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Influence of Sub-Freezing Conditions on Fuel Consumption and Emissions from Two Plug-In Hybrid Electric Vehicles

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Abstract

Dynamometer testing was conducted on a Hymotion Prius PHEV at several ambient temperatures ranging from 22°C to -18°C. Fuel consumption, electrical energy consumption and emissions were measured and several key vehicle parameters were recorded. This dynamometer testing was conducted at Environment Canada's ERMS cold chamber test facility. Testing included urban (UDDS) and highway (HWFET) cycles over the full charge depletion range of the vehicle.

For comparison with the dynamometer testing, a Hymotion Prius PHEV and a Hymotion Escape PHEV were tested on-road at an ambient temperature of -5°C. This on-road testing was conducted over a prescribed urban driving route that has several similarities to the UDDS cycle. An additional on-road study was conducted in an attempt to determine the impact of battery temperature on fuel consumption of PHEVs. This involved testing at sub-freezing temperature while regulating battery temperature to a normal operating temperature of 15°C.

The results showed a dramatic increase in fuel consumption (up to three times) in charge depletion operation at sub-freezing temperatures. A large percentage of this increased fuel consumption can be attributed to engine warm-up which takes roughly 10 minutes to reach steady state operating temperature. The battery warm up period is considerably longer as well (60 minutes) which results in the majority of the additional fuel consumption over the entire charge depletion operation. These results included the temperature limitations of the production NiMH battery since both the Hymotion Prius and the Hymotion Escape utilize a dual battery configuration (production NiMH battery and additional Li-ion battery). Advanced Li-ion technology batteries are more robust than NiMH at very low temperature operation which could reduce this effect of increased fuel consumption for PHEVs.

Keywords: PHEV (plug-in hybrid electric vehicle), energy consumption, environment, emissions, vehicle performance

1 Introduction

Plug-In Hybrid Electric Vehicles (PHEVs) rely upon the battery system for a significant amount of energy for propulsion to reduce petroleum fuel consumption. Previous studies on production Hybrid Electric Vehicles (HEVs) have shown that subfreezing conditions significantly reduce NiMH battery performance and this directly impacts fuel consumption [1]. Since the battery performance may be limited at sub-freezing temperatures, the engine is required to produce a greater amount of the power as requested by the driver. Other studies have shown that cold ambient temperature may have a more detrimental effect on fuel consumption of production HEVs compared to conventional vehicles [2].

While most current production HEVs employ NiMH battery technology, Li-ion technologies are the preferred choice for PHEVs. The impact of sub-freezing temperature on Li-ion battery performance has been studied, and a decrease in performance due to control restrictions on battery regeneration and increased internal resistance has been identified [3]. Thus, battery technology and control strategy are expected to play an important role in vehicle performance at cold temperatures.

2 Dynamometer Evaluation

A Hymotion Prius PHEV was tested in a climatically controlled chassis dynamometer test facility to evaluate the impact of sub-freezing temperatures on fuel consumption, electrical energy consumption, charge depletion range, emissions, and overall plug-in hybrid powertrain operation. The tests were performed using an 8.65” twin roll electric chassis dynamometer. Target coefficients were obtained from the U.S. EPA for warm and cold temperature testing, and coast down verification procedure was conducted on the dynamometer to obtain the set coefficients. A Hioki 3193 power meter was used to measure current and voltage of the A123Systems battery pack and the combined current and voltage of the A123Systems pack and production Prius NiMH battery. The Hioki 3193 integrates Ah and kWh in real time. The vehicle was instrumented with thermocouple sensors to measure interior, engine oil, and pre- and post- catalyst temperatures. Engine speed was determined based on the frequency obtained from the spark plug coil pack.

A CAN bus data acquisition system from A123Systems was used to record parameters including state of charge (SOC) for both batteries, temperatures, vehicle speed, and engine speed. The sampling frequency using this system was 2 Hz for most of the parameters.

Exhaust was collected, diluted, and analyzed using a CVS exhaust emissions sampling system and analyzer bench. The emission rates of THC, CO, CO_2, and NOx were determined by collecting a proportional sample of the dilute exhaust in Tedlar® bags and analysing the contents using a flame ionization detector (for THC), non-dispersive infrared instruments (for CO and CO_2) and a chemiluminescence instrument (for NOx). Dilute exhaust gas concentrations were also analyzed by these instruments on a second by second basis. Methane was analyzed using gas chromatography, and used to determine NMHC. Fuel consumption was determined by carbon balance.

2.1 Vehicle Description

The Hymotion Prius PHEV was selected for this study. This PHEV is based on a conventional Toyota Prius, but has been equipped with an additional 5 kWh battery system consisting of A123 Li-ion cells. An actively controlled DC-DC converter provides power from the Li-ion battery system to the hybrid high-voltage bus of the Prius to enable charge depletion operation. Once the Li-ion battery has been fully depleted, the vehicle operates in charge sustaining mode using the NiMH battery. Figure 1 shows a schematic of the Hymotion battery system and its connection to the production Prius powertrain. The vehicle tested during this study was a demonstration version. A production version is now available in North America.

