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U.S. Department of Energy – Advanced Vehicle Testing Activity: Plug-in Hybrid Electric Vehicle Testing and Demonstration Activities

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Abstract

The U.S. Department of Energy's Advanced Vehicle Testing Activity tests plug-in hybrid electric vehicles (PHEV) in closed track, dynamometer, and on-road testing environments. The purpose of this testing is to determine the potential of PHEV technology to reduce petroleum consumption. It also allows documentation of PHEV driving and charging profiles and electric charging infrastructure requirements. As of March 2009, the Advanced Vehicle Testing Activity has initiated testing on 12 PHEV models from aftermarket conversion companies and original equipment manufacturers. In addition to performing controlled dynamometer and on-road testing, AVTA has collected in-use data from 155 PHEVs operating in 23 U.S. states and Canadian provinces. This fleet has demonstrated an average increase in cumulative fuel economy of 22 to 55% when in charge depleting mode, as compared to charge sustaining mode. Charge depleting range has varied from 32 to 64 miles, depending on the vehicle and battery pack. In ideal conditions, some vehicles have achieved monthly fuel economy results of 80 to 120 miles per gallon through frequent charging and less aggressive driving styles.

Keywords: PHEV, demonstration, on-board data acquisition, secondary battery, vehicle performance

1 Introduction

The U.S. Department of Energy's (DOE) Advanced Vehicle Testing Activity (AVTA) tests plug-in hybrid electric vehicles (PHEV) in closed track, dynamometer, and on-road environments. The purpose of this work is to document the petroleum reduction potential of the PHEV concept. This work includes evaluating vehicle energy consumption and efficiency, as well as plug-in charging infrastructure requirements and the impact of plug-in vehicles on the electrical grid.

AVTA provides advanced technology vehicle performance benchmark data for technology modelers, research and development programs, and technology goal setters. AVTA testing results also assist fleet managers in making informed vehicle purchase, deployment, and operating decisions. AVTA is part of DOE's Vehicle Technologies Program. AVTA's light duty PHEV testing activities are conducted by the Idaho National Laboratory and the Electric Transportation Engineering Corporation, with.

Argonne National Laboratory performing dynamometer testing.

AVTA regularly reports PHEV test results to industry stakeholders [1, 2] and the general public via its website [3]. The purpose of this paper is to summarize PHEV testing and evaluation to date.

1.1 PHEV Testing Overview

As of March 2009, AVTA has initiated dynamometer, track, and controlled on-road testing of 12 PHEV models from original equipment manufacturers (OEM) and conversion companies. Eight PHEV conversion models have been evaluated in fleet usage.

The PHEV models tested are listed below, with battery pack or cell manufacturer listed separately, where appropriate. Note that when different battery chemistries or battery manufacturers are used by the same conversion company, they are considered different models due to potentially different battery and vehicle performance.

Aftermarket PHEV conversions are as follows:

- Toyota Prius with A123Systems Hymotion L5 conversion pack (5 kWh lithium-ion [Li-ion])
- Toyota Prius with Hybrids Plus conversion (5 kWh Li-ion)
- Toyota Prius with EnergyCS conversion
    - Valence (9 kWh Li-ion)
    - Altairnano (9 kWh Li-ion)
- Toyota Prius with Manzanita Micro conversion
    - Hawker (5 kWh valve-regulated lead acid)
    - Thunder Sky (5 kWh Li-ion)
- Ford Escape Hybrid with A123Systems Hymotion conversion (8.5 kWh Li-ion)
- Ford Escape Hybrid with Hybrids Plus conversion
    - Hybrids Plus (12 kWh Li-ion)
    - K2 Energy Solutions (13.3 kWh Li-ion)
- Ford Escape Hybrid with Electrovaya conversion (12 kWh Li-ion).

OEM PHEVs are as follows:

- Renault Kangoo with Saft battery (25 kWh nickel-cadmium)
- Ford Escape E85 PHEV with Johnson Controls/ Saft battery (12 kWh Li-ion).

1.1.1 Baseline track testing

The first step in the AVTA's PHEV testing program is baseline performance testing conducted on a closed track. Test metrics measured include the following:

- Acceleration 0 to 60 mph
- Acceleration 1/4 mile and 1 mile
- Braking from 60 mph
- Fuel economy with and without the air conditioning on at fixed speeds (usually 45 and 60 mph)
- Plug-in battery pack charging time
- Vehicle coast down coefficients.

1.1.2 Baseline dynamometer testing

Following track testing, PHEVs are tested on a chassis dynamometer. Each PHEV undergoes a 5-day testing regime, which includes (at least) 26 Urban Dynamometer Driving Schedule (UDDS), Highway Fuel Economy Driving Schedule (HWFEDS), and US06 test cycles. Testing includes charge depleting (CD) and charge sustaining (CS) test cycles, hot and cold starts, and repetition of cycles with and without air conditioning.

1.1.3 On-road accelerated performance testing

AVTA's PHEV test program includes a 5,440-mile accelerated on-road test, in which dedicated drivers follow repeated urban and highway driving routes on public roads. Drive cycles include combinations of urban and highway loops and range from 10 to 200 miles. Recharging occurs between each cycle repetition for varying durations to simulate daytime "opportunity" and overnight charging (see Table 1). Test vehicles are fueled with gasoline at the beginning and end of each 600-mile test cycle. Reported results include gasoline and electricity consumption.

Table 1: On-road accelerated testing procedure.

