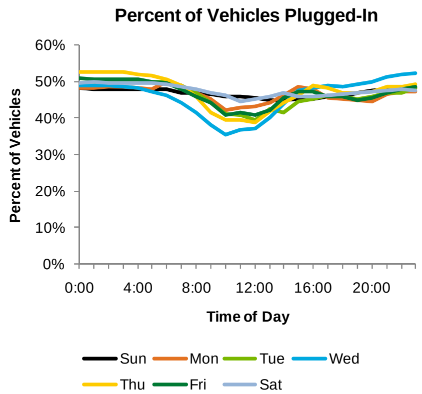

Figure 3: Percent of commercial-use vehicles plugged-in.

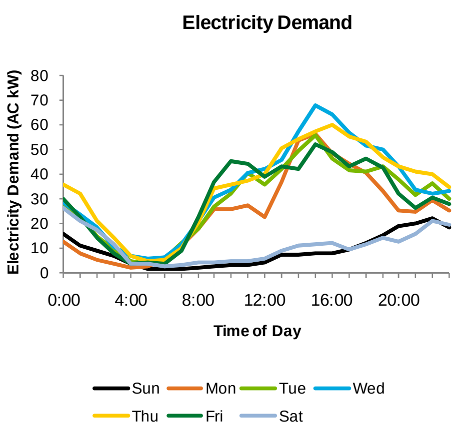

Figure 4: Commercial-use vehicle electricity demand.

The distribution of vehicles plugged-in (Figure 3) is much more uniform throughout the day and night for commercial-use vehicles than personal-use vehicles. There were two main reasons for this. First, while the average distance driven per day on days when the vehicle was driven was higher for the commercial-use group than the personal-use group, the weekly distance driven per commercial-use vehicle was much lower (see Section 5.2). This means that the commercial-use vehicles much less likely to be driven every day, in which case, they were usually left plugged-in the entire day. Secondly, on days when commercial-use vehicles were driven, they were able to plug in more often during the day. Charging during the day was possible because many commercial-use vehicles returned to their primary charging locations, such as a company motor pool, between trips during the day. They also plugged in at other locations during the day, such as a field office with an outlet designated for charging the company-owned vehicle. Charging behavior is explained further in Section 5.1.

Figure 4 shows that daily weekday peaks occurred between 2:00 and 7:00 p.m. becasue most vehicles that were driven returned to their primary charging locations at the end of the work day. Comparing days of the week, peak demand was lower and earlier in the day at the beginning and end of the work week and it peaked on Wednesday. Weekend peak demand occurred around 10:00 p.m. and was very low compared to weekdays because more vehicles remained plugged-in at their primary charging location over the weekend and less driving was done over the weekend. A small number of vehicles were taken home by employees or driven to special events on the weekend, such as promotions or fairs. Electricity demand on Saturday and Sunday increased gradually as those vehicles driven on the weekend returned to their home location (either personal residences or company fleet parking area) and plugged in at the end of the day.

5. Factors that Influence Electricity Demand

It important to characterize vehicle usage in order to understand the underlying causes of the observed electricity demand. Electricity energy and power demand from PHEV charging is determined by three factors:

1. Charging behavior (e.g., where, when, and for how long drivers choose to charge)
2. Driving behavior (e.g., distances driven between charging events)
3. Vehicle and charging infrastructure

characteristics (battery energy capacity, per-mile electricity consumption, and charge rate).

These three groups of factors are interrelated. Driving and charging behavior vary significantly across both use groups, along with vehicle per-mile electricity consumption.

5.1 Charging Behavior

5.1.1 Charging Time of Day

To further understand vehicle operator behavior, individual charging events were examined. First, charging events were categorized as weekday (WD) or weekend (WE) and as end-of-day or during-the-day. End-of-day charging events are those that occurred after the last trip of the calendar day, regardless of what time the last trip ended. During-the-day charging events are those that took place between trips in a calendar day. Tables 4 and 5 give the proportion of charging events and charging energy that fell into these categories.

Table 4: Personal-use group (one week) charging statistics.

End-of-day	**WD**	**WE**	**All**
Number of charging events	292	101	393
Percent of all charging events	55%	19%	74%
Charging energy consumed (AC kWh)	1,078	315	1,393
Percent of all energy consumed	65%	19%	84%
During-the-day	**WD**	**WE**	**All**
Number of charging events	109	29	138
Percent of all charging events	21%	5%	26%
Charging energy consumed (AC kWh)	207	59	266
Percent of all energy consumed	12%	4%	16%

Table 5: Commercial-use (total 2009) charging statistics.

End-of-day	**WD**	**WE**	**All**
Number of charging events	8,387	1,138	9,525
Percent of all charging events	58%	8%	66%
Charging energy consumed (AC kWh)	23,554	2,913	26,466
Percent of all energy consumed	66%	8%	74%
During-the-day	**WD**	**WE**	**All**
Number of charging events	4,503	321	4,824
Percent of all charging events	31%	2%	34%
Charging energy consumed (AC kWh)	8,688	5,63	9,251
Percent of all energy consumed	24%	2%	26%

Table 4 shows that for the personal-use group, 26% of charging events were during-the-day events. These consumed only 16% of the personal-use group’s total charging energy. Table 5 shows that for the commercial-use group, 34% of the charging events were conducted during the day and consumed 24% of the charging energy. This is consistent with the time-of-day grid impact trends discussed earlier, which indicated that the commercial-use PHEVs were plugged-in more often throughout the day. For both groups, during-the-day charging events were shorter and consumed less energy per charging event than end-of-day charging. This was due to shorter charging events and higher battery state of charge at the start of charging. Data in the tables also show that much less charging was done on the weekend for both groups.

5.1.2 Charging Location

One of the reasons for differences between the commercial-use and personal-use charging behavoir was access to charging locations away from the primary charging location. Few of the households in the personal-use group plugged into outlets at locations away from home. Figure 6 quantifies the distinct number of charging locations used per personal-use vehicle/household. It shows that the vast majority of vehicles plugged in exclusively at one location (their residence).

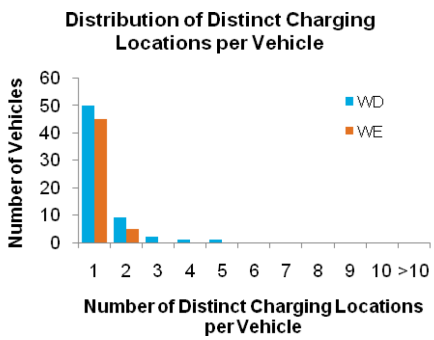

Figure 6: Personal-use group distinct charging locations per vehicle.

Households that did not plug in away from home reported two factors that limited away-from-home charging: (1) perceived lack of access to an electrical outlet and (2) unknown etiquette about plugging into an outlet that did not belong to them. Some households might have had access to an outlet away from home (within the reach of the extension cord) that did not belong to them, but felt uncomfortable asking permission to plug in. For instance, one household driver could have plugged in at work if she could have parked in her boss's parking space; however, she did not feel it would be appropriate to ask for such a privilege [7].

Interestingly, while the group as a whole did not charge away from home very often, those individuals who had access to and were willing to use away-from-home charging locations were plugged in 99% of the time while they were parked in those locations [8].

On the other hand, the commercial-use group had greater access to multiple charging locations, especially on weekdays when the vehicles were more likely to be driven (Figure 7).

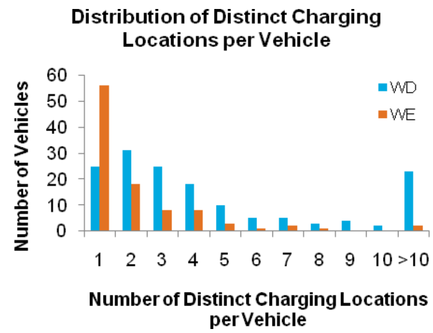

Figure 7: Commercial-use distinct charging locations per vehicle.

As mentioned earlier, many companies operating these vehicles had more than one office or work site between which the vehicles were driven. Many companies designated charging outlets for PHEV charging at multiple sites. Also, vehicles were often made available to multiple drivers for business or personal use. This means that, over time, a single vehicle may have spent time plugged-in at multiple business facilities or employees' homes.

5.2 Driving Behavior

Charging behavior and the impact of charging on the electric grid are inseparably connected to driving behavior. Clearly, a vehicle cannot be plugged in while it is being driven and the amount of electricity demanded from the electric grid is proportional to the amount of electricity consumed by the vehicle during driving.

Figures 8 and 9 show distributions of daily distance driven by the personal-use and commercial-use groups, respectively.