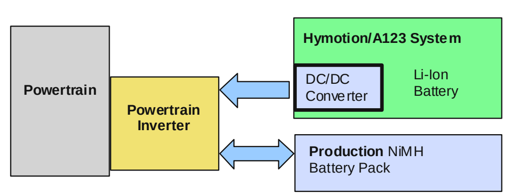

Figure 1: Hymotion PHEV battery system schematic

Figure 2: Hymotion Prius PHEV in Sub-Freezing Dynamometer Test Facility

2.2 Dynamometer Experiment Description

The vehicle was tested using two standard dynamometer test cycles developed by the U.S. EPA: the UDDS, and the HWFET. The UDDS was developed to simulate low speed urban driving with mild accelerations, and is currently used for determining emissions compliance in North America. The cycle has an average speed of 32 km/h and a maximum speed of 91 km/h. The HWFET, or highway fuel economy test, represents free-flow highway driving conditions and has an average speed of 78 km/h and maximum speed of 96 km/h. These cycles are shown in Figures 3 and 4.

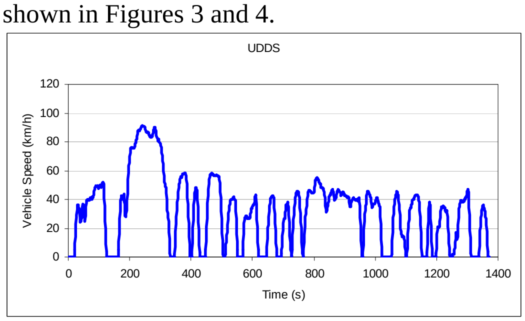

Figure 3: Speed versus time sequence for UDDS

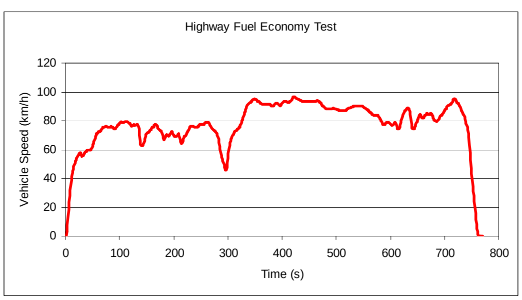

Figure 4: Speed versus time sequence for HWFET

Tests were conducted at temperatures of 22°C, -7°C, and -18°C. The following sets of tests were completed at each temperature:

- HWFET repeated in charge depletion mode until the A123Systems pack was fully depleted (full charge test)
- UDDS repeated in charge depletion mode until the A123Systems pack was fully depleted (full charge test)
- UDDS (cold-start and hot-start) and HWFET in charge sustaining mode
- Maximum heat and defrost tests; UDDS and HWFET in both charge depleting and charge sustaining modes

Prior to each set of tests, the vehicle was soaked for a minimum of 12 hours at the appropriate ambient test temperature. The A123Systems Li-ion pack was fully charged during the soak period prior to PHEV tests. AC charger current and voltage were recorded during charging. Between test repeats, the vehicle was soaked for 20 minutes at the ambient test temperature. Vehicle preconditioning for UDDS tests consisted of a UDDS in HEV mode (Li-ion pack disengaged). Each HWFET included a warm-up in HEV mode followed immediately by a test in PHEV mode.

2.3 Discussion of Dynamometer Test Results

Fuel and electrical energy consumption were strongly correlated to engine temperature and engine-on time, while pollutant emission rates were influenced by these factors as well as catalytic converter temperature. Results of five consecutive UDDS cycles at -7°C ambient temperature are given in Figure 5. Engine temperature rose continuously during the first UDDS. Although electrical energy was consumed at a rate of 172 DC Wh/mi, the IC engine was running for 1260 seconds of the 1340 second cycle; all-electric drive was disabled while the NiMH battery warmed up.

Engine-on time was much lower during the second and third UDDS cycles, and the rate of electrical consumption was higher while fuel consumption was lower. Differences in engine and catalytic converter temperatures may account for the increased THC emission rate on UDDS 3 compared to UDDS 2. UDDS 3 had slightly cooler starting temperatures because of the low engine-on time during the previous cycle (UDDS 2).

The Li-ion battery was fully depleted at 11.7 km into UDDS 3 (0.35 km from the end of the cycle), and thus UDDS 4 and UDDS 5 had increased engine-on time and fuel consumption rates, with only the NiMH battery to provide electrical energy. Reasonably steady-state engine operating temperature was not achieved until the end of UDDS 4. Due to the low engine-on time during UDDS 3, the engine temperature was lower at the start of UDDS 4 compared to UDDS 5, and this caused an increased fuel consumption rate on UDDS 4. Not only can changes in operating mode influence fuel consumption, but the timing of these changes (beginning / middle / end of a cycle) could have an impact on fuel consumption and emissions results.

