On-Road Evaluation of Advanced Hybrid Electric Vehicles over a Wide Range of Ambient Temperatures

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Abstract

In recent years, Hybrid Electric Vehicles (HEV's) have become a production viable and effective mode of efficient transportation. HEV's can provide increased fuel economy over convention technology vehicle, but these advantages can be affected dramatically by wide variations in operating temperatures. The majority of data measured for benchmarking HEV technologies is generated from ambient test cell temperatures at 22^{o}C.

To investigate cold and hot temperature affects on HEV operation and efficiency, an on-road evaluation protocol is defined and conducted over a six month study at widely varying temperatures. Two test vehicles, the 2007 Toyota Camry HEV and 2005 Ford Escape HEV, were driven on a pre-defined urban driving route in ambient temperatures ranging from -14^{o}C to 31^{o}C. Results from the on-road evaluation were also compared and correlated to dynamometer testing of the same drive cycle. Results from this on-road evaluation show the battery power control limits and engine operation dramatically change with temperature. These changes decrease fuel economy by more than two times at -14^{o}C as compared to 25^{o}C. The two vehicles control battery temperature in different manners. The Escape HEV uses the air conditioning system to provide cool air to the batteries at high temperatures and is therefore able to maintain battery temperature to less than 33^{o}C. The Camry HEV uses cabin air to cool the batteries. The observed maximum battery temperature was 44^{o}C.

Key words:

Camry HEV, Escape HEV, fuel economy, battery temperature, wide range of temperatures

Introduction

Current hybrid electric vehicles are optimized to maximum fuel economy while maintaining good performance and drivability. Extreme temperatures, both hot and cold, affect the fuel economy and performance of all vehicles. Conventional gasoline vehicles show a decrease in fuel economy of 1.2 to 1.8 times at -30^{o}C as compared to 20^{o}C [1]. In a hybrid electric vehicle the battery system characteristics, engine operation and even the overall control strategy may drastically change at extreme temperatures. This study investigates at the fuel economy, battery characteristics, engine operation, and overall hybrid control strategy of two hybrid electric vehicles over a wide range of temperatures (-14^{o}C to 31^{o}C) over an urban driving route. These results will also be compared to a controlled temperature test of the same driving cycle on a chassis dynamometer (22^{o}C).

1. Vehicles Evaluated

Two hybrid vehicles are evaluated over the varying temperature ranges through the on-road route. The vehicles are a 2007 Toyota Camry HEV and a 2005 Ford Escape HEV shown in Figure 1. The Camry HEV was chosen because it is the latest hybrid vehicle produced from Toyota and the Escape HEV was chosen for comparison because it is a mid-size SUV and has a similar power split powertrain architecture as well as similar displacement engine. Both vehicles also use NiMH battery packs of similar size. Table 1 below shows the main vehicle specifications.

Figure 1. 2007 Camry HEV and a 2005 Escape HEV in -14^{o}C on-road evaluation

Table 1 - Vehicle specifications

Parameter	**2007 Camry HEV**	**2005 Escape HEV**
Type of vehicle	Sedan	SUV
Test weight of vehicle [kg]	1815	1815
NiMH Battery [kWhrs]	1.6 kWhr [2]	1.8 kWhr [3]
Engine Displacement [L]	2.4L	2.3L

2. "ANL City Cycle" for On-road Evaluation

A predetermined urban driving route is used for all of the vehicles on-road driving in this study. This driving route is referred to as the "ANL City Cycle". The ANL City Cycle is a road course on the grounds of Argonne National Laboratory. This driving route or cycle, shown in red in Figure 2, is repeated six times with approximately fifteen seconds between cycles. A "pre-cycle", shown in orange, is also conducted which is the route from the parking lot to the driving evaluation loop where the ANL City Cycles are conducted.

Figure 2. ANL City Cycle Evaluation Loop at Argonne National Laboratory

The ANL City Cycle is similar to the UDDS drive cycle because both are low speed stop and go driving but the ANL City Cycle has higher peak and average accelerations. The characteristics of the ANL City Cycle and the UDDS Cycle are shown in Table 2.

Table 2 - Cycle characteristics

	UDDS	ANL City Cycle
Maximum Acceleration [m/sec^2]	1.48	2.41
Minimum Acceleration [m/sec^2]	-1.48	-2.68
Average Positive Acceleration [m/sec^2]	0.50	0.74
Average Negative Acceleration [m/sec^2]	-0.58	-0.77
Average Vehicle Speed [mph]	19.5	24.7
Maximum Vehicle Speed [mph]	56.7	48.0
Cycle Distance [mi]	7.45	3.24

The ANL City Cycle is driven at typical urban speeds and includes several stop signs but no traffic lights. Avoiding traffic lights in driving route increases drive cycle repeatability by reducing the variability of time waiting for a green light. Other vehicles on the road during evaluation create traffic which introduces more variability but as shown in Figure 3 the repeatability of the on-road evaluation is still rather good.