On average, the personal-use group drove 45 miles per day on days when the vehicle was driven and 286 miles per vehicle per week. The commercial-use group drove 48 miles per day when driven and 174 miles per vehicle per week.

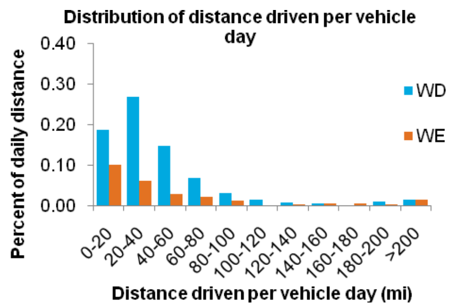

Figure 8: Personal-use daily driving distance.

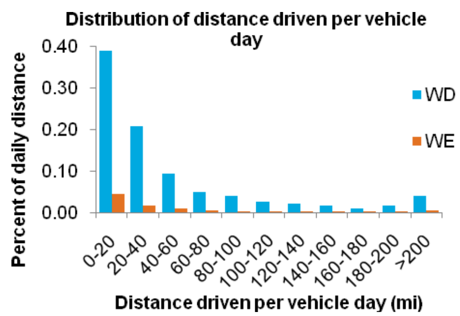

Figure 9: Commercial-use daily driving distance.

6. Discussion of Behavior

6.1. Variation within Use Groups

Thus far, discussion has emphasized behavioral differences between the two use groups. It is important to note that there also was tremendous variation within each group. For example, charging frequency and distance driven between charging events (or per day) varied from one household, commercial-use fleet, and vehicle to another. For the personal-use group, these differences were attributable to differences between, and even within, specific households. Within the final week of each household's data, weekly driving distances varied from 60 to 947 miles, plug-in events per day varied from 0.4 to 3.0, and percent of miles driven in CD mode varied from 13 to 100%. Commercial-use vehicles exhibited similarly wide.

6.2. Underlying Charging Motivations

Most households in the personal-use group had some degree of routine, such as commuting to work, trips to drop off or pick up kids from daycare, or a weekly trip to the grocery store. Similarly, most commercial-use vehicles were used for specific business purposes (such as making customer calls) rather than simply being demonstration vehicles. Therefore, both groups had to incorporate charging their PHEVs into their exisiting routines. The extent to which vehicle drivers prioritized vehicle charging or were able to fit charging into their routines varied. These differences in priority depended upon many factors, including the following:

- Lifestyle or work pace
- Vehicle mission
- Understanding of the vehicle, including ability to determine the battery's state of charge
- Access to charging infrastructure away from the home or fleet location
- Actual and perceived benefit of plugging in, including private and social benefits
- Perceived social acceptability (or lack thereof) of plugging into an outlet that did not belong to them.

Some vehicle drivers typically plugged in their vehicles whenever parked for a significant amount of time at a known charging location. For example, one personal-use vehicle was plugged-in approximately 94% of the time when it was parked at home. That household reported they made charging the vehicle a priority, citing the time they would save at the gas station and the relative ease of plugging in [7].

Other households plugged in the vehicle when they were done driving for the day or when the vehicle was parked in the garage for nightly storage. In some cases, even though the vehicle was parked at a charging location with an empty battery, vehicle operators waited to plug in until later. This behavior was seen most in the personal-use group and in the commercial-use group where one or a small number of people drove the vehicle.

Finally, a small group of households were among the most advanced PHEV users. They were often cognizant of the state of charge of the vehicle's battery and their upcoming travel. These households tended to plug in the vehicle only when they felt it was necessary to maintain charge depleting operation for their anticipated travel.

7. Context for Interpreting Charging Behaviors

The behavior presented in this paper is specific to driving and charging of a blended PHEV conversion with a 5-kWh plug-in battery, Level 1 charging using a standard 110-V NEMA 5 plug, in an environment with the following:

- Minimal designated public vehicle charging infrastructure;
- Unknown etiquette for plugging into outlets owned by others;
- Minimal real-time feedback from the vehicle informing the driver of the battery state of charge or operating mode (CD vs. CS);
- No time-of-day use electricity tariffs or incentives in most areas and limited awareness among vehicle drivers or fleet operators of incentives in areas where they were present; and
- No grid-side charge control.

Analysts should exercise caution when translating results from this demonstration to studies where conditions differ.

8. Conclusion

This paper describes the effects of driving and charging on electricity demand to charge 5-kWh, blended-operation PHEVs observed in undirected, real-world conditions. The vehicles were from samples of two fleets, neither of which can be said to be representative of the population from which they were drawn, but varied enough to exhibit a broad range of driving and charging behaviors. One is drawn from households in northern California and the other is drawn from commercial fleets in the U.S., Canada, and Finland.

The time of day when the PHEVs were plugged in by households looks, generally, as has been widely imagined: the highest percent of vehicles were plugged-in from midnight to 6 a.m. The percentages decline in a wide trough, reaching a minimum in early afternoon before rising as PHEV drivers arrive home throughout the evening. There are substantial differences in the details across weekdays. Most notably, no more than two-thirds to three-fourths of vehicles were plugged-in on at any time on weekdays and less than 60% on weekend days.

The distribution of commercial-use fleet vehicles plugged into the grid versus time of day is more nearly uniform throughout the day, at between 40 and 70%. However, this masks two distinct patterns. First, many commercial-use vehicles went undriven for days at a time and were plugged-in this whole time. Second, other commercial-use vehicles were driven frequently and caused a drop in percentage of vehicles plugged-in during the day-time hours.

For personal-use vehicles on weekdays, peak power demand to charge the PHEVs and the period of greatest variability in demand between days of the week occurred during an evening peak that started around 4:00 p.m. and rose until 10:00 p.m. Another small peak occurred between 8:00 and 11:00 a.m. due to those few household commuters who found a place to charge at work. Because of the relatively small battery size in the vehicles in this study, batteries were nearly always fully charged during the night. Therefore, charging power demand declined to near zero every morning by 5:00 to 6:00 a.m. However, power demand rarely actually dropped to zero throughout any day because of the incidence of during-the-day charging between the households multiple stops and returns to home throughout a day. On weekends, peak demand also occurred at 10:00 p.m., but at lower magnitude than on weekdays because fewer vehicles were plugged-in and those that were typically had a higher state of charge.

For the commercial-use group, peak demand occurred between 2:00 and 7:00 p.m. on weekdays, varying with the day of the week, and around 10:00 p.m. on the weekend. Weekend demand was significantly less than weekday demand.

Reasons for the differences in demand between the two use groups include differences in access to charging infrastructure during the day and at multiple locations, the total distances driven, and charging energy consumed. While much of the driving, charging, and power data are presented in summary forms that eases description and comparison, it should be reiterated that wide variation in charging and driving behavior was observed within each use group and within each behavioral unit (i.e., household or fleet) within each group.

9. Acknowledgments

Funding for AVTA is provided the U.S. Department of Energy's Vehicle Technologies Program.

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[8] Hymotion Prius PHEV Charging and Driving Behavior Report (commercial-use vehicles), http://avt.inl.gov/phev.shtml.

11. Authors

John Smart
Idaho National Laboratory,
2351 N Boulevard, Idaho Falls, ID 83415, USA
john.smart@inl.gov

Mr. Smart is a vehicle test engineer in the Energy Storage and Transportation Systems department at INL.

Jamie Davies
Institute of Transportation Studies
University of California, Davis
One Shields Avenue
Davis, CA 95616 USA
Email: jdavies@ucdavis.edu

Jamie is a graduate student researcher at the Plug-in Hybrid and Electric Vehicle Research Center of the

UC Davis Institute of Transportation Studies. Jamie's research is based around characterizing consumers' use of PHEVs, including driving and charging behaviors.

Matthew Shirk
Idaho National Laboratory,
2351 N Boulevard, Idaho Falls, ID
83415, USA
matthew.shirk@inl.gov

Mr. Shirk is a vehicle test engineer in the Energy Storage and Transportation Systems department at INL.

Casey Quinn
Idaho National Laboratory,
2351 N Boulevard, Idaho Falls, ID
83415, USA
casey.quinn@inl.gov

Casey is a mechanical engineering graduate student intern from Colorado State University, studying the interaction of PHEVs with the electric grid.

Dr. Kenneth S. Kurani
Institute of Transportation Studies
University of California, Davis
One Shields Avenue
Davis, CA 95616 USA
Email: knkurani@ucdavis.edu

Dr. Kurani has been conducting and directing research into consumer response to alternative fuel and electric-drive vehicles for the past 25 years.