A summary of fuel and electrical energy consumption rates is given in Figure 6. Electrical energy consumption is for the Li-ion pack and does not include electrical energy in and out of the NiMH pack. Efficiency generally decreases at lowered ambient temperatures, with more energy consumed overall. This effect is most apparent on the UDDS as opposed to the HWFET where the engine and vehicle component temperatures are raised over a warm-up drive, and then maintained thanks to the high speeds of the highway cycle. The rate of electrical energy use was similar at 22°C and -7°C, but was diminished at -18°C and during cold-start at -7°C. The power required from the Li-Ion pack was reduced by the control system at these lower temperatures, and all-electric drive was disabled. The use of maximum heat and defrost at cold ambient temperature further decreased the overall efficiency and raised fuel consumption rates by 2 – 20% under most conditions. The increase in fuel consumption was more pronounced when the base case had very little engine-on time and the high auxiliary load caused more frequent engine operation (i.e. UDDS 2 at -7°C has very low fuel consumption relative to the corresponding max heat and defrost scenario).

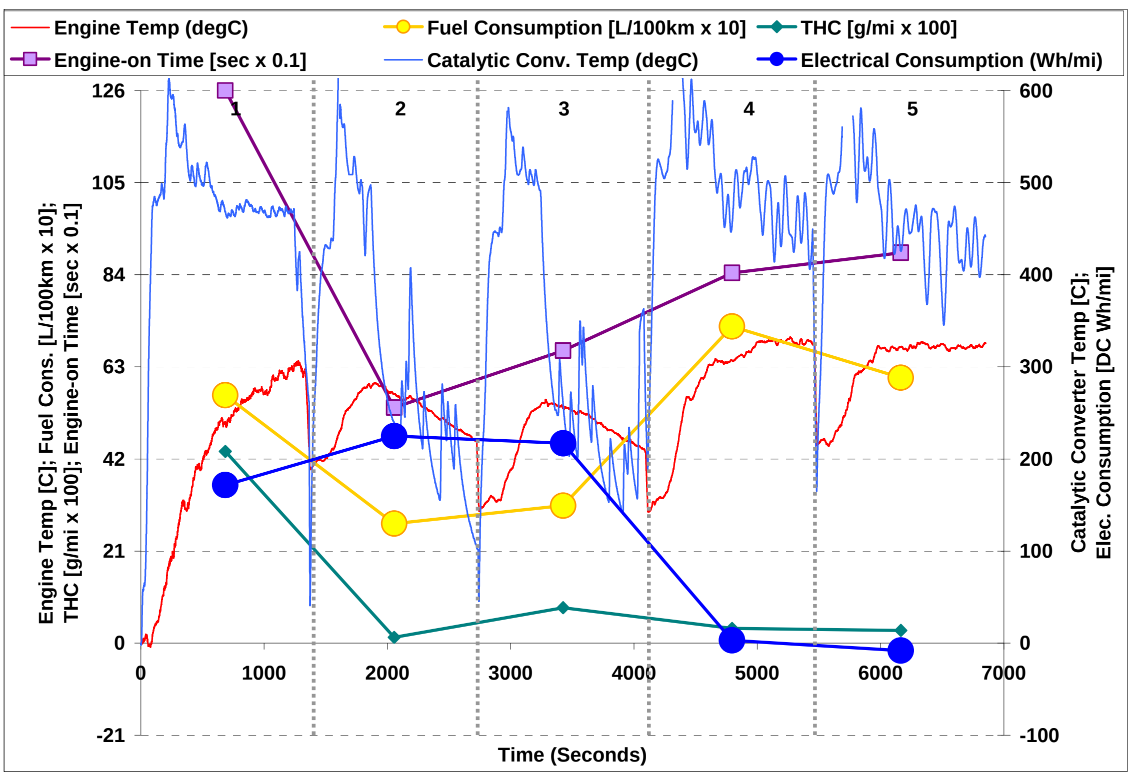

Figure 5: Hymotion Prius PHEV fuel and electrical energy consumption, THC emission rate, engine and catalytic converter temperatures over five consecutive UDDS cycles at -7°C ambient temperature