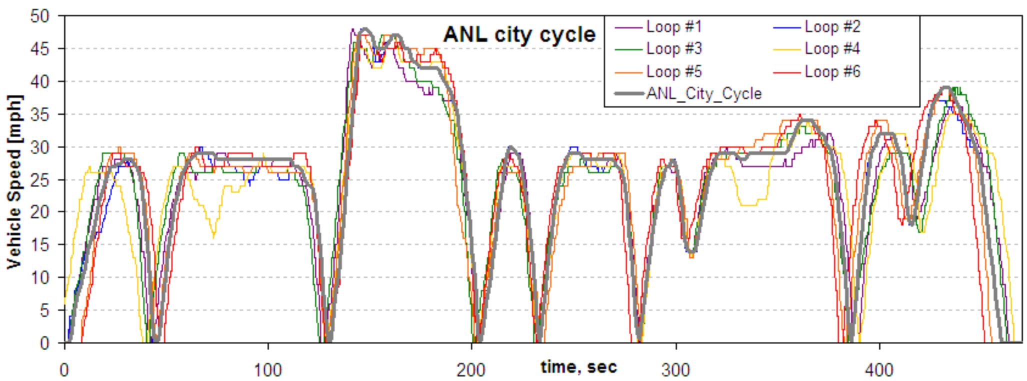

Figure 3. ANL City Cycle Evaluation Loop repeatability

On-road vehicle evaluation was conducted from January to July to take full advantage of the temperature variations in the Great Lakes region of the U.S. since a climatically controlled dynamometer test facility is not available. Evaluation at -15°C, 0°C, 15°C, 30°C was conducted on-road over the ANL City Cycle. The on-road evaluation is conducted in the early morning after the vehicle has been parked outside overnight to allow the vehicle to equilibrate to a steady state temperature near the ambient temperature. The cabin temperature control is set to 70°C and a low fan setting. The vehicle evaluation conducted at 30°C was the only exception. It was initiated in the late afternoon after the vehicle equilibrated to the high daytime temperature. The interior temperature setting was again set to 70°C and a low fan setting with the air conditioner off.

The same evaluation regiment was also conducted in the Advanced Powertrain Research Facility at Argonne National Laboratory. This facility includes a four wheel drive chassis dynamometer inside a climatically controlled environment. The testing for this study was conducted at 22°C and 45% relative humidity. An average from the six repeated evaluation loops was used to create a representative speed trace for dynamometer testing. Figure 4 shows one Pre City Cycle and six ANL City Cycles as used for testing on the chassis dynamometer.

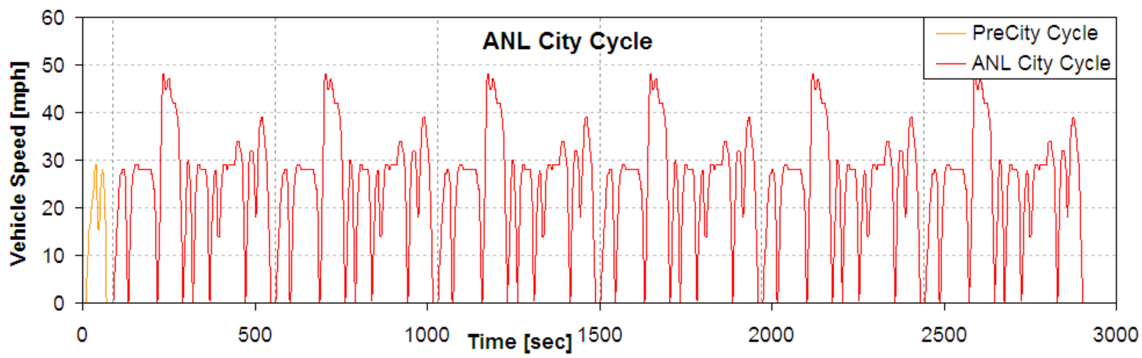

Figure 4 – ANL City Cycle repeated six times for each on-road evaluation

3. Data Acquisition

Several key parameters were recorded during testing including temperatures, speeds, and battery current and voltage with a Scan Tool connected to the OBD port of the vehicle. A laptop was used to record and store the data at 3Hz obtained from the scan tool as show in Figure 5. The fuel economy measurement and distance traveled was manually recorded from the vehicle dashboard display.


Figure 5 – Scan Tool and Laptop used for data acquisition

4. Results and Analysis of Camry HEV

4.1 On-Road Evaluation

On-road evaluation of the Camry HEV was conducted to determine the change in fuel economy, battery characteristics, and control system operation over a wide range of temperatures. On-road data is collected and analyzed for four temperature ranges from -14^{o}C to 31^{o}C as well as dynamometer testing in a controlled dynamometer test facility at 22^{o}C.

The Camry HEV was driven on-road with an ambient temperature of -14^{o}C over the ANL City Cycle as previously described. Several of the measurements from this on-road evaluation are show in Figure 6. The temperature of the vehicle's powertrain components, battery, and coolant begin at nearly a steady temperature of -14^{o}C. These temperatures increase as the vehicle is driven over the ANL City Cycle route. Some components asymptotically approach a steady state operating temperature by the end of the six cycles such as engine coolant temperature and motor temperature. Battery temperature on the other hand continues to increase. The fuel economy for each cycle, also shown in Figure 6, increases as component temperatures increase and reaches a repeatable fuel economy by the third cycle. For the pre-cycle and the first two full cycles, the engine was on 100% of the time. By the third cycle, the powertrain begins to operate with an engine start/stop operation which turns off the engine at as the vehicle approaches zero speed which dramatically increases fuel economy.