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Appendix E
Charging and Driving Behavior Report for Hymotion Prius – Personal Use

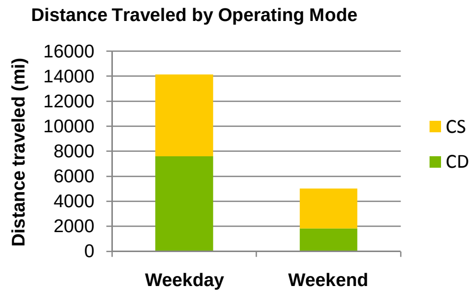
Vehicle Technologies Program

North American PHEV Demonstration

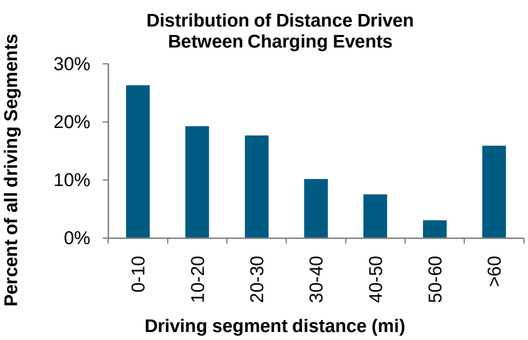
Charging and Driving Behavior Report for Hymotion Prius (Gridpoint data logger)

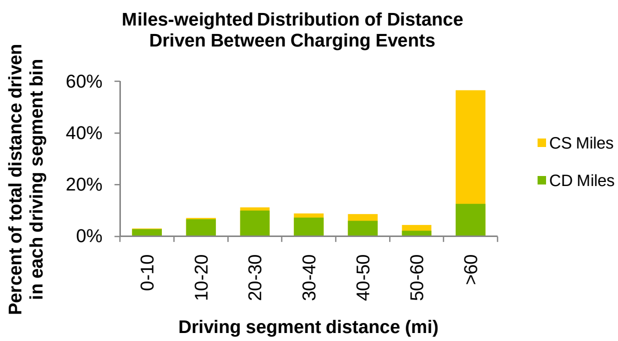
Fleet Type: Personal-use
Number of households: 67
Date range: Sep 2008 - Mar 2010
Charging rate: Level 1
Charge control: Uncontrolled
Battery Capacity: 5 kWh

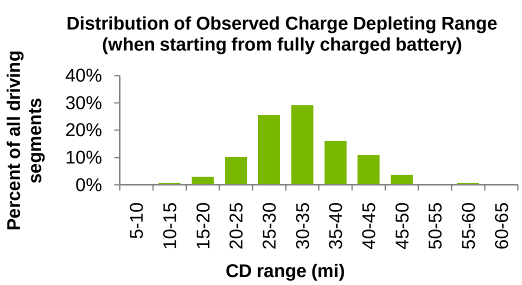
	Weekday	Weekend	Overall
Number of trips	1,735	510	2,245
Total distance driven (mi)	14,142	5,026	19,168
Number of charging events	401	130	531
Charging energy consumed (AC kWh)	1,285	373	1,659
Charge depleting (CD) distance driven (mi)	7,596	1,828	9,425
Percent of total distance	54%	36%	49%
Charge sustaining (CS) distance driven (mi)	6,545	3,198	9,743
Percent of total distance	46%	64%	51%

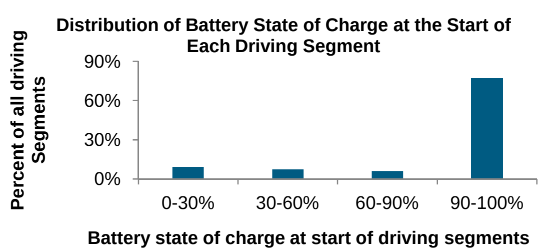


Driving segments between charging events [1]

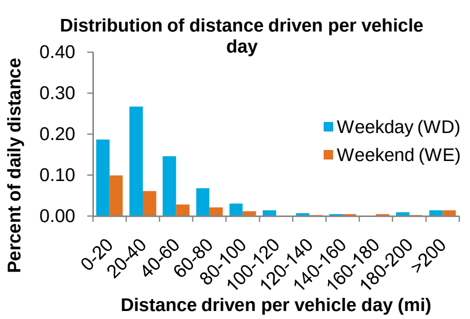


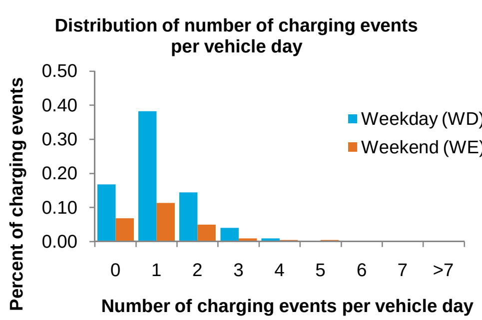






Driving and charging per vehicle day	Weekday	Weekend	Overall
Average number of charging events per vehicle day [2]	1.1	1.1	1.1
Average distance driven per vehicle day (mi) [2]	44.6	47.4	45.3

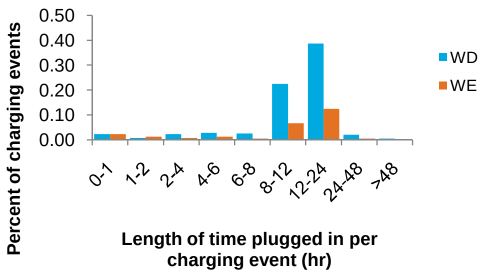




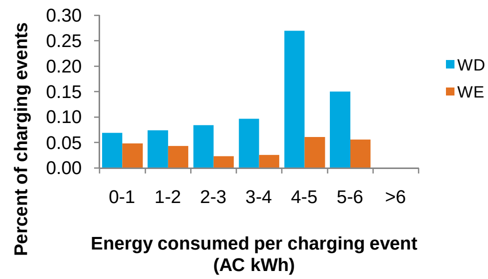
[1] A driving segment is defined as the combination of all trips between two consecutive charging events
[2] Considers only days when the vehicle was driven, not all calendar days

Charging events started after all trips in a day	Weekday	Weekend	Overall
Number of charging events	292	101	393
Percent of all charging events	55%	19%	74%
Charging energy consumed (AC kWh)	1078	315	1393
Percent of all energy consumed	65%	19%	84%

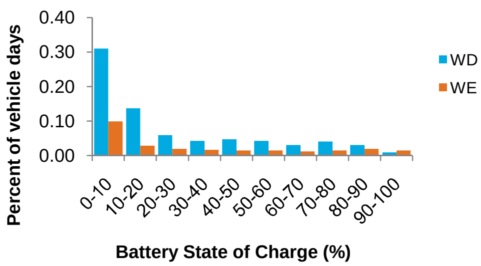
Distribution of Length of Time Plugged in per Charging Event



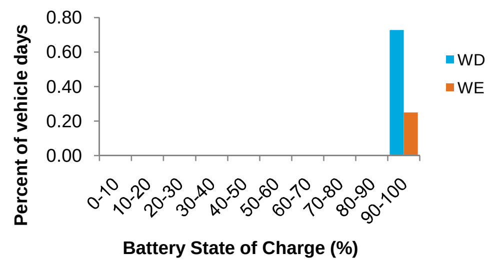
Distribution of AC Energy Consumed per Charging Event



Battery State of Charge after the Last Trip of the Day when Driven

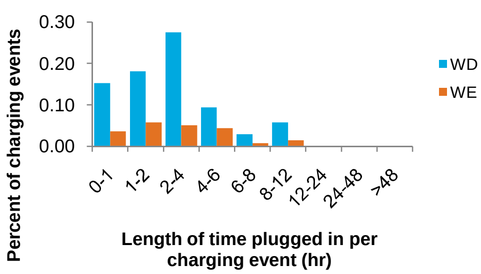


Battery State of Charge before the First Trip of the Day when Charged the Night Before

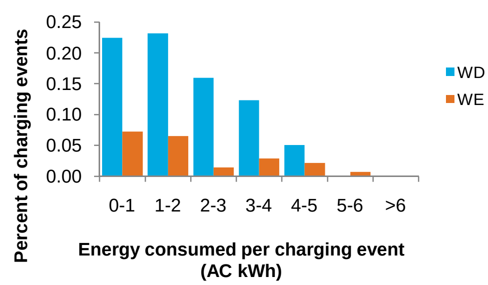


Charging events started between trips in a day	Weekday	Weekend	Overall
Number of charging events	109	29	138
Percent of all charging events	21%	5%	26%
Charging energy consumed (AC kWh)	207	59	266
Percent of all energy consumed	12%	4%	16%