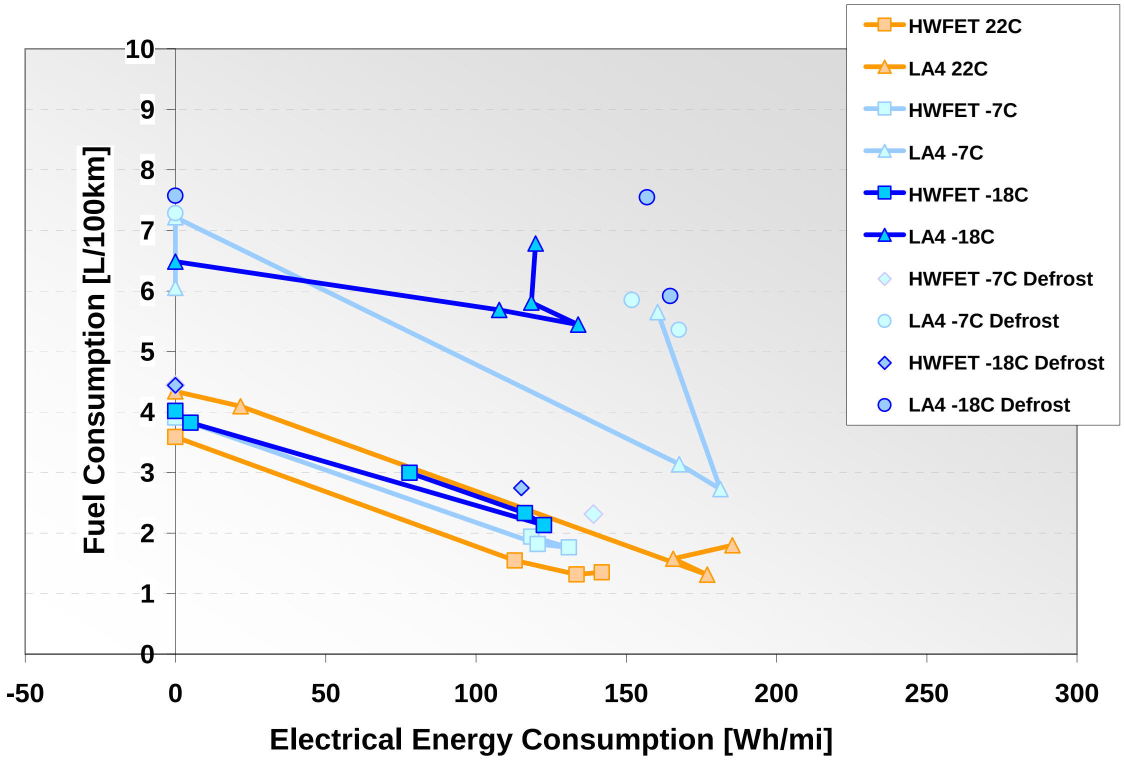

Figure 6: Energy consumption of a Hymotion Prius PHEV from dynamometer testing under highway and urban driving conditions at ambient temperatures of 22°C, -7°C, and -18°C

Charging efficiencies, charge depletion ranges, and equivalent all electric ranges are shown in Table 1. The blended charge depletion range was similar at 22°C and -7°C, but increased substantially at -18°C due to the lower rate of electrical energy use. Electric range fraction and equivalent all electric range, as defined by the California Air Resources Board (CARB) [4], decrease substantially with decreasing temperature.

Charging rate was slower at -18°C, with the Li-ion pack taking up to 6.3 hours to fully charge. The battery usable capacity decreased with decreasing temperature as well, with total energy discharged by the Li-ion pack decreasing by as much as 18% at -18°C. Round trip efficiencies based on the energy charged vs. energy provided to the powertrain ranged from 67% to 79%.

Figure 7 shows engine-on times and pollutant emission rates over consecutive UDDS cycles. Emission rates of CO and THC were highest during cold-start at cold ambient temperature, and decreased drastically following the cold-start cycle. Although cold ambient temperature cools the engine and catalytic converter, increased engine-on time at -18°C resulted in lower CO and THC emission rates in later cycles. Conversely, the NO_x emission rate was increased due to increased IC engine operation at -18°C.

Figure 8 shows engine-on time and emissions over 4 consecutive HWFETs at 22°C and -7°C. Due to the decreased electrical consumption rate at -18°C, only 5 consecutive HWFETs were required to deplete the Li-ion battery. Emission rates of CO and THC are much lower under highway driving conditions as a result of higher engine and catalytic converter temperatures. NO_x emissions were increased under conditions of high combustion temperatures and/or low catalytic converter temperatures.

Table 1: Charging efficiencies and charge depletion ranges

	HWFET			UDDS		
Ambient Temperature (°C)	**22**	**-7**	**-18**	**22**	**-7**	**-18**
Charge Depletion Distance (km)	48.7	48.2	49.6	37.5	35.6	45.1
Electric Range Fraction (%)	60.8	52.9	35.1	49.4	36.6	19.2
Equivalent All-Electric Range (km)	30.1	26.2	23.2	23.7	13.2	9.2
Hymotion Electrical Energy Use (DCkWh)	4.0	3.8	3.3	4.1	3.8	3.5
Charging Energy (ACkWh)	5.1	5.2	4.7	5.2	5.1	5.3
Round Trip Efficiency (%)	78	73	71	79	75	67
Charging Time (Hours)	5.1	5.4	6.0	5.2	5.0	6.3