Cycle (mi)	Urban (10 mi)	Highway (10 mi)	Charge (hr)	Reps (N)	Total (mi)	Reps (%)	Miles (%)
10	1	0	4	60	600	37%	11%
20	1	1	8	30	600	19%	11%
40	4	0	12	15	600	9%	11%
40	2	2	12	15	600	9%	11%
40	0	4	12	15	600	9%	11%
60	2	4	12	10	600	6%	11%
80	2	6	12	8	640	5%	12%
100	2	8	12	6	600	4%	11%
200	2	18	12	3	600	2%	11%
Total	2,340	3,100	1,344	162	5,440		
Average	43%	57%	8.3	18			

This testing provides a broad view of vehicle energy consumption as distance driven between charging events, charging time, and route type vary.

For more information on AVTA test procedures, a comprehensive PHEV test manual can be found at the AVTA website [4].

1.1.4 Fleet demonstrations

In addition to controlled testing, AVTA monitors vehicle performance in uncontrolled fleet usage. The purpose of these fleet evaluations is threefold:

- Measure PHEV energy consumption during undirected operation across a wide range of usage conditions
- Understand how varying vehicle driving and charging behavior impacts energy efficiency
- Document charging profiles and electrical energy demand in order to assess the potential impact of PHEVs on the electrical power infrastructure.

PHEV fleet demonstrations have been in progress since late 2007. As of March 2009, AVTA has collected data from 155 PHEVs operating in 23 U.S. states and Canadian provinces.

Figure 1 shows the distribution of the fleet. Numbers in black represent vehicles from which data have been collected. Red numbers indicate vehicles that are expected to begin operation in 2009.

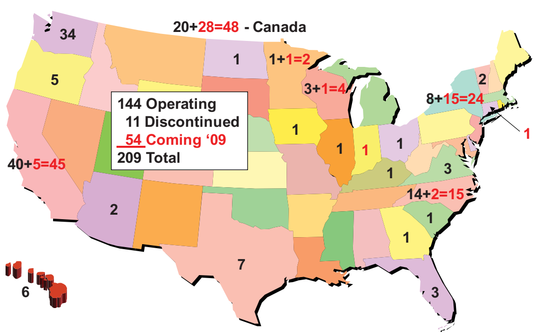

Figure 1: Distribution of vehicles in AVTA/DOE PHEV fleet demonstration.

These fleet demonstrations are made possible by participation of over 75 organizations, including the following types:

- 36 electric utilities
- 2 clean-air agencies
- 10 city, county, and state governments
- 7 private companies and advocacy organizations
- 8 universities and colleges
- 4 Canadian province agencies
- 2 PHEV conversion companies
- 1 sea port
- 1 U.S. Department of Defense

Fleet testing partners include the following:

- A123Systems
- EnergyCS
- New York State Energy Research and Development Agency
- National Rural Electric Cooperative Association
- University of California Davis
- Fairfax County, Virginia
- Google.org
- Austin Energy
- Central Vermont Public Service Corporation
- Duke Energy
- Advanced Energy
- Progress Energy
- San Diego Gas and Electric
- Basin Electric
- Buckeye Power
- Wisconsin Public Power Inc.
- Madison Gas and Electric
- SCANA Corporation
- City of Seattle
- Port of Seattle
- Seattle City Lights
- Hawaii Center for Advanced Transportation Technologies.

Vehicles are driven by fleet participants to perform a variety of missions. The majority of the vehicles in the fleet are driven for commercial use by more than one driver. Approximately 10% of the miles logged in the fleet were logged by vehicles driven for private use.

Vehicles are equipped with onboard controller area network (CAN) data loggers. These loggers capture time history data to monitor gasoline and electricity consumption and numerous other vehicle, charging, and environmental parameters. Automated database routines store and analyze these data. Summary metrics are generated to quantify energy consumption and characterize vehicle operation and charging behavior. Reports are sent to fleet participants monthly, and overall fleet summary reports are posted to the AVTA website [5]. Basic results from fleet data analysis are presented in this paper. More detailed analyses will be presented in future works.

2 Test Results

Table 2 summarizes AVTA testing progress by vehicle, as of March 2009. Results for each test are shown in subsequent sections.

Table 2: AVTA testing summary.

Vehicle	Baseline Testing	Accelerated Testing	Vehicle in Fleet
Hymotion Prius	Complete	Complete	Yes
EnergyCS Prius (Valence)	Complete	Complete	Yes
EnergyCS Prius (Altairnano)	Not scheduled	Not scheduled	Yes
Hybrids Plus Prius	Deferred	Deferred	No
Manzanita Prius (Hawker)	Not scheduled	Not scheduled	Yes
Hymotion Escape	Complete	Complete	Yes
Hybrids Plus Escape (Hybrids Plus)	Complete	Deferred	Yes
Electrovaya Escape	Complete	Complete	No
Renault Kangoo	Complete	Complete	No
Ford Escape E85 PHEV	Test results protected by non-disclosure agreement		
Remaining Models	In initial testing		

3 Baseline Dynamometer Testing

3.1 Toyota Prius with A123Systems Hymotion Conversion

The Hymotion plug-in conversion from A123Systems is a supplemental, 5 kWh Li-ion battery pack. This pack is installed next to the stock Toyota Prius 1.3 kWh nickel-metal hydride (NiMH) battery pack. The Hymotion pack is charged by plugging into a standard 110 V outlet. It does not accept regenerative braking or engine charging. The stock Toyota NiMH pack is not charged by the grid; rather, it maintains its function of accepting regenerative braking and engine charging. The Toyota Prius with Hymotion conversion pack (hereafter referred to as the Hymotion Prius) operates in blended mode, meaning the internal combustion engine (ICE) cycles on and off during CD operation.