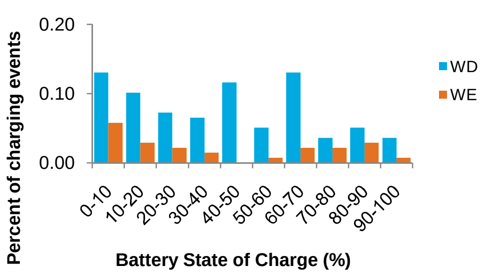
Distribution of Length of Time Plugged in per Charging Event



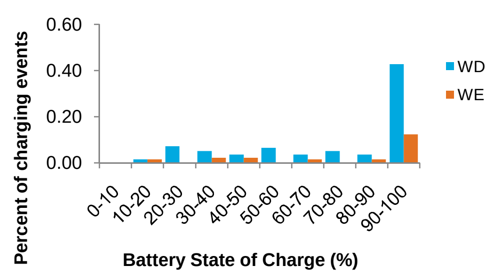
Distribution of AC Energy Consumed per Charging Event



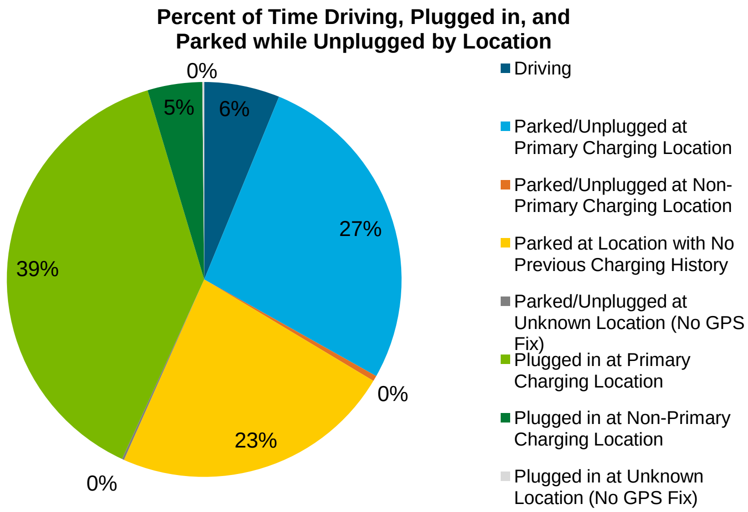
Battery State of Charge at the Start of Charging Events between Trips

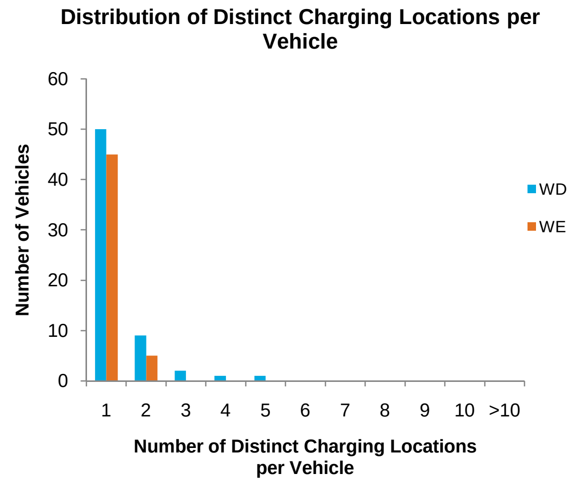


Battery State of Charge at the End of Charging Events between Trips



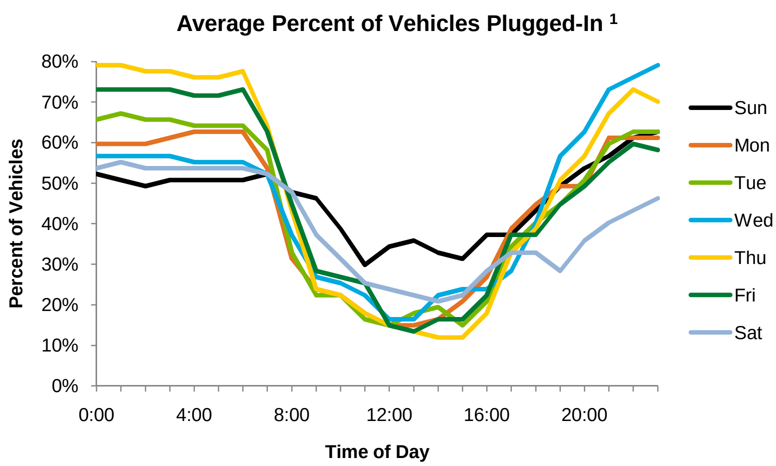
Vehicle Usage and Location

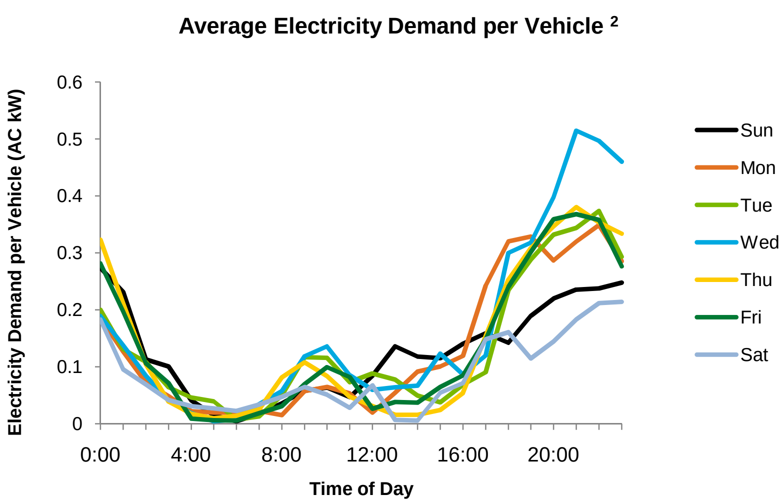




PHEV Charging Impact on the Electrical Grid

Each of the 67 households in the personal-use vehicle group operated a vehicle for 4 to 6 weeks. Grid impact was assessed by sampling all charging events that occurred during each household's last week with the vehicle. All 67 weeks analyzed were assumed to occur during the same calendar week.





Appendix F
Charging and Driving Behavior Report for Hymotion Prius – Commercial Use

North American PHEV Demonstration

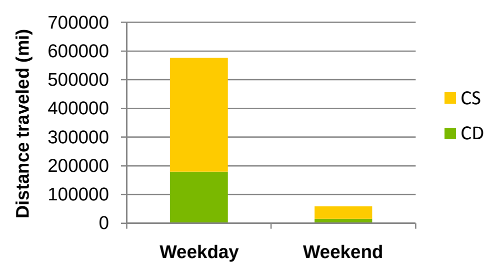
Vehicle Technologies Program

Charging and Driving Behavior Report for Hymotion Prius (Gridpoint data logger)

Fleet Type:	**Commercial-use**	**Charging rate:**	**Level 1**
Number of vehicles:	**153**	**Charge control:**	**Uncontrolled**
Date range:	**Jan - Dec 2009**	**Battery Capacity:**	**5 kWh**

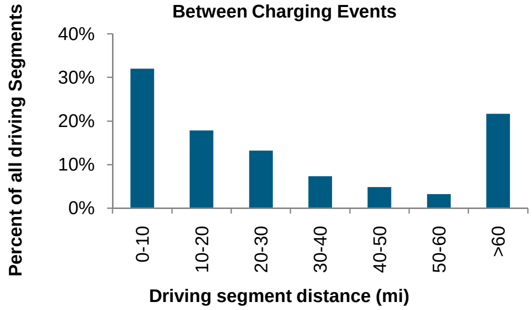
	Weekday	Weekend	Overall
Number of trips	61,134	5,309	66,443
Total distance driven (mi)	575,891	58,893	634,784
Number of charging events	12,902	1,461	14,363
Charging energy consumed (AC kWh)	32,253	3,478	35,731
Charge depleting (CD) distance driven (mi)	179,351	15,767	195,118
Percent of total distance	31%	27%	31%
Charge sustaining (CS) distance driven (mi)	396,540	43,127	439,667
Percent of total distance	69%	73%	69%

Distance Traveled by Operating Mode

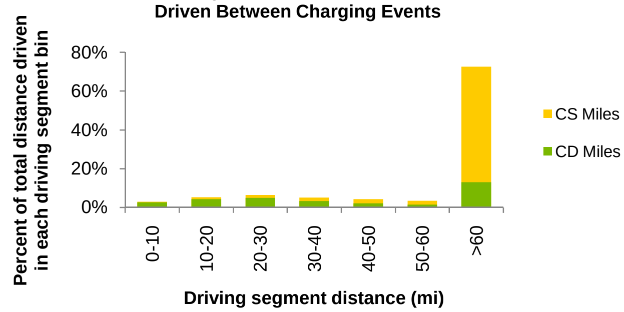


Driving segments between charging events [1]