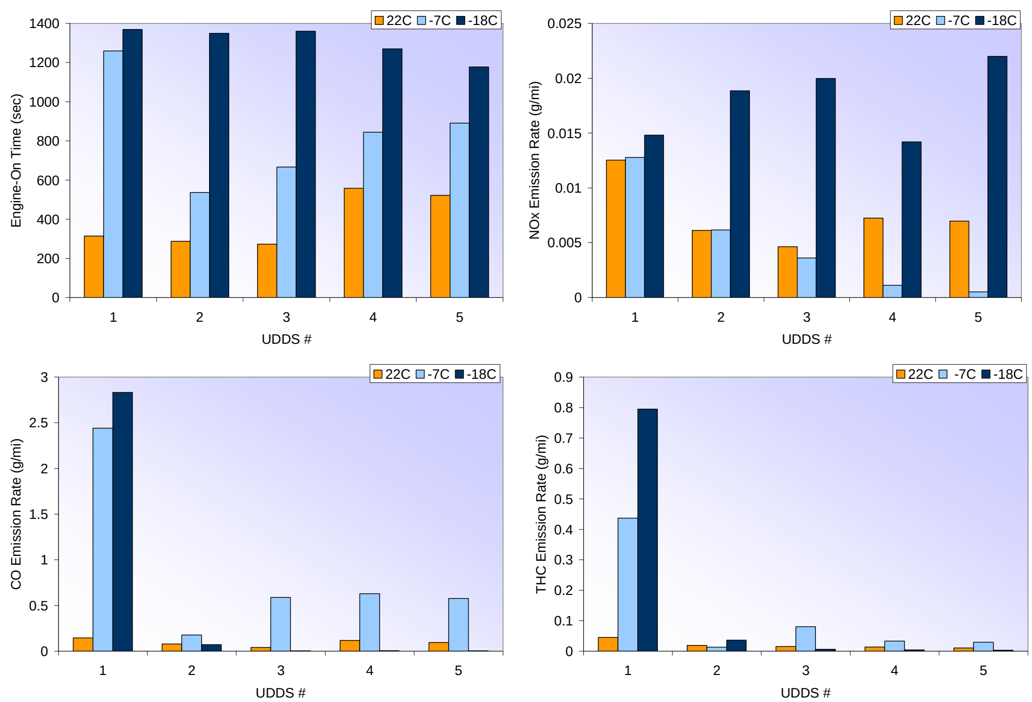

Figure 7: Engine-on time and emission rates of THC, CO, and NOx over consecutive UDDS repeats on the chassis dynamometer at 22°C, -7°C, and -18°C

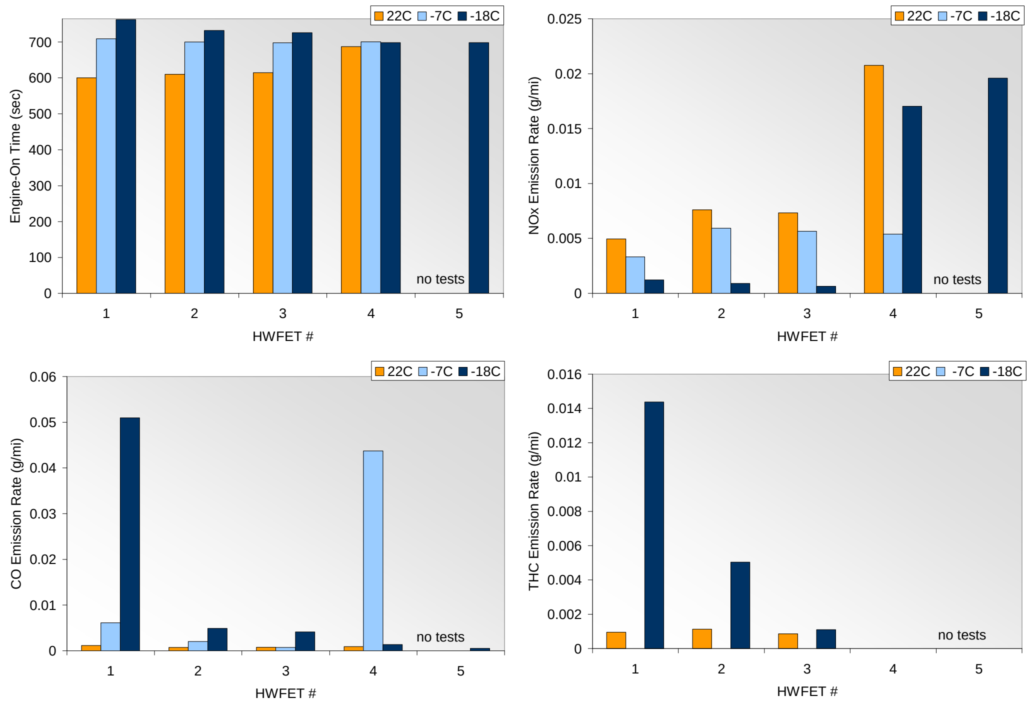

Figure 8: Engine-on time and emission rates of THC, CO, and NOx over consecutive HWFET repeats on the chassis dynamometer at 22°C, -7°C, and -18°C

3 On-Road Testing

Testing was also conducted on-road during ambient temperatures below freezing. The ambient temperature range was between -15°C and -5°C. This testing on-road, though not as accurate as the dynamometer testing, can be correlated to the dynamometer testing due to good repeatability, similar driving intensity, and similar ambient temperature.

3.1 Vehicle Description

A Hymotion Prius PHEV and a Hymotion Escape PHEV (Figure 9) were tested in subfreezing temperatures to determine the impact of battery performance on fuel consumption. The Hymotion Prius tested in this on-road evaluation has the same components and sizing as the Hymotion Prius tested in the dynamometer facility. This demonstration version did, however, have a slightly different control strategy.