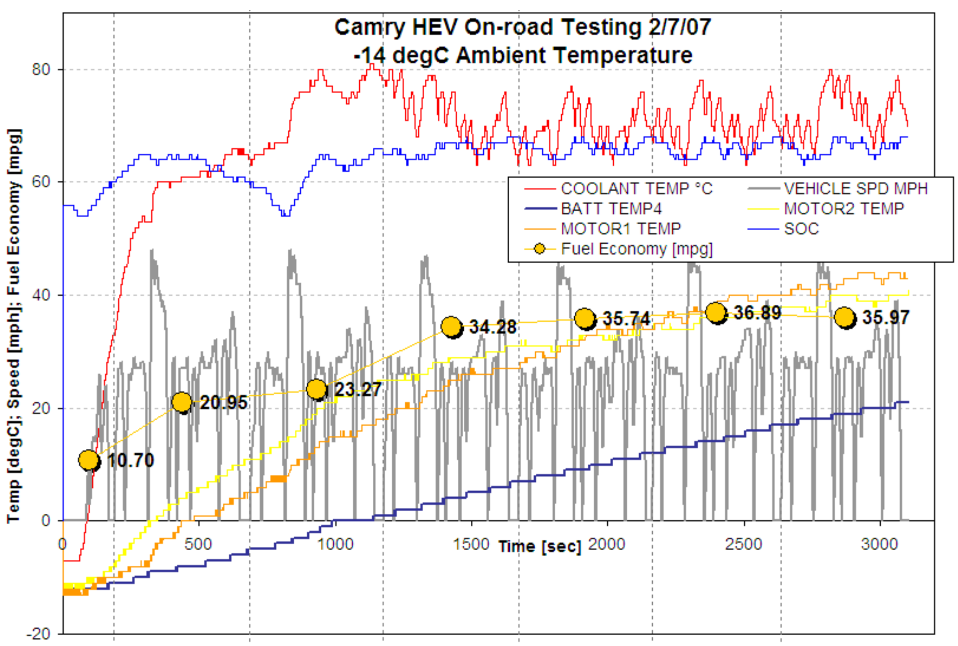

Figure 6 – On-road evaluation of the Camry HEV at -14^{o}C ambient temperature

For determining the sensitivity of powertrain operation with respect to battery temperature, many measurements and calculated parameters are plotted as a function of battery temperature in Figure 7. The four separate on-road evaluations at the four different ambient temperatures are plotted on this single figure which introduces slight discontinuities between the individual tests but the general trend are still predominant. The positive and negative battery control power limits can be seen on the graph, which create an envelope around the battery power. Battery power was calculated from measured battery voltage and battery current. Figure 7 shows the battery power control limits are restricted for negative power (regenerative braking) below 17^{o}C and positive power (assist) below 25°C. If the trend is extrapolated to colder temperatures, it appears the battery power would approach zero at approximately -30°C.

The nominal battery power limits at 25°C are 25 kW and -24 kW but when the battery temperature is above 35°C to 40°C the regenerative braking power limit is limited to only -6 kW. The average absolute battery power and percentage engine on time are also plotted. A few general trends can be seen. The average absolute battery power increases slightly as the battery power limits are increased with increasing temperature until the regenerative braking is limited with increasing battery temperatures above 35°C. The fuel economy trend shows a dramatic increase as temperature increases. The discontinuity in fuel economy between the four on-road evaluations is mainly due cold start effects but the overall increasing trend is very apparent. The fluctuating fuel economy at temperatures above 40°C appears to be a result of decreasing engine on time and negative battery power being limited to 6 kW which increases and decreases fuel economy respectively. Over the course of the study, the maximum battery temperature was observed to be 44°C at an ambient condition of 31°C and the minimum battery temperature was observed to be -12°C at an ambient condition of -14°C.

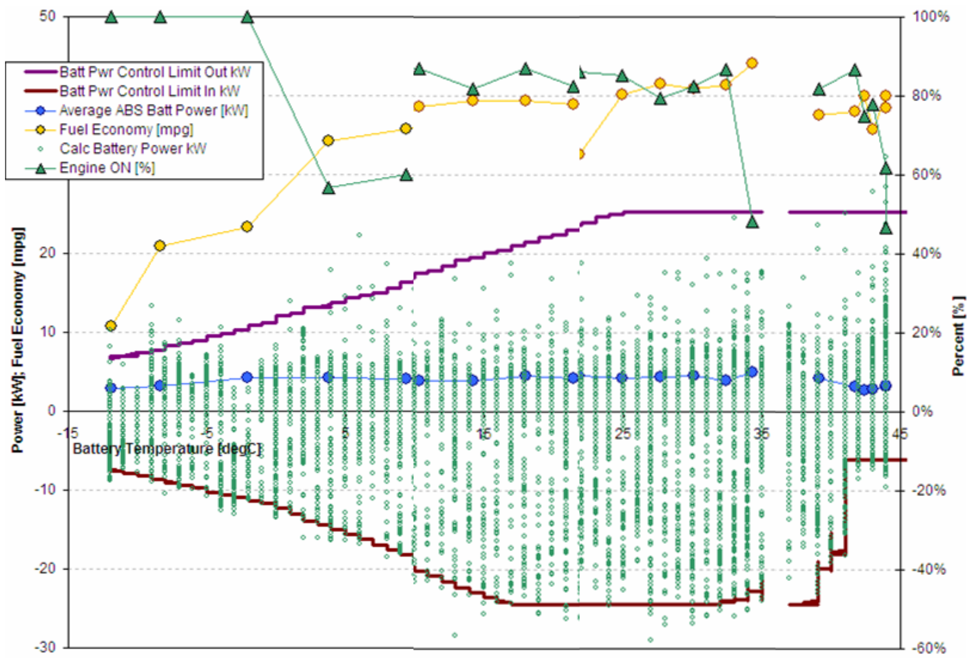

Figure 7 –Camry HEV powertrain operation variation with change in battery temperature (-14°C to 31°C ambient temperature)

4.2 Dynamometer Testing

The same ANL City Cycle was conducted on a chassis dynamometer at a controlled ambient temperature of 22°C. The dynamometer test cell is able to collect up to four test phases because there are four emissions bags. Since the ANL City Cycle is repeated six times, the testing was divided into 2 halves. A pre-cycle and three consecutive ANL City Cycles were initiated after a 12 hour soak period at 22°C. Within ten minutes of completing these cycles, three more ANL City Cycles were conducted to complete the single pre-cycle and six repeated ANL City Cycles. The testing being conducted in two halves did create a discontinuity in some measurements especially temperatures as compared to the on-road evaluation at a similar ambient temperature (20°C).The dynamometer coefficients used for testing are the EPA target ABC's shown in table 3. The test class weight of the Camry HEV is 4000 lbs.

Table 3 - Target coefficients used for dynamometer testing of Camry HEV

A [lbs]	B [lbs/mph]	C [lbs/mph^2]
33.391	-0.0302	0.0205

The same scan tool and laptop data acquisition is used for the dynamometer testing to enable a direct comparison to the on-road evaluation. The emissions benches using carbon balance calculations were used to determine fuel economy over each cycle to compare to the dashboard displayed fuel economy calculated by the vehicle. This comparison is shown in Figure 8. The dashboard displayed fuel economy is slightly higher than the carbon balance calculated fuel economy most likely due to the fuel properties used for the dashboard calculation differing from the actual fuel used.