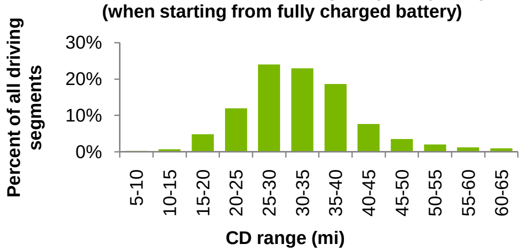
Distribution of Distance Driven Between Charging Events



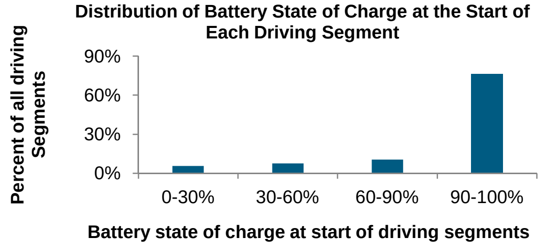
Miles-weighted Distribution of Distance Driven Between Charging Events



Distribution of Observed Charge Depleting Range (when starting from fully charged battery)

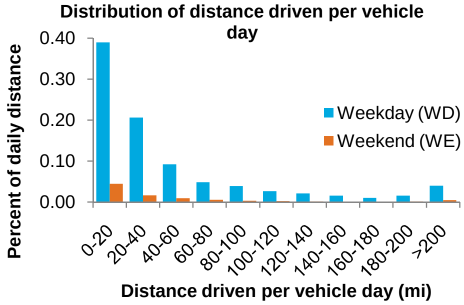


Distribution of Battery State of Charge at the Start of Each Driving Segment

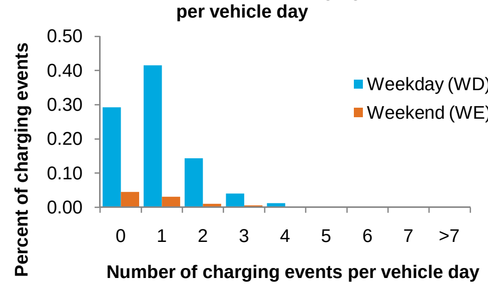


Driving and charging per vehicle day	Weekday	Weekend	Overall
Average number of charging events per vehicle day [2]	1.0	0.8	1.0
Average distance driven per vehicle day (mi) [2]	48.2	47.8	48.2

Distribution of distance driven per vehicle day



Distribution of number of charging events per vehicle day

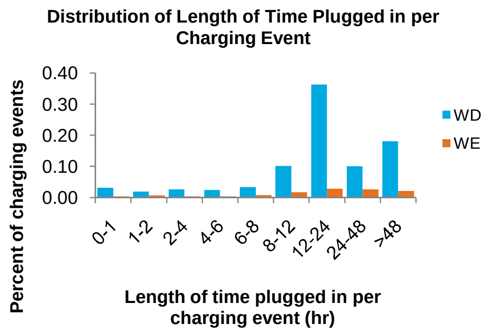


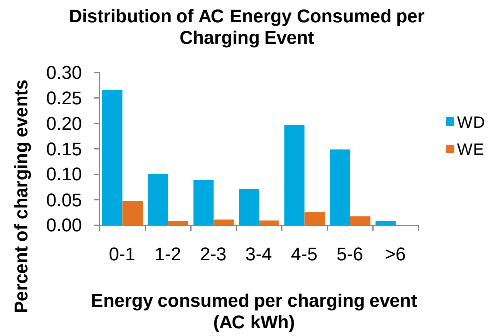
[1] A driving segment is defined as the combination of all trips between two consecutive charging events

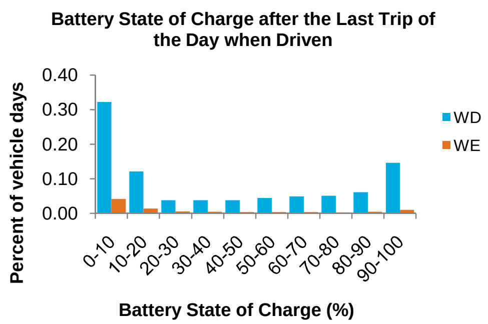
[2] Considers only days when the vehicle was driven, not all calendar days

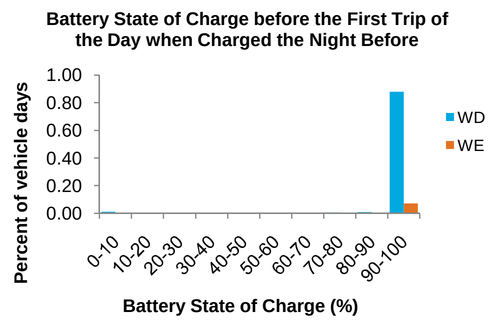
Idaho National Laboratory

Charging events started after all trips in a day	Weekday	Weekend	Overall
Number of charging events	8397	1140	9537
Percent of all charging events	58%	8%	66%
Charging energy consumed (AC kWh)	23564	2915	26479
Percent of all energy consumed	66%	8%	74%

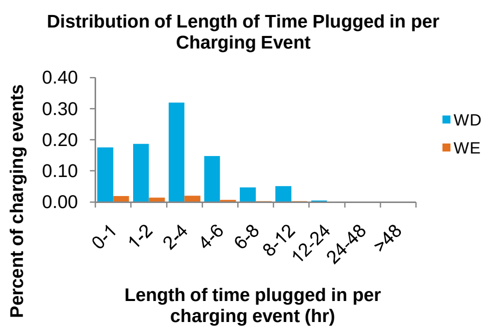


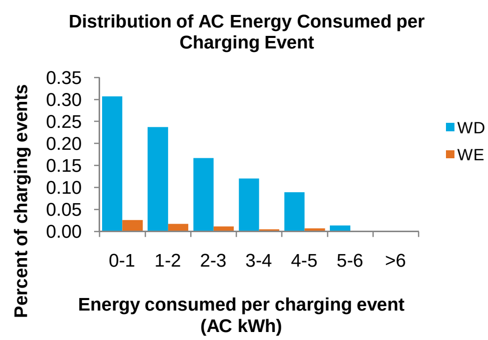


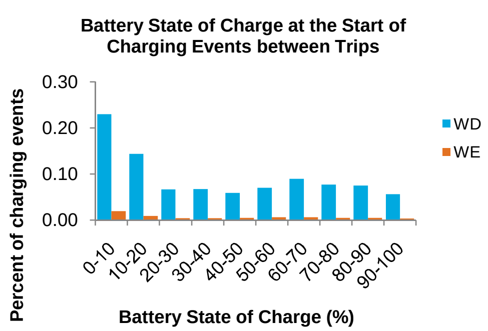


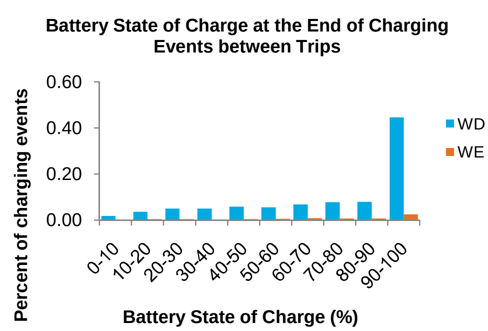


Charging events started between trips in a day	Weekday	Weekend	Overall
Number of charging events	4505	321	4826
Percent of all charging events	32%	2%	34%
Charging energy consumed (AC kWh)	8689	563	9252
Percent of all energy consumed	24%	2%	26%