Results shown in this section and Section 4 are from a Hymotion Prius with a production prototype, or "v1," battery pack.

Figure 2 shows gasoline fuel consumption and electrical energy consumption of the Hymotion Prius in repeated UDDS cycles. The first three cycles show CD operation, starting with a cold start in the first cycle. The transition to CS mode takes place during the fourth cycle as the Hymotion battery pack depletes fully. Remaining cycles represent CS mode performance and demonstrate how cumulative gasoline fuel economy decreases as the distance driven in CS mode increases.

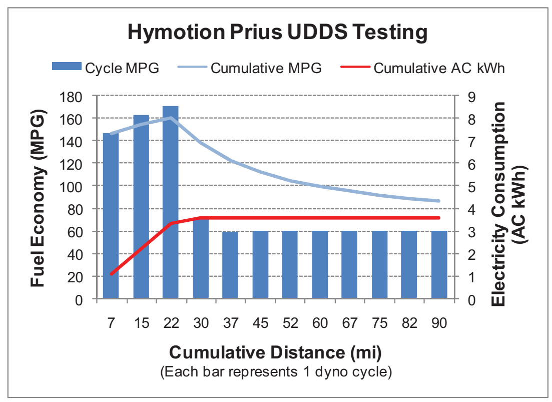

Figure 2: Hymotion Prius UDDS testing.

Figure 3 shows gasoline and electricity consumption of the Hymotion Prius in repeated HWFEDS cycles, beginning with a cold start.

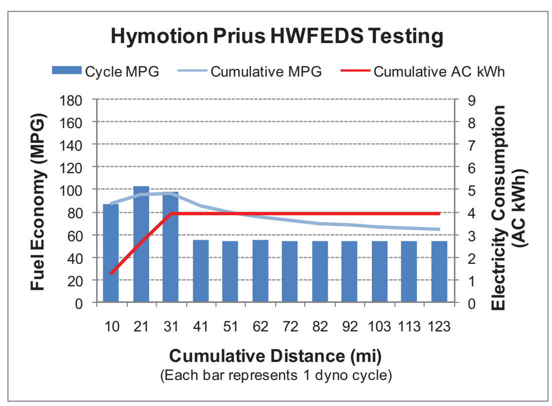

Figure 3: Hymotion Prius HWFEDS testing.

3.2 EnergyCS Prius Conversion with Valence Battery

EnergyCS converted a Toyota Prius to a PHEV by replacing the stock Prius NiMH pack with a 9 kWh Li-ion battery pack. The EnergyCS pack is charged by plugging into a standard 110 V outlet.

It also accepts regenerative braking and engine charging. The Toyota Prius with EnergyCS conversion pack (hereafter referred to as the EnergyCS Prius) is a blended-mode PHEV.

As previously mentioned, EnergyCS has produced packs with cells from multiple manufacturers. Test data shown in this section and Section 4 come from an EnergyCS Prius with Valence cells.

Figure 4 shows gasoline and electricity consumption of the EnergyCS Prius in repeated UDDS cycles.

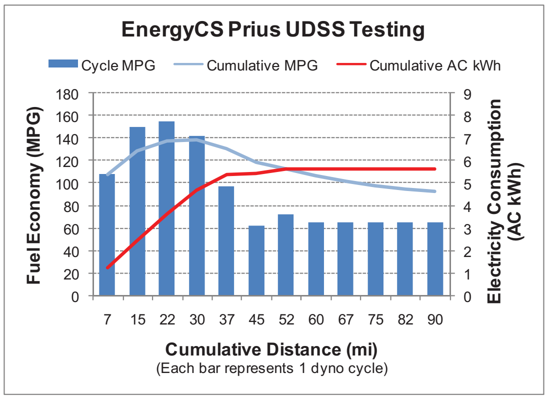

Figure 4: EnergyCS Prius UDDS testing.

Figure 5 shows gasoline and electricity consumption of the EnergyCS Prius in repeated HWFEDS cycles.

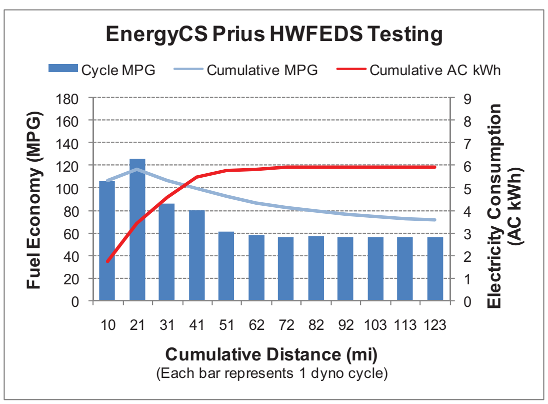

Figure 5: EnergyCS Prius HWFEDS testing.

3.3 Hymotion Escape Conversion with A123Systems Battery

Similar to the Hymotion Prius, the A123Systems Hymotion conversion pack for the Ford Escape Hybrid is a supplemental battery pack installed adjacent to the stock Ford 1.8 kWh NiMH pack.

The Hymotion pack for the Escape is a 12 kWh Li-ion pack, which is charged by plugging into a standard 110 V outlet. It does not accept regenerative braking or engine charging. The Ford Escape with Hymotion conversion (hereafter called the Hymotion Escape) operates in blended mode.

Figure 6 shows gasoline and electricity consumption of the Hymotion Escape in repeated UDDS cycles.