During the dynamometer testing shown in Figure 8, the fuel economy changed considerably from the third cycle and fifth cycle, from 42.7mpg to 50.7mpg respectively. This increase resulted from a change in engine operation despite all other indications of the two cycles being nearly identical including engine coolant temperature and SOC.

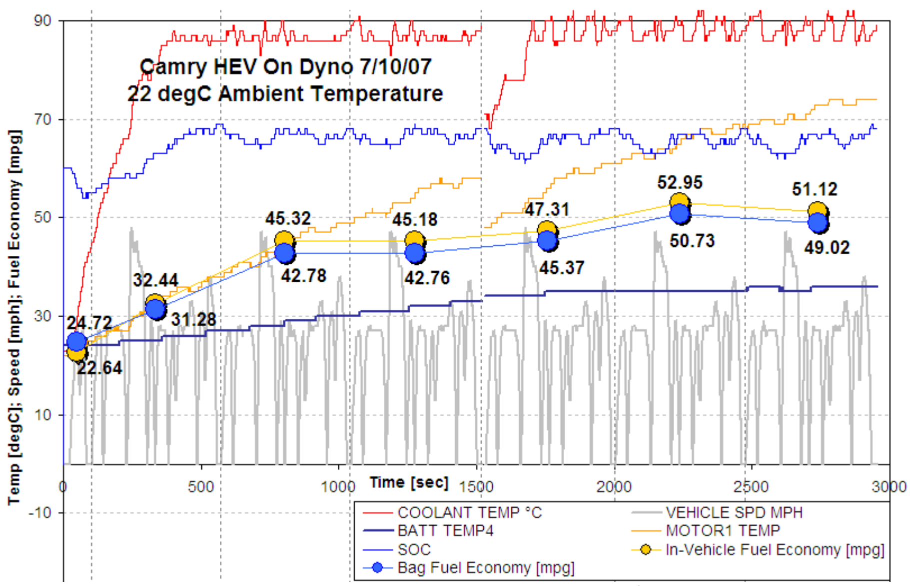

Figure 8 – Dynamometer testing of the Camry HEV at 22^{o}C ambient temperature

Figure 9 shows the engine speed over cycle #3 and cycle #5 for the dynamometer testing from Figure 8. During cycle #3 the engine was operating for nearly the entire cycle. The grey areas indicate when the engine is not operating. The “engine warm up request” from the vehicle control system was on through most of the test. In cycle #5 the “engine warm up request” was not requested by the vehicle control system which allows the engine to have start/stop operation. This change in engine operation as seen here from cycle #3 to cycle #5 was also observed during the on-road evaluations. Perhaps this “engine warm up request” algorithm is a function of calculated catalyst temperature.

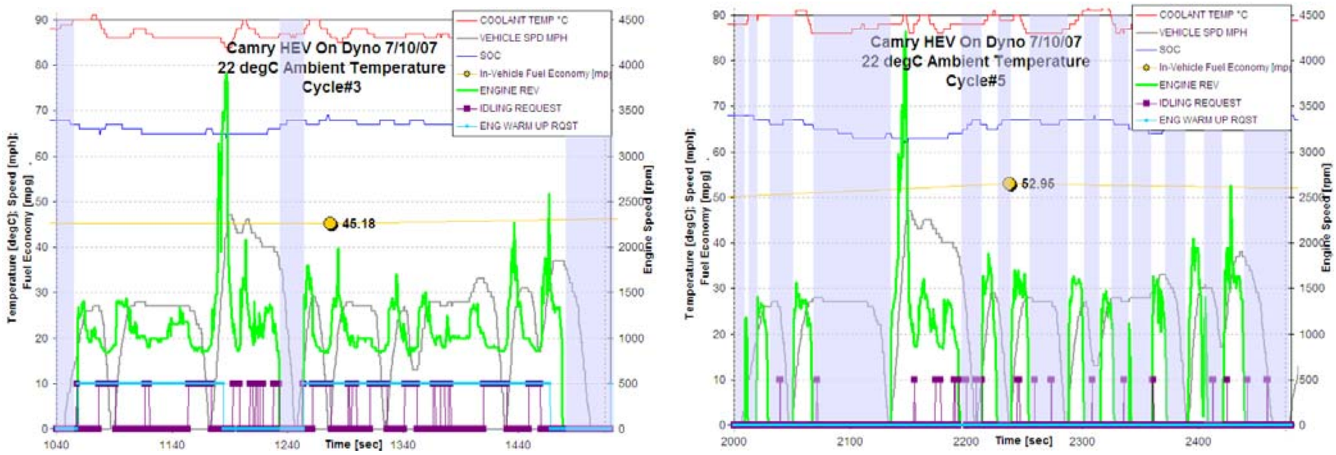

Figure 9 – Engine operating variations were observed during testing and evaluation

4.3 Battery Operating Characteristics

Two of the signals recorded during the on-road evaluation were battery current and battery voltage as reported by the HEV controller. These signals were able to be recorded at 3 Hz. Figure 10 show the current and voltage operation of the Camry HEV battery over the wide operating range of on-road evaluation drive cycles. Note the range voltage operation decreases as temperature increase as well as the dramatic change in internal resistance. The trend lines shown for each temperature range are a least squares fit to the data points within the temperature range. These slope of these trend lines are the internal resistance of the battery. Note the dramatic change in the internal resistance with change in temperature. Also the open circuit voltage, which is the y-axis crossing, is higher at lower temperatures. The minimum and maximum operating battery temperature recorded during on-road evaluations were -14°C and 44°C respectively.