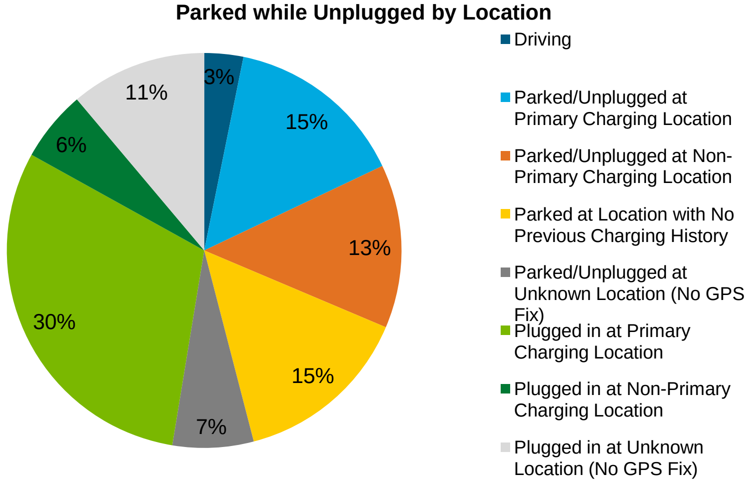




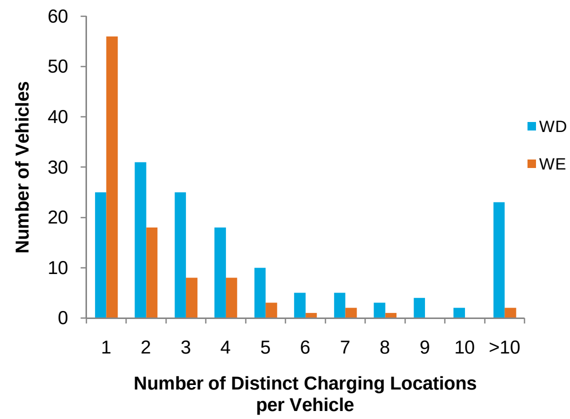


Vehicle Usage and Location

Percent of Time Driving, Plugged in, and Parked while Unplugged by Location



Distribution of Distinct Charging Locations per Vehicle

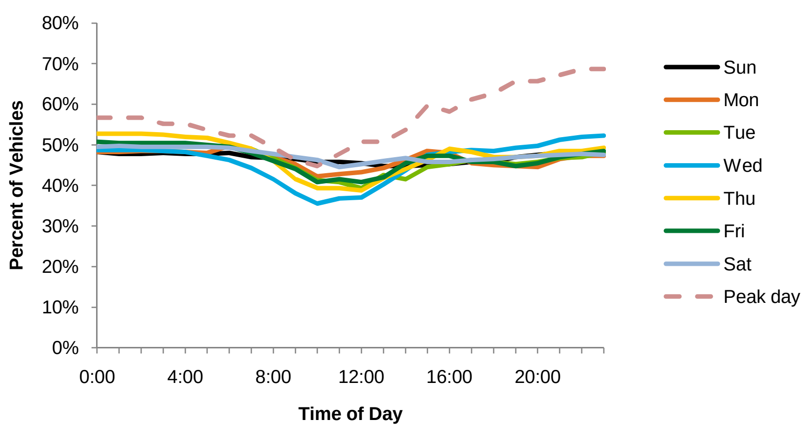


PHEV Charging Impact on the Electrical Grid

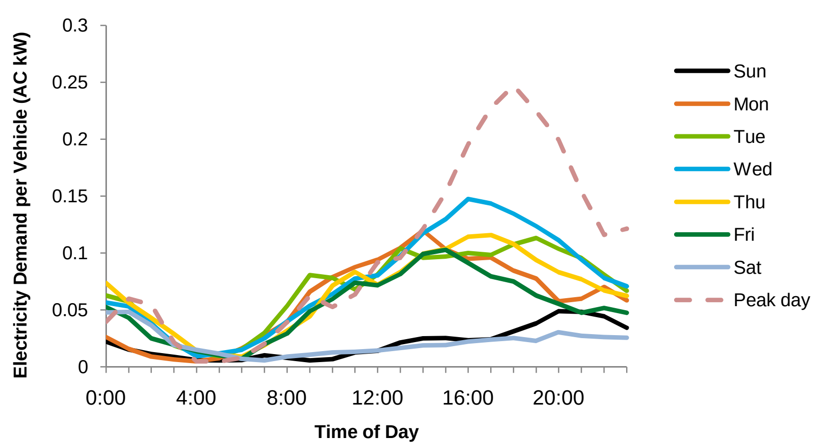
Grid impact was assessed by randomly sampling weeks during the reporting period. Data was sampled each week from a fixed number of vehicles which were driven during the week. Data was not necessarily sampled from the same vehicles each week.

Number of weeks randomly sampled from the reporting period:	6
Number of vehicles sampled each week:	67
Total number of distinct vehicles included in the sample:	103

Average Percent of Vehicles Plugged-In [1]



Average Electricity Demand per Vehicle [2]



[1] The peak day curve in this plot represents the percent of vehicles plugged-in on the calendar day with peak demand.

[2] The peak day demand curve represents the single calendar day which experienced the absolute peak power demand.

Appendix G
Fleet Summary Report for Hymotion Prius with V2Green Data Logger

North American PHEV Demonstration

Vehicle Technologies Program

Fleet Summary Report: Hymotion Prius (V2Green data logger)

Number of vehicles: 184

Reporting Period: Apr 08 - Sept 11

Date range of data received: 4/18/2008 to 9/30/2011

Number of days the vehicles were driven: 1254

All Trips Combined

Overall gasoline fuel economy (mpg)	48
Overall AC electrical energy consumption (AC Wh/mi) [1]	52
Overall DC electrical energy consumption (DC Wh/mi) [2]	38
Total number of trips	310,808
Total distance traveled (mi)	2,899,288

Trips in Charge Depleting (CD) mode [3]

Gasoline fuel economy (mpg)	62
DC electrical energy consumption (DC Wh/mi) [4]	142
Number of trips	125,321
Percent of trips city / highway	87% / 13%
Distance traveled (mi)	569,686
Percent of total distance traveled	20%

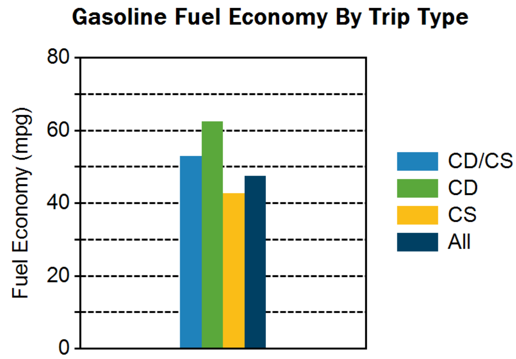
Trips in both Charge Depleting and Charge Sustaining (CD/CS) modes [5]

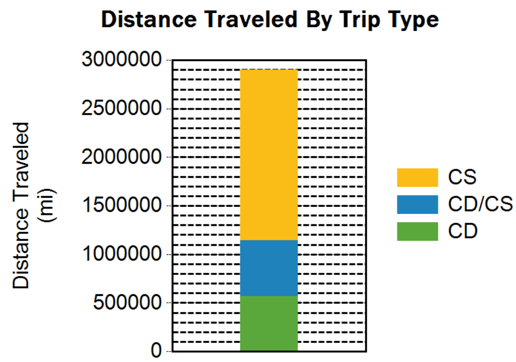
Gasoline fuel economy (mpg)	53
DC electrical energy consumption (DC Wh/mi) [6]	49
Number of trips	22,078
Percent of trips city / highway	47% / 53%
Distance traveled (mi)	576,256
Percent of total distance traveled	20%

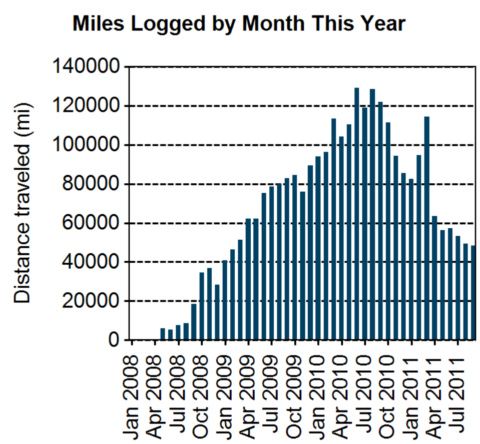
Trips in Charge Sustaining (CS) mode [7]

Gasoline fuel economy (mpg)	43
Number of trips	163,400
Percent of trips city / highway	77% / 23%
Distance traveled (mi)	1,756,775
Percent of total distance traveled	61%

Number of trips when the plug-in battery pack was turned off by the vehicle operator [8]	13962
Distance traveled with plug-in battery pack turned off by the vehicle operator (mi) [9]	299,452







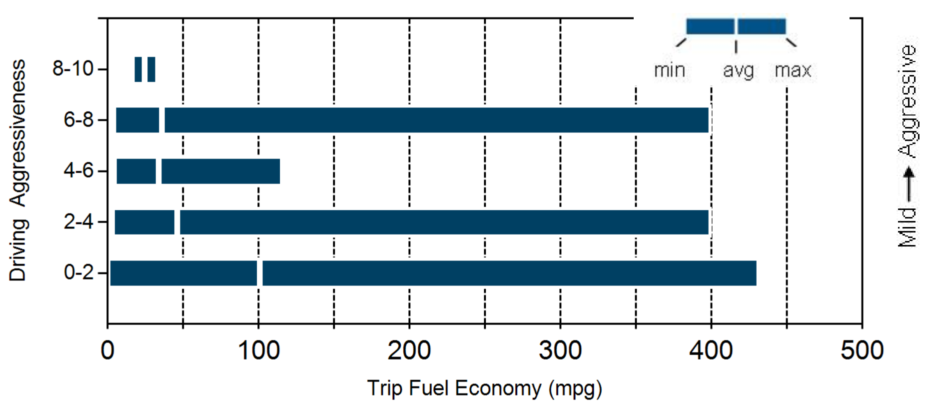
Notes: 1 - 9. Please see http://avt.inl.gov/pdf/phev/ReportNotes.pdf for an explanation of all PHEV Fleet Testing Report notes.