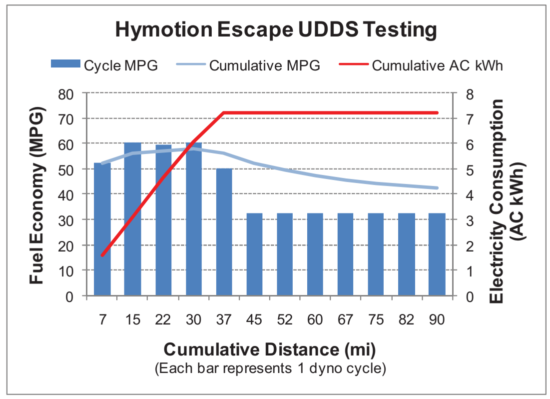

Figure 6: Hymotion Escape UDDS testing.

Figure 7 shows gasoline and electricity consumption of the Hymotion Escape in repeated HWFEDS cycles.

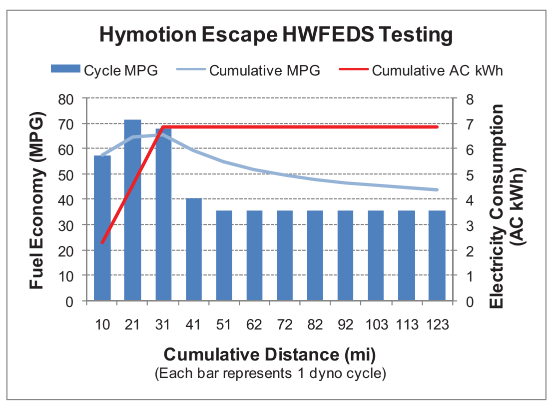

Figure 7: Hymotion Escape HWFEDS testing.

3.4 Hybrids Plus Escape Conversion with Hybrids Plus Battery

Hybrids Plus converted a Ford Escape Hybrid to a PHEV by replacing the stock Escape NiMH pack with a 12 kWh Li-ion battery pack. The Hybrids Plus pack is charged by plugging into a standard 110 V outlet. It also accepts regenerative braking and engine charging. The Ford Escape Hybrid with Hybrids Plus conversion pack (hereafter referred to as the Hybrids Plus Escape) operates in blended mode.

Hybrids Plus has produced Escape conversion packs of different designs. Results shown in this paper comes from the original Hybrids Plus Escape 12 kWh Li-ion pack.

Figure 8 shows gasoline and electricity consumption of the Hybrids Plus Escape in repeated UDDS cycles.

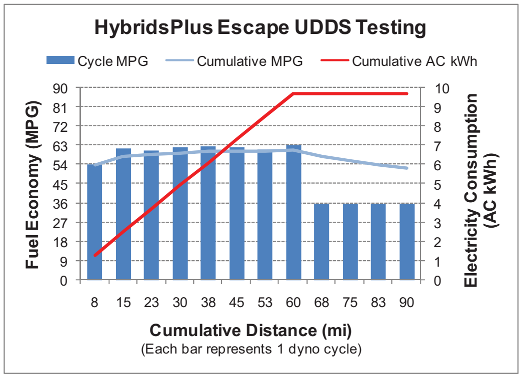

Figure 8: Hybrids Plus Escape UDDS testing.

Figure 9 shows gasoline and electricity consumption of the Hybrids Plus Escape in repeated HWFEDS cycles.

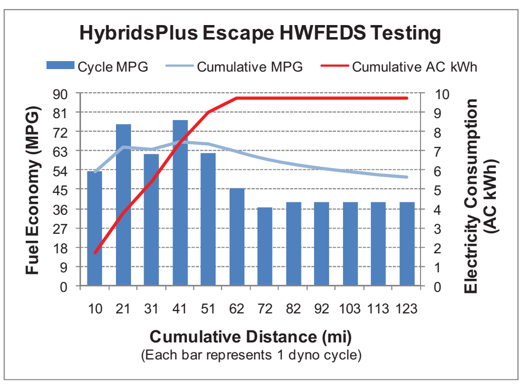

Figure 9: Hybrids Plus Escape HWFEDS testing.

3.5 Electrovaya Escape Conversion with Electrovaya Battery

The Electrovaya PHEV conversion of a Ford Escape Hybrid involves replacement of the stock Ford Escape HEV battery. Electrovaya uses a 12 kWh Li-ion battery pack, which is charged by plugging into a standard 110 V outlet. The pack also accepts regenerative braking and engine charging. The Ford Escape Hybrid with Electrovaya conversion pack (hereafter referred to as the Electrovaya Escape) operates in blended mode.

Figure 10 shows gasoline and electricity consumption of the Electrovaya Escape in repeated UDDS cycles.

Figure 11 shows gasoline and electricity consumption of the Electrovaya Escape in repeated HWFEDS cycles.

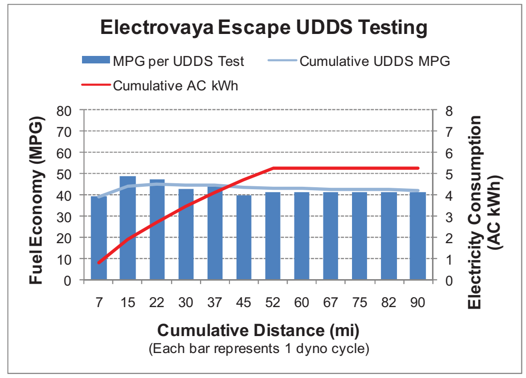

Figure 10: Electrovaya Escape UDDS testing.