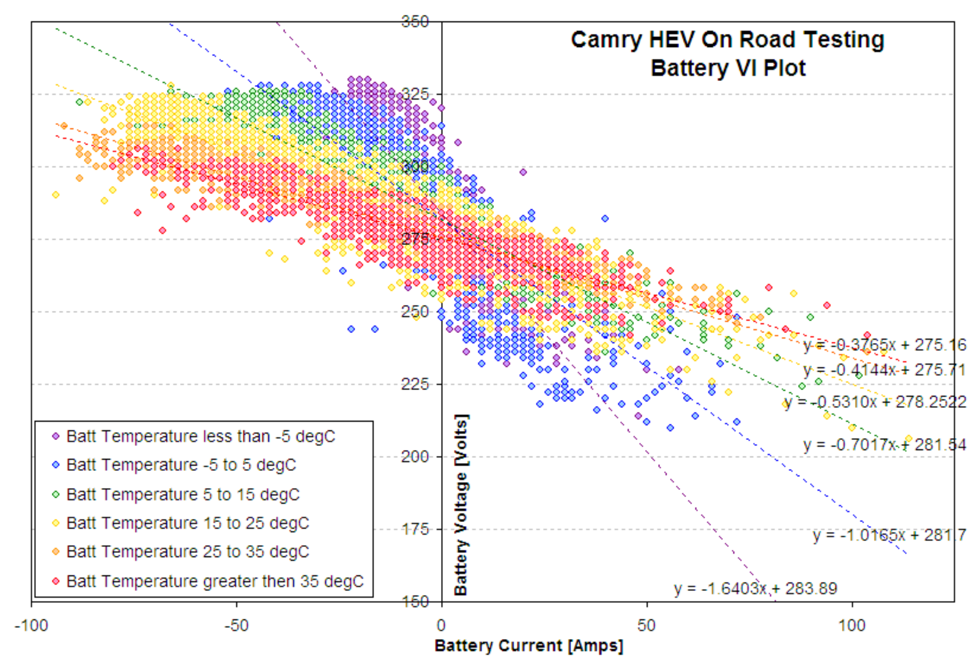

Figure 10 – Camry HEV battery voltage / current plot

5. Results and Analysis of Escape HEV

5.1 On-Road Evaluation

On-road evaluation of the Escape HEV was conducted to determine the change in fuel economy, battery characteristics, and control system operation over a wide range of temperatures. This evaluation was conducted from -10°C to 30°C in the same manner as the Camry HEV on-road evaluation to allow for direct comparison. Dynamometer testing was also conducted to correlate to the on-road data collected.

The Escape HEV was driven on-road with an ambient temperature of -10°C over the ANL City Cycle. A few of the measurements from this on-road evaluation are show in Figure 6. Fewer signals are available from the Scan Tool data acquisition system for the Escape HEV as compared to the Camry HEV including battery control power limits and SOC. The temperature of the vehicle's powertrain fluids begins at -15°C but the battery begins at -8°C. The batteries are quite isolated from the ambient temperature which results in slow heat transfer from the battery from the previous day operation. The fuel economy for each cycle, also shown in Figure 11, increases as component temperatures increase and reaches a repeatable fuel economy by the third cycle. At the beginning of driving, after the cold start, the engine operated 100% of the time but as the coolant and other powertrains components temperatures increased, the powertrain begins to operate with an engine start/stop operation by the second cycle which dramatically increases fuel economy as similarly observed with the Camry HEV.

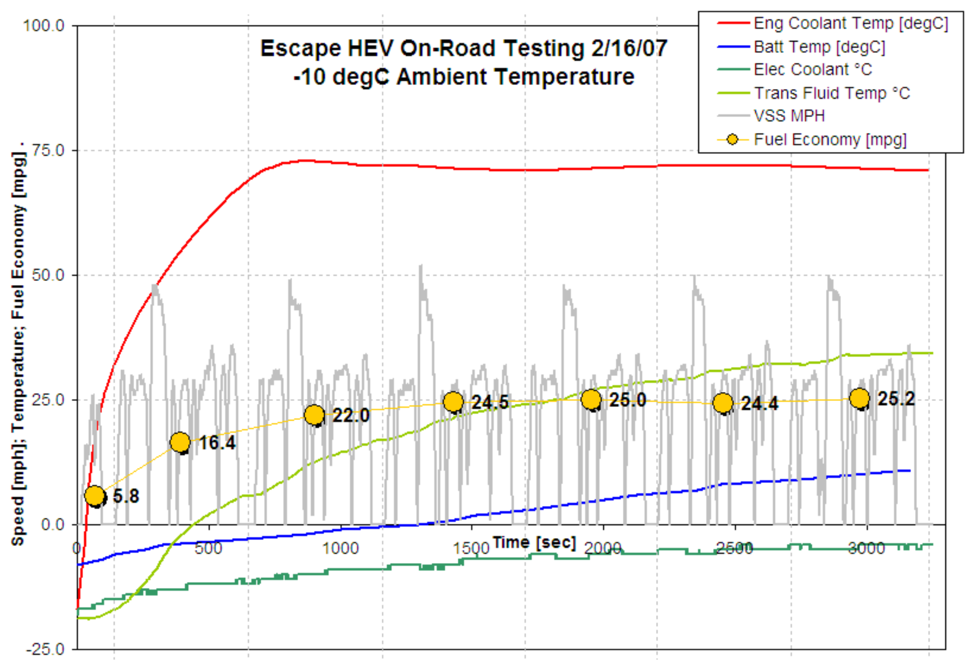

Figure 11 – On-road evaluation of the Escape HEV at -10°C ambient temperature

The sensitivity of powertrain operation with respect to battery temperature is shown in Figure 12 for several measured signals and calculated parameters. Since the battery power control limits are not available from the data acquisition system, estimated power limits are shown on Figure 12 as the bold dashed lines which create an envelope around the plotted battery power. The power limit trend shows increasing power utilization with increasing battery temperature. Unlike the Camry HEV battery power limits, The Escape HEV power limits appear to linearly increase with temperature without a nominal constant power limit. Also there is no reduction in regenerative battery power at high temperatures. This is mainly due to the maximum battery temperature is carefully controlled to 32°C. The regenerative braking power reduction in the Camry HEV occurred above 40°C.

A general trend of fuel economy increasing as battery temperature increases can be seen in Figure 12. The amount of engine operating time and the average engine power decrease as the battery temperature increases because the battery is able to be utilized more. This increase in utilization can be seen by the slight increase in absolute average battery power which is also shown by the increase in battery power control limits with increasing battery temperature.