The Hymotion Escape PHEV is a conversion PHEV based on a Ford Escape Hybrid. The vehicle has the same basic architecture as the Hymotion Prius but a larger capacity battery which in turn is able to provide higher power. The Hymotion Escape uses the Ford Escape Hybrid NiMH battery system and adds in parallel an additional 8-kWh Li-ion battery comprised of A123 Li-ion cells. An actively controlled DC-DC converter transfers power from the Li-ion battery system to the hybrid high-voltage bus to enable charge depletion operation.

Figure 9: Hymotion Prius PHEV and Hymotion Escape PHEV

3.2 On-Road Experiment Description

On-road testing was conducted at subfreezing conditions. The testing procedure closely imitates the dynamometer test procedures in terms of vehicle temperature preparation. The vehicles are cold soaked outside overnight for more than 12 hours before testing to allow the entire vehicle to approach steady-state temperature. The vehicle is also fully charged with the charge event ending in the early evening such that charging is not occurring during the soak period 12 hours before the beginning of the start of the test the next morning. The driving test cycle, called the "Argonne City Cycle", is similar to the UDDS cycle. Both are shown in Figure 10. For the Argonne City Cycle, typical speeds are 50 km/h, and accelerations are mild. Each cycle or driving loop is 5.3 km long and lasts approximately 10 minutes. The cycle is repeated six times to provide enough time and distance for all of the vehicle systems to approach steady-state operating temperature. Because this on-road driving cycle had been used previously and found to have good repeatability for on-road testing [1], it can again be used with a certain level of confidence to provide good experimental results for comparison to the highly precise dynamometer testing performed. This repeatability is achieved by pre-described accelerator pedal angles for all vehicle accelerations. Also the driving route does not involve traffic lights since this will introduce significant variability in rest time between driving.

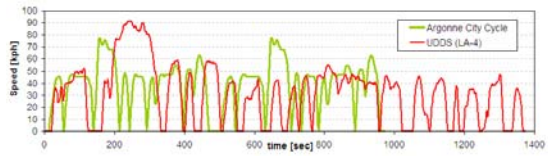

Figure 10: Argonne City Cycle comparison to UDDS (LA4) Cycle

A CAN bus data acquisition system was used to record several dozen parameters at 10 Hz from the vehicle's CAN bus. The channels included battery current, battery voltage, temperatures, vehicle speed, and engine speed. Fuel economy and distance traveled were manually recorded from the dashboard display throughout the testing. Benchmark testing was conducted over several ambient temperatures from -15°C to 22°C on the Argonne City Cycle. Fuel and electrical energy consumption was calculated. Additional testing was conducted to isolate the impact of the battery temperature on the same parameters. This was accomplished by maintaining battery temperature at 15°C during the cold soak period such that the battery is at normal operating temperatures during the testing. This temperature regulation was accomplished by a small heater around the battery (both the Hymotion and the NiMH). This temperature regulation was only on during the soak period, not during testing.

3.3 Discussion of On-Road Testing Results

All testing was conducted after the vehicle was fully charged and cold soaked overnight (>12 hours). Testing was conducted at temperatures ranging form -15°C to 22°C but the following discussion will focus on the testing performed at -5°C. After the soak period, the powertrain, driveline, and battery system temperatures were all –5°C (+/–2°C) at the beginning of the test. A sample result from the -5°C ambient condition testing of the Hymotion Prius is shown in Figure 11. The fuel consumption decreased rapidly at the beginning of the test but it quickly began to approach the steady state charge depletion fuel consumption of 2.3 L/100km after completing two cycles of the Argonne City Cycle driving loop. The fuel consumption varies but is generally lower after the 32 km of driving while the electrical energy consumption increases. This result closely correlates to the results seen in Figure 4 from the -7°C dynamometer testing (UDDS) of the Hymotion Prius. This correlation is expected since the vehicles, ambient temperatures, and driving cycles are similar.

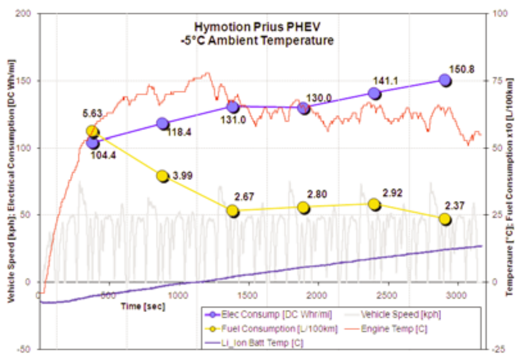

Figure 11: On-road test of Hymotion Prius, cold soaked at -5°C before testing

The same on-road testing was conducted for the Hymotion Escape PHEV. The results from testing at -5°C for the Hymotion Escape are shown in Figure 12. Similarly to the Hymotion Prius, the fuel consumption on the Hymotion Escape decreased rapidly at the beginning of the test but slowed as it approached the steady state fuel consumption of 5.0 L/100km near the end of the 32 km Argonne City Cycle driving loops.