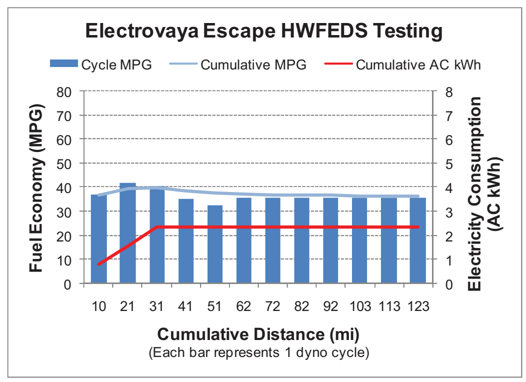

Figure 11: Electrovaya Escape HWFEDS testing.

3.6 Renault Kangoo

The 2003 Renault Kangoo is a series PHEV, with true electric-only operation during CD mode. It has a 25 kWh Saft nickel-cadmium battery pack. When the pack is fully depleted, a 0.5 L, two-cylinder ICE runs to generate electrical energy for tractive power.

Table 3 summarizes gasoline and electricity consumption of the Renault Kangoo in different dynamometer testing scenarios

Table 3: Renault Kangoo dynamometer energy consumption.

Test Cycle	Electricity Consumption (AC kWh/mi)	Fuel Economy (mi/gal)
Battery Only – UDDS	0.268	N/A *
Battery Only - HWFEDS	0.155	N/A

(continued on next page)

Battery Only @ Constant 45 mph	0.271	N/A
Battery and Gas Cold UDDS	0.144	42.3
Battery and Gas Hot UDDS	0.110	39.4
Battery and Gas Hot HWFEDS	0.042	40.9

* Gasoline fuel economy is shown as "N/A" when tests are performed in electric mode only

4 On-Road Accelerated Testing

4.1 Hymotion Prius

Table 4 shows on-road accelerated testing results for the Hymotion Prius. As expected, fuel consumption increases as distance between charging events increases beyond the end of CD operation. (See Section 5 for discussion on CD range.)

Table 4: Hymotion Prius accelerated testing results.

Cycle	Urban	Highway	Charge	Reps	Total	Electricity	Gasoline	
(mi)	(10 mi)	(10 mi)	(hr)	(N)	(mi)	AC 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

4.2 EnergyCS Prius

Table 5 shows on-road accelerated testing results for the EnergyCS Prius. The three 40-mile cycles exhibited low electrical energy consumption and fuel economy due to a pack failure.

Table 5: EnergyCS Prius accelerated testing results.

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	115.58	4.78	128.1
20	1	1	8	30	600	86.21	7.95	77.9
40	4	0	12	15	600	25.00	14.29	42.7
40	2	2	12	5	600	31.52	11.05	56.1
40	0	4	12	5	600	32.44	11.36	55.5
60	2	4	12	10	600	65.00	5.90	103.7
80	2	6	12	8	640	39.04	10.09	65.8
100	2	8	12	6	600	22.67	8.81	70.8
200	2	18	12	3	600	12.98	10.46	57.8
Total	2340	2500	984	147	4840	Weighted Average		66.1

4.3 Hymotion Escape

Table 6 shows on-road accelerated testing results for the Hymotion Escape.

Table 6: Hymotion Escape accelerated testing results.

Cycle	Urban	Highway	Charge	Reps	Total	Electricity	Gasoline	
(mi)	(10 mi)	(10 mi)	(hr)	(N)	(mi)	AC kWh	Gals	MPG
10	1	0	4	60	600	198.93	11.52	53.1
20	1	1	8	30	600	163.29	13.51	45.7
40	4	0	12	15	600	57.51	14.91	41.1
40	2	2	12	15	600	76.29	15.99	38.7
40	0	4	12	15	600	114.14	11.92	51.5
60	2	4	12	10	600	97.18	13.70	45.3
80	2	6	12	8	640	77.69	16.05	41.3
100	2	8	12	6	600	58.64	15.69	39.8
200	2	18	12	3	600	26.09	17.72	33.5
Total	2340	3100	1344	162	5440	Weighted Average		42.5

4.4 Hybrids Plus Escape

On-road accelerated testing for the Hybrids Plus Escape with Hybrids Plus pack was deferred per the request of Hybrids Plus. A test is in progress for the Hybrids Plus Escape with cells from K2 Energy Solutions.

4.5 Electrovaya Escape

Table 7 shows on-road accelerated testing results for the Electrovaya Escape.

Table 7: Electrovaya Escape accelerated testing results.

Cycle	Urban	Highway	Charge	Reps	Total	Electricity	Gasoline	
(mi)	(10 mi)	(10 mi)	(hr)	(N)	(mi)	AC kWh	Gals	MPG
10	1	0	4	60	600	135.24	9.55	65.1
20	1	1	8	30	600	101.13	17.54	34.7
40	4	0	12	15	600	71.3	16.42	37.3
40	2	2	12	15	600	69.8	14.34	43.1
40	0	4	12	15	600	55.84	20.73	29.8
60	2	4	12	10	600	44.79	16.64	37.3
80	2	6	12	8	640	42.72	16.30	40.8
100	2	8	12	6	600	20.85	21.17	29.2
200	2	18	12	3	600	13.31	19.01	30.9
Total	2340	3100	1344	162	5440	Weighted Average		36.7

4.6 Renault Kangoo

Table 8 shows on-road accelerated testing results for the Renault Kangoo. The two longest cycles were omitted due to problems with the vehicle's ICE and inverter.

Table 8: Renault Kangoo accelerated testing results.