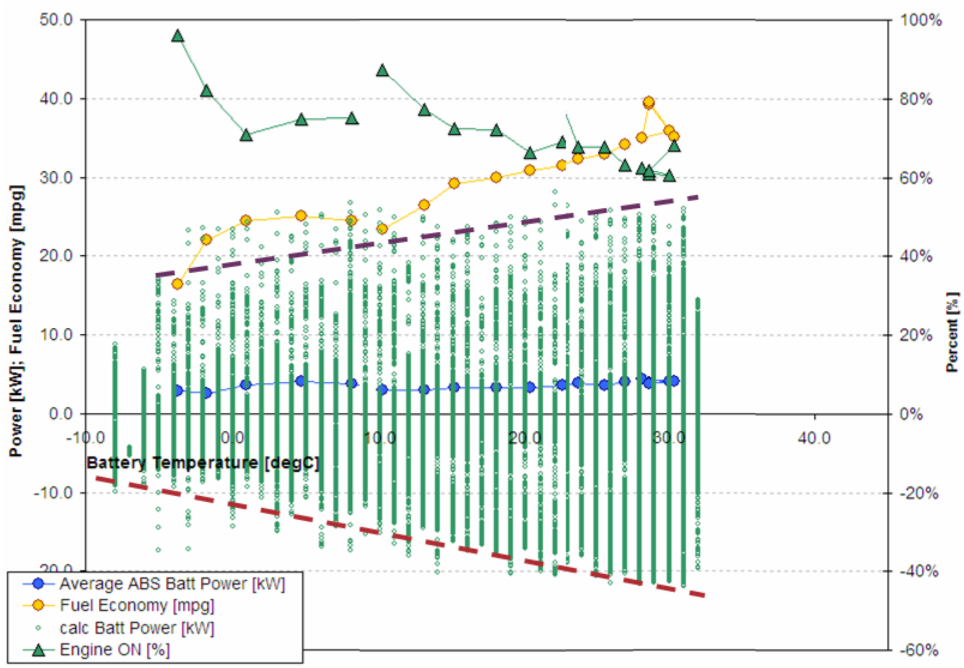

Figure 12 – Escape HEV powertrain operation variation battery temperature increases (-10°C to 30°C)

At the battery temperatures near 30°C, the fuel economy fluctuates because the air conditioner operates to cool the battery system. It turns on and off as needed to control battery temperature when the engine is on. The highest fuel economy approaches 40mpg when the air conditioner is not operating. Figure 13 shows two cycles driving at 30°C ambient temperature. In cycle #2 the air conditioner is not operating where as in cycle #3 the air conditioner is operating for most of the cycle. With the air conditioner operating, the battery temperature can be seen decreasing dramatically but the overall fuel economy of the cycle is less than cycle #2. This utilization of the air conditioner controls the maximum battery temperature for the Escape HEV to 32°C for these on-road evaluations which is much less than the maximum 44°C for the Camry HEV for similar ambient conditions of 30°C.

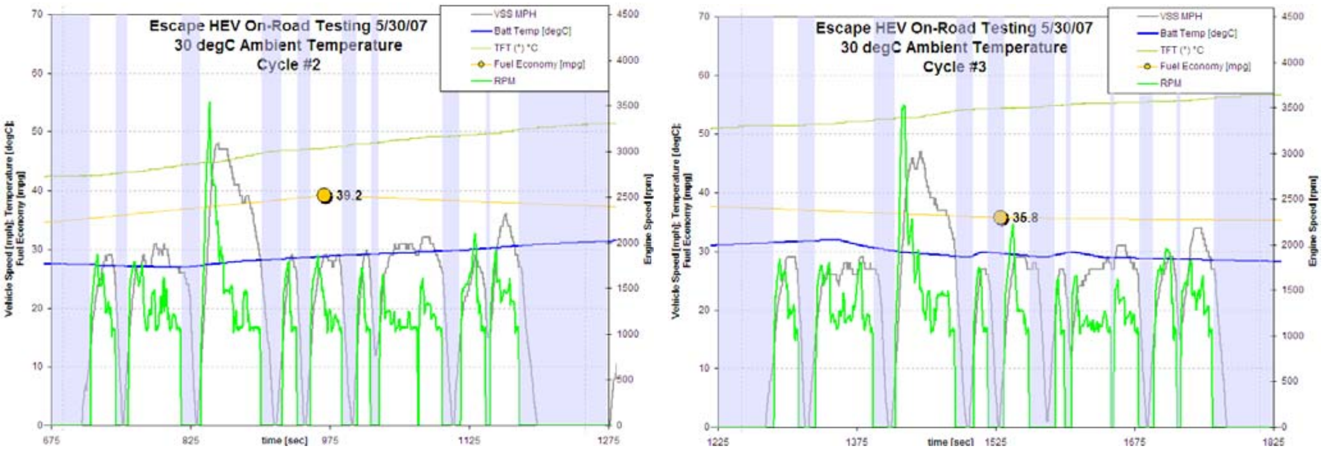

Figure 13 – Air conditioner is used to cool batteries but the engine operating time is unchanged

5.2 Dynamometer Testing

The ANL City Cycles were conducted on a chassis dynamometer at a controlled ambient temperature of 22^{o}C in the same manner as the Camry HEV as previously described. Since the vehicle is equipped with AWD, the dynamometer was configured for 4WD operation. The dynamometer coefficients used for testing are the EPA target ABC's shown in table 4. The test class weight for the Escape HEV is 4000 lbs.

Table 4 - Target coefficients used for dyno testing of Escape HEV

A [lbs]	B [lbs/mph]	C [lbs/mph^2]
23.1	0.8437	0.0253

Again the Scan Tool and laptop data acquisition are used for the dynamometer testing to enable a direct comparison to the on-road evaluation. The emissions benches using carbon balance calculations were used to determine fuel economy over each cycle to compare to the dashboard displayed fuel economy calculated by the vehicle. This comparison is shown in Figure 14. The dashboard fuel economy display is slightly higher than the actual fuel economy measurement which was similarly seen in the Camry HEV. The properties of the fuel used during dynamometer testing, which is Tier II certification fuel, may be different from the fuel used by the manufacturer to calibrate the fuel economy display which may be the primary cause of the fuel economy differences. The fuel economy variation from cycle to cycle shown in Figure 14 is higher than expected because the air conditioner is cycling on and off to cool the battery system.