The engine coolant temperature nearly reached steady state operating temperature after about 5.6 km of driving. This correlates to the quick decrease in fuel consumption at the beginning of the test. The battery temperature on the other hand was still rising at the end of the 1-hour test. This correlates to the slow asymptotic decrease in fuel consumption over the remainder of the test.

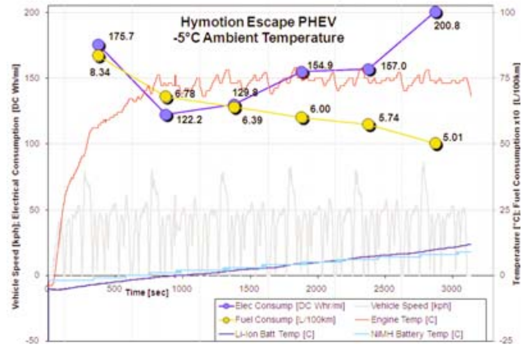

Figure 12: On-road test in which entire vehicle was cold soaked at -5°C before testing

The results for the on-road testing are shown on Figure 13 for the Hymotion Escape PHEV and the Hymotion Prius PHEV for various ambient temperature conditions. As the ambient temperature increases from -15°C to -5°C to 5°C, notice how the electrical depletion rate increases and the fuel consumption rate decreases for the Hymotion Escape PHEV. This is due to powertrain temperature and battery temperature effects. The cold start cycles are indicated on the figures and show significantly increased fuel and energy consumption. The Hymotion Prius PHEV shows a similar trend to the Hymotion Escape except as the temperature transitions from -5°C to 30°C only a decrease in fuel consumption is seen without an increase in electrical energy consumption.

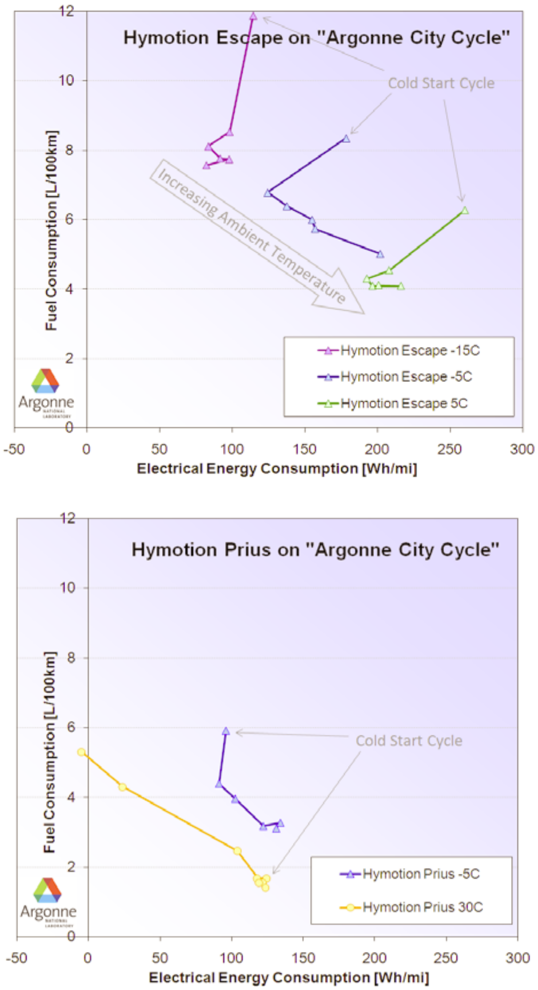

Figure 13: On-Road test results of a Hymotion Prius and Hymotion Escape

3.4 Battery temperature impact on fuel consumption

Additional testing was conducted to isolate the impact of the battery temperature on the fuel and electrical energy consumption. This was accomplished by maintaining battery temperature at 15°C during the cold soak period such that the battery begins at normal operating temperature for the testing which means the battery has full power capability at the start of the test. This temperature regulation was accomplished by a small heater around the battery (both the Hymotion and the NiMH). This temperature regulation was only used during the soak period, to prepare the battery for the testing sequence. Figure 14 shows the results from Figure 13 with the addition of the testing incorporating the warmed battery. For testing with the cold initial battery and warm initial battery, the engine warm-up can be seen by the dramatic decrease in fuel and electrical energy consumption from the first cycle to the second cycle. For the warm initial battery tests, the subsequent cycles resulted in reasonably consistent fuel and electrical energy consumption. In contrast the testing with the cold soaked battery shows progressively decreasing fuel consumption with increased electrical energy consumption.