Cycle	Urban	Highway	Charge	Reps	Total	Electricity		Gasoline	
(mi)	(10 mi)	(10 mi)	(hr)	(N)	(mi)	AC kWh	Mi/kWh	Gals	MPG
10	1	0	4	60	600	359.60	1.7	0	
20	1	1	8	30	600	131.96	4.6	0	
40	4	0	12	5	200	35.18	5.6	0	
40	2	2	12	5	200	33.22	6.0	0	
40	0	4	12	5	200	28.60	7.0	0	
60	2	4	12	10	600	57.96	10.4	13.3	45.1
80	2	6	12	8	640	44.62	14.4	16.6	38.6
100	2	8	12	6	600	Deleted			
200	2	18	12	3	600	Deleted			
Total	1560	1480	876	123	3,040				

5 Fleet Demonstration

Table 9 contains basic statistics for fleet data collected in 2008.

Table 9: AVTA/DOE PHEV fleet 2008.

Vehicle Model	Number of Vehicles	Trips Logged	Distance Logged (mi)
Hymotion Prius (v1 and v2 packs)	102	32,814	296,601
EnergyCS Prius (Valence)	5	1,966	16,470
EnergyCS Prius (Altairnano)	2	915	7,312
Manzanita Prius (Hawker)	2	1,436	16,122
Hymotion Escape	2	675	11,065
Hybrids Plus Escape (Hybrids Plus)	7	2,737	20,475
Total	120	40,543	368,045

5.1 Hymotion Prius

As with on-road accelerated testing, the primary metrics used to summarize PHEV fleet performance are fuel consumption and electrical energy consumption. Results are broken down by operating mode (CD or CS) relative to trips taken. Table 10 shows 2008 results for the fleet of 102 Hymotion Priuses. Note that a CD trip is one that begins and ends in CD mode. A mixed trip begins in CD mode and ends in CS mode. A CS trip begins and ends in CS mode.

Table 10: Hymotion Prius energy consumption.

	Fuel Economy (mi/gal)	Electrical Energy Consumption (AC Wh/mi)
Overall	48	72
CD Trips	63	183*
Mixed Trips	52	
CS Trips	41	0

* This calculation considers miles from CD trips and the CD portion of mixed trips.

The majority of data in this section comes from production (or "v2") packs, although some vehicles in the fleet had "v1" packs in early 2008.

Sixty-three of these vehicles have the V2Green data logger, which measures alternating current (AC) energy from the grid directly. The remainder of Hymotion Priuses in the fleet have a data logger that measures direct current (DC) energy at the battery. For the latter group, AC energy was calculated by using an AC-to-DC efficiency of 78%, based on observed average charger efficiency during dynamometer.

The average CD range from Hymotion Prius fleet data was observed to be 31.6 mi. This is the distance driven in one or more trips, starting with a full state of charge in the Hymotion battery pack and ending when the pack is fully depleted. It is important to note that CD range is not synonymous with all-electric range for blended-mode PHEVs. The ICE may cycle on and off during CD mode to meet tractive power and accessory load demands, heat the catalytic converter, and for other reasons.

5.1.1 Driving and charging behavior as they affect vehicle performance

The Hymotion Prius and other conversion PHEVs tested to date exhibit a wide range of energy efficiency as driving, charging, and external conditions vary. Figure 12 expands on cumulative fuel economy metrics shown in Table 10 to demonstrate this variation in the Hymotion Prius. Similar trends are seen with the other blended-mode conversion PHEVs evaluated by AVTA. Figure 12 contains distributions of monthly vehicle fuel economy by operating mode. All vehicle months in 2008 when a vehicle drove more than 300 miles are included in these distributions. The tops and bottoms of the boxes represent the 75th and 25th percentiles, respectively. Center bars represent median values. Individual data points shown are statistically considered outliers.

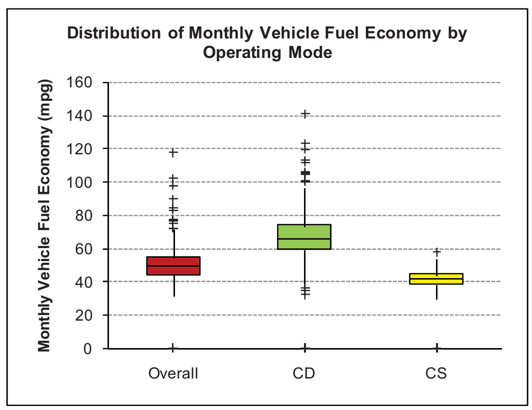

Figure 12: Distribution of 2008 Hymotion Prius monthly vehicle fuel economy.

The single largest factor determining a PHEV's fuel efficiency is its operating mode, which is a function of distance driven relative to charging frequency and duration. Hymotion Prius fleet driving is broken down by operating mode as shown in Table 11.

Table 11: Hymotion Prius driving by operating mode.

Trip Type	Trips	Distance (mi)	Percent of Total Distance
CD	17,913	85,225	29%
Mixed	2,894	72,737	24%
CS	12,007	138,642	47%

Note that nearly half of the trips taken began in CS mode, meaning the Hymotion pack had been fully depleted prior to the start of the trip. This high proportion of driving in CS mode greatly reduces overall vehicle fuel economy.

Additional metrics describing plug-in charging are given in Table 12.

Table 12: Plug-in charging frequency.

Average number of charging events per vehicle per month when driven	17.8
Average number of charging events per vehicle per day when driven	1.1
Average distance between charging events	39.0
Average number of trips between charging events	4.3

Although the vehicles are being charged, on average, more than once for every day they are driven (Table 12, line 2), they are being driven further between charging events (Table 12, line 3) than their average CD range of 31.5 miles. This suggests the need for increased day-time "opportunity charging" to increase the proportion of miles travelled in CD mode.