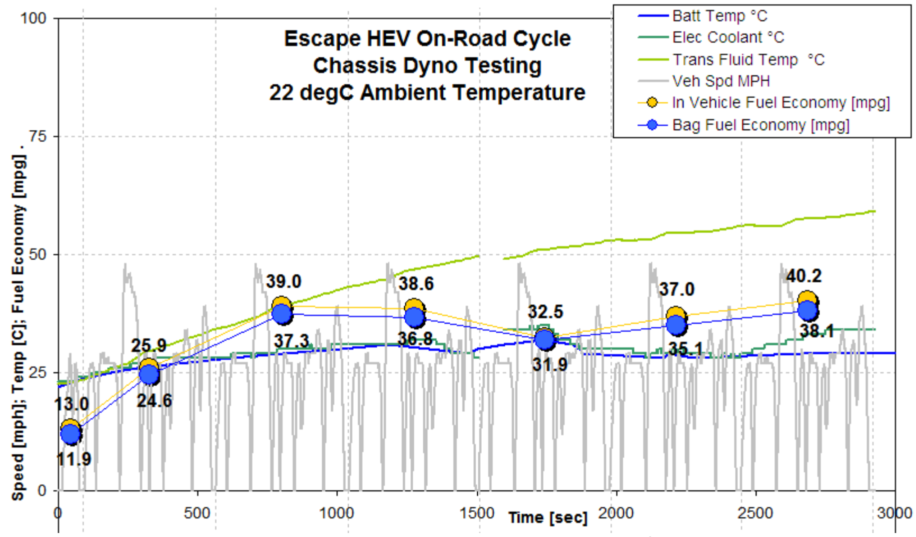

Figure 14 – Dynamometer testing of the Escape HEV at 22°C ambient temperature

5.3 Battery Operating Characteristics

The battery voltage, current, and temperature were recorded during the on road evaluation. Figure 15 shows the voltage and current plotted within various temperature regions. Trend lines of the data, which correlate to internal resistance, are shown for each temperature region. Notice how the internal resistance dramatically changes with change in temperature by more than three times. The open circuit voltage of the battery does not appear change in accordance to temperature. The open circuit voltage was lowest at low temperatures which promotes charging of the battery by the control system. This aids to warm the battery. At high battery temperatures the Escape HEV controls the temperature to 32°C or less for the driving conditions of this study by use of the air conditioning system. Therefore no data is available above 35°C.

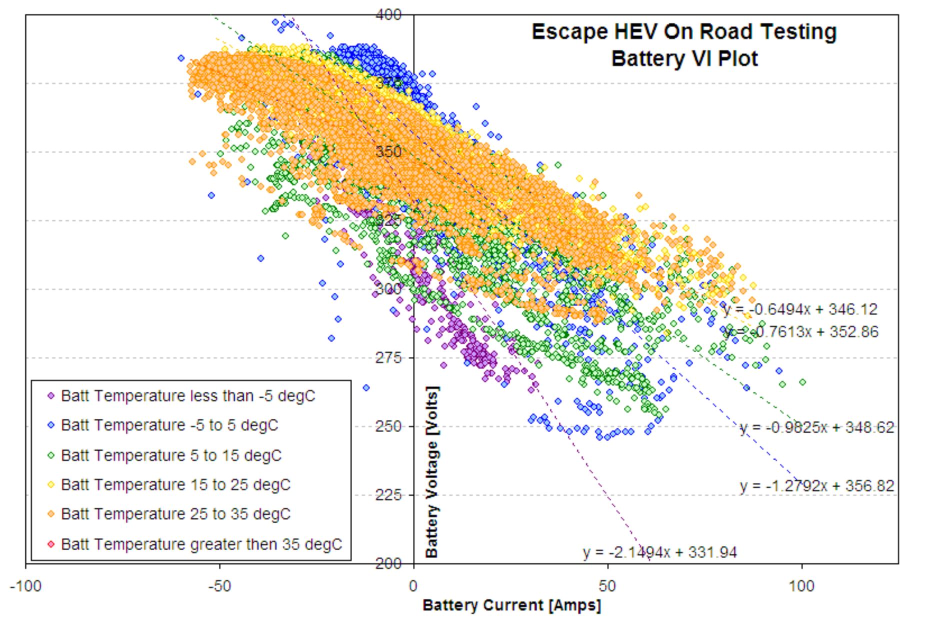

Figure 15 – Escape HEV battery voltage / current plot

6. Comparison of Camry HEV and Escape HEV

Since the two vehicles in this study have several similarities including weight, engine size, powertrain configuration, and battery capacity a few direct comparisons can be made between the vehicles. Fuel economy increases as battery temperature increases for both vehicles, but the Camry HEV does show a descending trend in fuel economy above 30°C. The Escape battery temperature is controlled to less than 33°C so no descending trend is observed. These fuel economy trends in Figure 16 show a change greater than two times for both vehicles from -14°C to 31°C ambient condition. The battery energy obtained through regenerative braking is also shown on Figure 16. This trends correlates closely to the fuel economy trend for both vehicles.