Trips in Charge Depleting (CD) mode	City	Highway
Gasoline fuel economy (mpg)	60	66
DC electrical energy consumption (DC Wh/mi)	166	109
Percent of miles with internal combustion engine off	33%	15%
Average trip aggressiveness (on scale 0 - 10)	1.8	1.8
Average trip distance (mi)	3.0	15.0

Trips in both Charge Depleting and Charge Sustaining (CD/CS) modes		
Gasoline fuel economy (mpg)	53	53
DC electrical energy consumption (DC Wh/mi)	79	44
Percent of miles with internal combustion engine off	27%	9%
Average trip aggressiveness (on scale 0 - 10)	1.9	1.6
Average trip distance (mi)	8.6	41.7

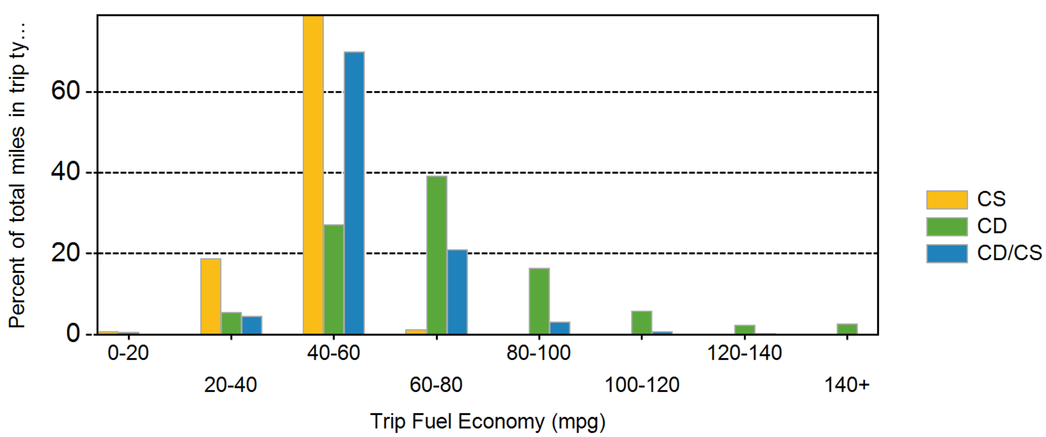
Trips in Charge Sustaining (CS) mode		
Gasoline fuel economy (mpg)	36	46
Percent of miles with internal combustion engine off	23%	8%
Average trip aggressiveness (on scale 0 - 10)	2.0	1.7
Average trip distance (mi)	3.5	35.2

Effect Of Driving Aggressiveness on Fuel Economy This Year



Aggressiveness factor is based on accelerator pedal position. The more time spent during a trip at higher accelerator pedal position, the higher the trip aggressiveness.

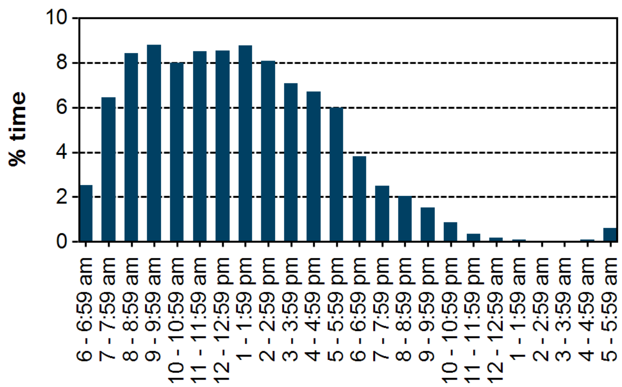
Trip Fuel Economy Distribution By Trip Type



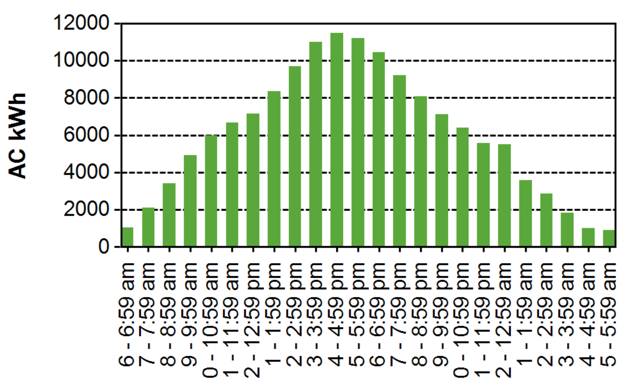
Plug-in charging

Average number of charging events per vehicle per month when driven	13
Average number of charging events per vehicle per day when vehicle driven	0.9
Average distance driven between charging events (mi)	51.7
Average number of trips between charging events	5.5
Average time plugged in per charging event (hr)	24.3
Average time charging per charging event (hr)	2.7
Average energy per charging event (AC kWh)	2.7
Average charging energy per vehicle per month (AC kWh)	34.4
Total number of charging events	56,037
Total charging energy (AC kWh)	151,331

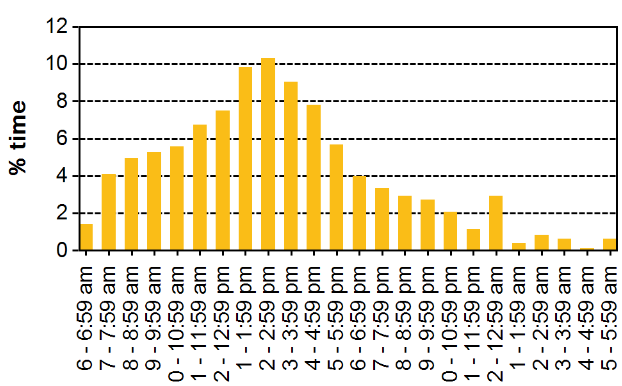
Time of Day When Driving



Time of Day When Charging



Time of Day When Plugging In



Appendix H
Fleet Summary Report for Hymotion Prius with Kvaser Data Logger

North American PHEV Demonstration

Vehicle Technologies Program

Fleet Summary Report - Hymotion Prius (Kvaser data logger)

Number of vehicles: 44

Reporting Period: Jan 08 - Dec 10

Date range of data received: 1/1/2008 to 12/31/2010

Number of days the vehicles were driven: 366

All Trips Combined

Overall gasoline fuel economy (mpg)	45
Overall DC electrical energy consumption (DC Wh/mi) [2]	55
Total number of trips	53478
Total distance traveled (mi)	439699

Trips in Charge Depleting (CD) mode [3]

Gasoline fuel economy (mpg)	58
DC electrical energy consumption (DC Wh/mi) [4]	134
Number of trips	29767
Percent of trips city / highway	84% / 16%
Distance traveled (mi)	142124
Percent of total distance traveled	32%

Trips in both Charge Depleting and Charge Sustaining (CD/CS) modes [5]

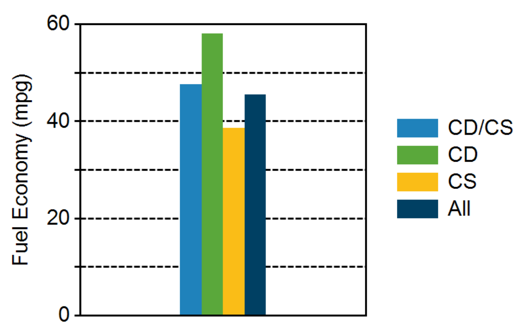
Gasoline fuel economy (mpg)	48
DC electrical energy consumption (DC Wh/mi) [6]	53
Number of trips	5116
Percent of trips city / highway	51% / 49%
Distance traveled (mi)	97993
Percent of total distance traveled	22%

Trips in Charge Sustaining (CS) mode [7]

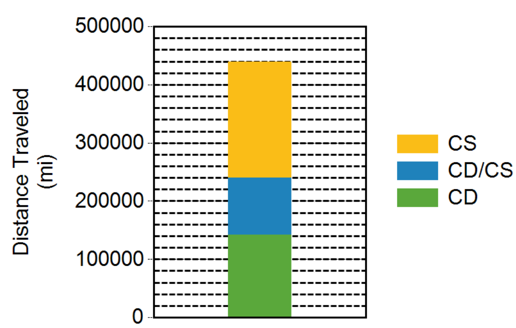
Gasoline fuel economy (mpg)	39
Number of trips	18595
Percent of trips city / highway	71% / 29%
Distance traveled (mi)	199583
Percent of total distance traveled	45%