There are several factors which may explain the lack of charging in the fleet. Because this is a largely commercial fleet where vehicles are most often used for accomplishing daily work tasks, vehicle operators may not be focused on looking for charging opportunities during the day. Also, work responsibilities may limit operators' access to charging infrastructure or time for charging. Furthermore, it is unclear how many operators are aware of the need for increased charging. Finally, commercial fleet vehicle operators may not be motivated to plug in their vehicles, because they likely do not personally pay for the more expensive gasoline fuel they consume instead.

AVTA has begun to study the impact of charging infrastructure availability on charging patterns [6]. Additional studies are being planned to examine charging behavior of private vehicle owners, and to explore the impact on driver education on charging patterns. Studies involving PHEVs operating in "rich" charging environments are also being planned.

Looking beyond operating mode and charging frequency, the energy efficiency of the Hymotion Prius and other blended-mode PHEV conversions is highly sensitive to usage conditions, due to vehicle system design limitations. Aftermarket conversion companies have limited ability to change the stock vehicle's control strategy, which was designed for a hybrid electric vehicle (HEV) system with much less electrical energy and power capacity. Hardware limitations, such as HEV-optimized electric drive component power limits and transaxle kinematics, also constrain fuel economy improvements as a PHEV.

One area where this sensitivity is manifested is driving aggressiveness. As a driver's demand for power increases beyond the capacity of the electric drive subsystem, the ICE must come on to meet power demand, even while in CD mode. Figure 13 shows how fuel economy decreases as driving aggressiveness increases in individual trips. In this case, aggressiveness is defined as the percent of time spent with the accelerator pedal position beyond 40% of full pedal travel during individual trips. Results come from 700 CD trips driven in ideal conditions (warm ambient and vehicle operating temperatures and no climate control usage). Trips meeting these criteria were randomly selected from 2008 data.

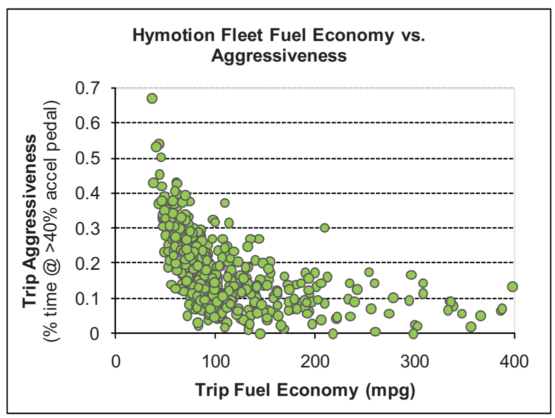

Figure 13: Driving aggressiveness versus fuel economy.

Other sources of performance variation include route type (e.g., city, rural, and highway.), ambient and vehicle temperature, use of climate control, and so on. These factors are explored in other works [7].

5.1.1 Charging behavior as it affects the electrical grid

As there is much interest in how PHEVs will affect the electrical grid, metrics are provided that summarize plug-in charging time and energy consumption. Table 13 shows 2008 results for 63 Hymotion Priuses equipped with the V2Green data logger. This logger measures AC energy directly during charging.

Table 13: Charge time and energy consumption.

Duration of charging event – average time drawing power from the grid per charging event (hr)	2.8
Duration of charging event – average time plugged in per charging event (hr)	17.4
Average energy consumed per charging event (AC kWh)	2.5
Average energy consumed per vehicle per month (AC kWh)	46.4
Total number of charging events	3,974
Total charging energy consumption (AC kWh)	10,128

Note that the average time spent plugged in per charging event (Table 13, row 2) is high because fleet vehicles are often left plugged in over the weekend.

Figures 14 and 15 show the time of day when driving and charging, respectively, for the 63 Hymotion Priuses with V2Green logger.

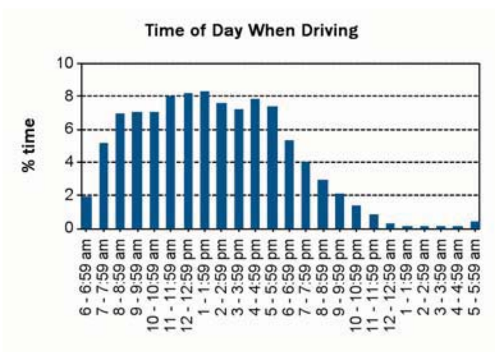

Figure 14: Time of day when driving

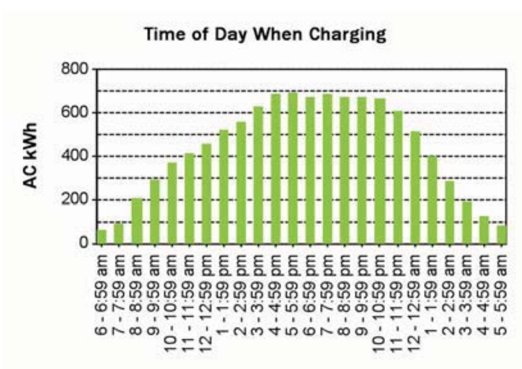

Figure 15: Time of day when charging versus charging energy.

5.2 EnergyCS Prius

Data is being collected from five EnergyCS Priuses with Valence battery packs and two EnergyCS Priuses with Altairnano battery packs. Results are still being processed for data from vehicles with Valence packs at the time of this writing. Results presented in this section come from EnergyCS Priuses with Altairnano batteries. Tables 14 and 15 show 2008 energy consumption and trips/distance with respect to operating mode for these vehicles.

Table 14: EnergyCS Prius energy consumption.