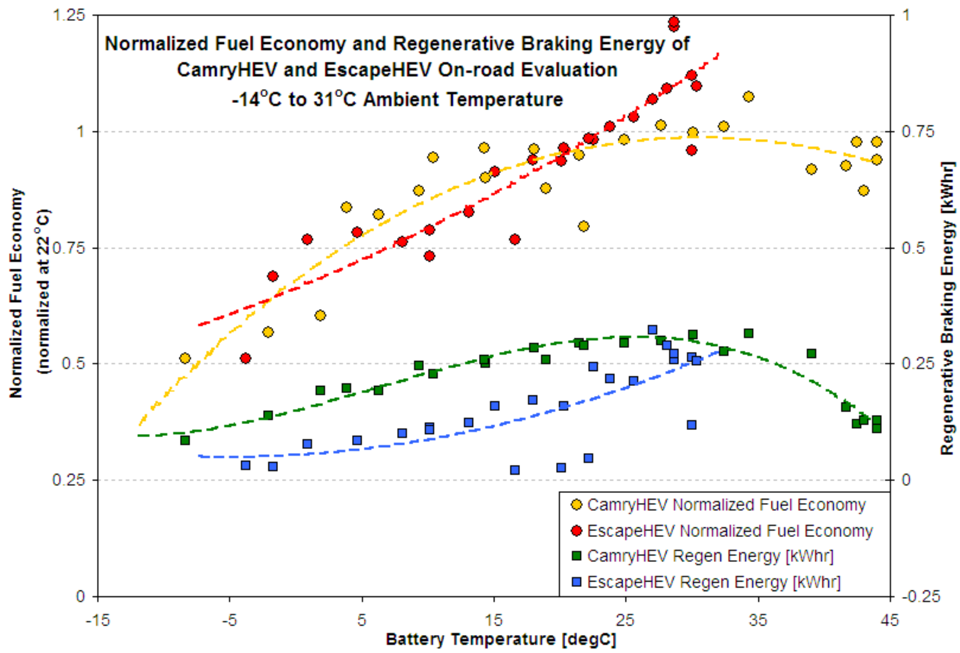

Figure 16 – Fuel Economy and Regenerative Braking trends of Camry HEV and Escape HEV

Investigating the battery temperature rise from a cold start is important to understanding the operation of the vehicle. Figure 17 shows the battery temperature rise and battery losses (I^2R) for both the Camry HEV and the Escape HEV from a cold start at ambient conditions below -10C.

The battery losses from internal resistance increase the battery temperature which is a beneficial side effect since fuel economy generally increases with increasing battery temperature. In Figure 17 the overall rate of temperature rise of the Camry HEV battery is greater than the Escape HEV but the charging event near the beginning of the test shows a dramatic increase in Escape HEV battery temperature. This charging is mainly due to the controls maintaining a proper battery state of charge (SOC), but increasing the battery temperature is a benefit despite the high losses from the high internal resistance at cold temperatures.

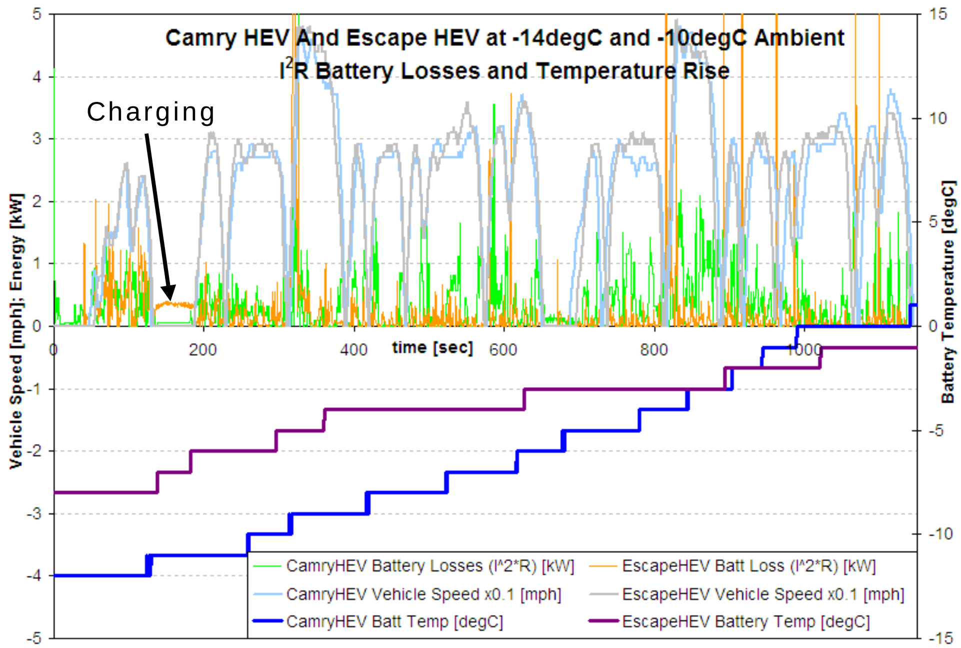

Figure 17 – Temperature Rise and Battery Losses of Camry HEV and Escape HEV Battery

7. Summary

The 2005 Ford Escape HEV and 2007 Toyota Camry HEV, shown in figure 18, were driven on-road over a predefined urban style driving loop. Data was collected and analyzed for powertrain operation, battery characteristics, and controls functionality. This on-road evaluation was conducted at a wide range of temperatures. Both vehicles show a dramatic change in fuel economy, nearly double, with respect to ambient temperature variations from -15°C to 20°C. Battery power for both vehicles was limited at low temperatures. The Camry HEV also showed a decreased regenerative braking power limit above 40°C battery temperature, but the Escape HEV battery power was not limited at higher temperatures because the battery system temperature was controlled to less than 33°C by the use of the air conditioning system. The internal resistance changed with temperature as expected. The Camry HEV open circuit voltage was higher at colder temperatures where as the Escape HEV battery internal resistance changes could not be correlated to temperature.

The vehicles performed very well in the extremely wide range of temperatures with ease of starting and driving as expected with no drivability compromises, but the fuel economy was dramatically affected (2x) at low ambient temperatures because of battery characteristics and operation. This study showed the affect of temperature on hybrid electric vehicles but with plug-in hybrid electric emerging, the effect of battery operation in cold and hot ambient conditions may become very important as the vehicle's fuel economy is tied even more directly to the battery utilization in plug-in hybrid electric vehicles.

Figure 18. 2005 Escape HEV and 2007 Camry HEV in 30^{o}C on-road evaluation

8. Acknowledgments

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