Number of trips when the plug-in battery pack was turned off by the vehicle operator [8]	2621
Distance traveled with plug-in battery pack turned off by vehicle operator(mi) [9]	41200

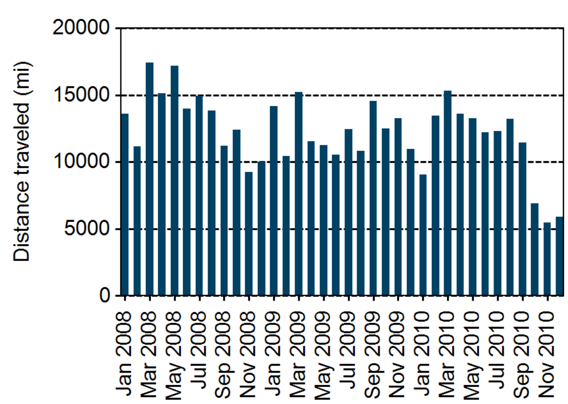
Gasoline Fuel Economy By Trip Type



Distance Traveled By Trip Type



Miles Logged by Month This Year



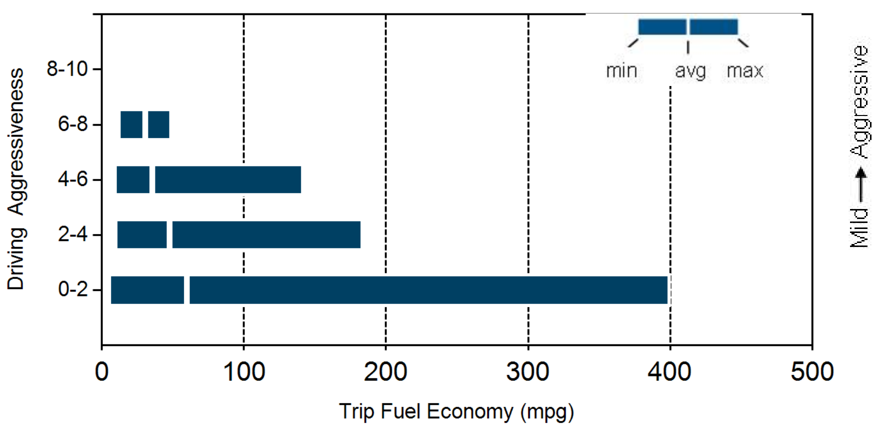
Notes: 1 - 9. Please see http://avt.inel.gov/phev/reportnotes for an explanation of all PHEV Fleet Testing Report notes.

Trips in Charge Depleting (CD) mode	City	Highway
Gasoline fuel economy (mpg)	56	61
DC electrical energ consumption (DC Wh/mi)	157	109
Percent of miles with internal combustion engine off	34%	12%
Average trip aggressiveness (on scale 0 - 10)	2.1	2.0
Average trip distance (mi)	3.0	13.8

Trips in combined Charge Depleting and Charge Sustaining (CD/CS) modes		
Gasoline fuel economy (mpg)	47	48
DC electrical energy consumption (DC Kw/mi)	78	48
Percent of miles with internal combustion engine off	28%	7%
Average trip aggressiveness (on scale 0 - 10)	2.2	1.7
Average trip distance (mi)	6.1	32.7

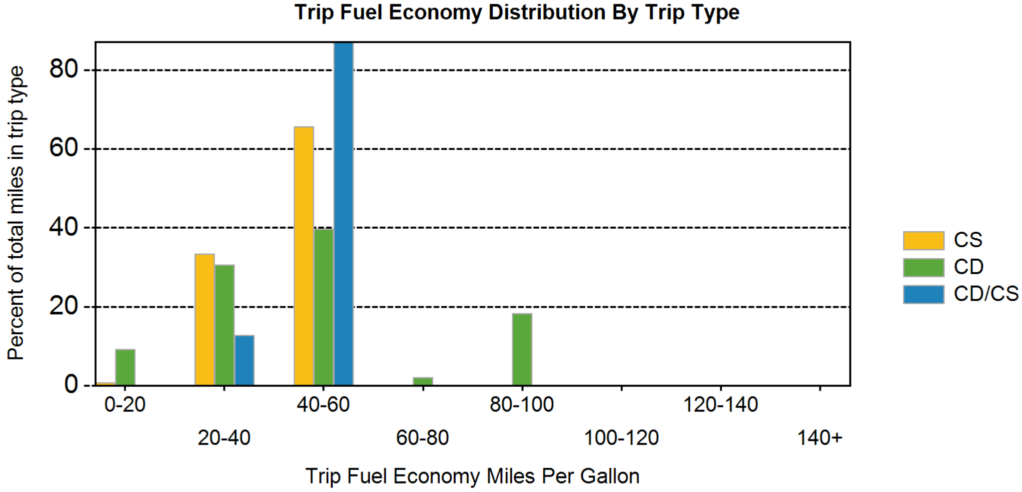
Trips in Charge Sustaining (CS) mode		
Gasoline fuel economy (mpg)	34	40
Percent of miles with internal combustion engine off	24%	6%
Average trip aggressiveness (on scale 0 - 10)	1.8	1.5
Average trip distance (mi)	3.6	28.6

Effect Of Driving Aggressiveness on Fuel Economy



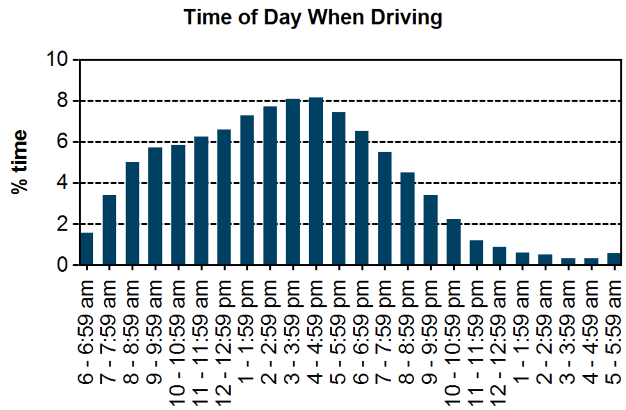
Aggressiveness factor is based on accelerator pedal position. The more time spent during a trip at higher accelerator pedal position, the higher the trip aggressiveness.

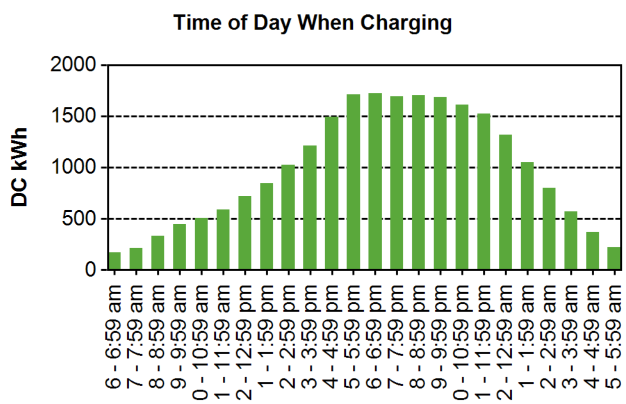
Trip Fuel Economy Distribution By Trip Type

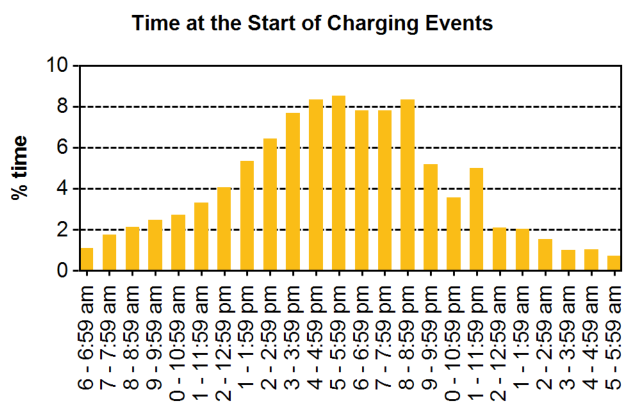


Plug-in charging

Average number of charging events per vehicle per month when driven	22
Average number of charging events per vehicle per day when vehicle driven	1.5
Average distance driven between charging events (mi)	30.2
Average number of trips between charging events	3.7
Average time charging per charging event (hr)*	2.0
Average energy per charging event (DC kWh)	1.6
Average charging energy per vehicle per month (DC kWh)	35.3
Total number of charging events	14564
Total charging energy (DC kWh)	23579







* Time charging per charging event is the average length of time per charging event when the vehicle was drawing power from the electrical grid. It does not necessarily represent the total duration when the vehicle was plugged in per charging event.