	Fuel Economy (mpg)	Electrical Energy Consumption (AC Wh/mi)
Overall	60	73
CD Trips	73	161*
Mixed Trips	68	
CS Trips	47	0

* This calculation considers miles from CD trips and the CD portion of mixed trips.

The EnergyCS data logger records DC energy only. AC charging energy for these vehicles was calculated by multiplying DC energy discharged during driving by a round-trip efficiency of 77%. This efficiency value was observed during dynamometer testing.

Table 15: EnergyCS driving by operating mode.

Trip Type	Trips	Distance (mi)	Percent of Total Distance
CD	475	1,724	24%
Mixed	101	3,157	43%
CS	339	2,431	33%

The average CD range for these vehicles is 31.5 miles.

Metrics describing plug-in charging profiles are given in Table 16.

Table 16: EnergyCS plug-in charging profiles.

Average number of charging events per vehicle per month when driven	17.2
Average number of charging events per vehicle per day when driven	1.2
Average distance between charging events	33.7
Average number of trips between charging events	4.2

5.3 Toyota Prius with Manzanita Micro Conversion

The Toyota Prius with Manzanita Micro conversion (or Manzanita Prius) uses a 5–kWh, Hawker valve-regulated lead acid (VRLA), supplemental battery pack. The pack does not broadcast any parameters to CAN; therefore, it is not possible to sense the operating mode of the vehicle. Table 17 shows 2008 overall energy consumption for two Manzanita Priuses with the Hawker VRLA pack.

Table 17: Manzanita Prius energy consumption.

	Fuel Economy (mpg)	Electrical Energy Consumption (AC Wh/mi)
Overall	46	33

AC energy was measured directly for these vehicles using the V2Green data logger.

Manzanita Micro recently introduced another Prius conversion pack with a Thunder Sky Li-ion battery pack. A fleet partner recently introduced this conversion into the fleet.

5.4 Hymotion Escape

Tables 18 and 19 show 2008 energy consumption and trips/distance with respect to operating mode for two Hymotion Escapes.

Table 18: Hymotion Escape energy consumption.

	Fuel Economy (mpg)	Electrical Energy Consumption (AC Wh/mi)
Overall	29	40
CD Trips	33	118+
Mixed Trips	30	
CS Trips	27	0

+ This calculation considers miles from CD trips and the CD portion of mixed trips.

AC energy was calculated by using an AC-to-DC efficiency of 81%, based on observed average charger efficiency during dynamometer testing.

Table 19: Hymotion Escape driving by operating mode.

Trip Type	Trips	Distance (mi)	Percent of Total Distance
CD	375	2,605	24%
Mixed	90	3,037	27%
CS	210	5,422	49%

The average CD range for these vehicles is 51.7 miles.

Metrics describing plug-in charging profiles are given in Table 20.

Table 20: Hymotion Escape plug-in charging profiles.

Average number of charging events per vehicle per month when driven	6.6
Average number of charging events per vehicle per day when driven	0.7
Average distance between charging events (mi)	101.5
Average number of trips between charging events	6.2

5.5 Hybrids Plus Escape

Tables 21 and 22 show 2008 energy consumption and trips/distance with respect to operating mode for seven Hybrids Plus Escapes with Hybrids Plus packs.

Table 21: Hybrids Plus Escape energy consumption.

	Fuel economy (mpg)	Electrical Energy Consumption (AC Wh/mi)
Overall	38	111
CD Trips	40	162*
Mixed Trips	43	
CS Trips	32	0

* This calculation considers miles from CD trips, as well as the CD portion of mixed trips

AC energy was measured directly for these vehicles using the V2Green data logger.

Table 22: Hybrids Plus Escape driving by operating mode.

Trip Type	Trips	Distance (mi)	Percent of Total Distance
CD	2,104	12,130	59%
Mixed	57	3,164	15%
CS	576	5,180	25%

The average CD range for these vehicles is 63.8 miles.

Metrics describing plug-in charging profiles are given in Table 23.

Table 23: Hybrids Plus Escape plug-in charging profiles.

Average number of charging events per vehicle per month when driven	30.7
Average number of charging events per vehicle per day when driven	2.0
Average distance between charging events	29.3
Average number of trips between charging events	3.9

6 Conclusion

AVTA testing of PHEVs in controlled conditions shows potential for significant petroleum displacement. AVTA fleet demonstrations also show that some conversion PHEVs operating in actual-use conditions have achieved impressively high fuel economy (i.e., 80 to 120 miles per gallon for Prius conversions) sustained over significant distances. On average, however, most conversion PHEVs evaluated in the field fall short of this potential. A major reason for this is that the vehicles are not plugged in often enough relative to the distance driven. This may be due to such factors as operator awareness, time availability, and availability of charging infrastructure. Future work is warranted to understand the impact of these factors on charging behavior and to identify enablers to overcoming obstacles to plug-in charging.

Fleet average CD fuel economy was 22 to 55% higher than CS fuel economy, depending on the vehicle. While these gains are significant, they again fall short of the vehicles' demonstrated petroleum displacement potential. The difference is largely a result of pronounced vehicle sensitivities to varying driving conditions, which sensitivities are possibly due to the limits of aftermarket conversion vehicle design. Some of these sensitivities can be managed through modifying driving behavior, as has been shown with driving aggressiveness. Further improvement may require more highly integrated conversion PHEVs or purpose-built, optimized PHEVs. AVTA will continue partnering with industry and government stakeholders to evaluate these vehicles as they become available.

Acknowledgments

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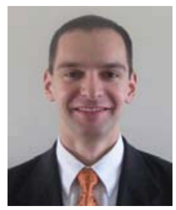
Authors



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