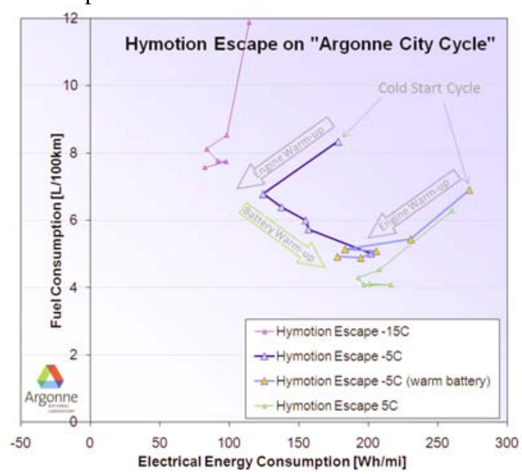

Figure 14: Fuel consumption of the Hymotion Escape with the battery cold soaked and warm soaked

To fully quantify this fuel consumption impact of the battery temperature as compared to the impact of the powertrain warm-up and driveline warm-up, Figure 15 shows the percent increase in fuel consumption over steady-state fuel consumption at -5°C. For an ambient temperature of -5°C, the steady-state charge depleting fuel consumption is 5.0 L/100km, and the electrical energy consumption is 200 DC Wh/mi.

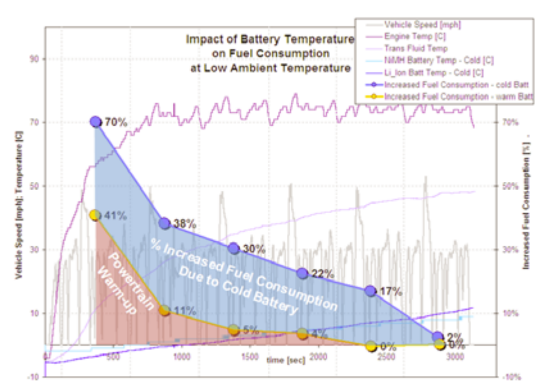

Figure 15: Fuel consumption differences between the cold and warm battery tests

For the first test cycle, the increase in fuel consumption was 70% when the entire vehicle starts from a steady state temperature of -5°C. With the experimental testing (initial battery temperature maintained at 15°C), the increase in fuel consumption for the first cycle is only 41%. This is due to the increased inefficiency of powertrain and driveline during the warm-up period at sub-freezing temperatures. The difference between the two sets of tests, shown in blue, is the effect of battery system operating at sub-freezing temperatures. As the engine quickly warms up, the fuel consumption impact rapidly decreases as seen in both tests. Once the engine is at steady-state operating temperature, which takes approximately ten minutes to reach, the transmission and driveline cold inefficiencies cause the remaining fuel consumption impact as they continue to warm-up towards steady state temperature. In contrast the rise in the battery system temperature from -5°C to 10°C is fairly slow, approximately one hour, which made the fuel consumption impact from the battery temperature a more prolonged effect than the powertrain warm-up impact. Even after the hour of testing the battery system had not reached steady state temperature but the battery power had reached full power capability once battery temperatures reach 10°C.

Comparing the engine on/off operation, the two tests were nearly the same, but the fuel consumption and the electrical energy consumption were quite different as shown previously. This dramatic impact is likely to be highly dependent on battery chemistry as it relates to cold temperature performance. This vehicle uses the production battery calibration in the Escape powertrain control system to protect the NiMH battery at sub-freezing conditions since it has reduced power capability at sub-freezing temperatures. The added cold temperature performance benefits from the Li-ion battery system could not be fully utilized with this NiMH battery calibration.

4 Comparison of Dynamometer and On-Road Test Results

Both on-road testing and chassis testing of the Hymotion Prius PHEV showed increasing fuel consumption rates during charge depletion operation as ambient temperatures decreased and unchanged electrical consumption rates between -7°C / -5°C and 22°C / 30°C. Chassis testing, however, showed a decreased rate of electrical consumption at -18°C and during cold-start at both -7°C and -18°C. The electrical contribution was limited at these colder temperatures.

During charge depletion operation at -5°C / -7°C, after the engine warm-up period is complete, the engine coolant typically operates under 60°C due to minimal engine utilization. This was seen both on the UDDS cycle as well as during the on-road testing. This low temperature operation of the engine due to minimizing fuel consumption may cause an undesired effect of decreased engine efficiency. This impact needs to be studied in more detail to investigate if an optimized trade-off can be achieved. This trade-off is between minimizing fuel consumption and emissions by maintaining high engine and catalytic converter operating temperatures and minimizing fuel consumption through reduced engine operation.

Charge depletion range was similar for the Hymotion Prius PHEV when driven on the UDDS cycle on the chassis dynamometer, and on the Argonne City Cycle on-road due to the similarity in the driving intensity, ambient temperature, and initial conditions. The on-road testing did show significantly more variability than the dynamometer testing, as expected, due to variations in temperature, driver demand and on-road surface and grade variations.

5 Summary

Cold ambient temperature significantly impacts PHEV fuel consumption and emissions during charge depletion operation. Some of the increase in fuel consumption is due to inherent engine and powertrain warm-up characteristics that are common for all vehicles. This study also observed a fuel consumption increase due to limited battery power capabilities and usable capacity at cold ambient temperatures. This effect is highly dependent on the battery chemistry and cold temperature performance of the battery system. For the Hymotion Escape tested in this study, this impact was highly dependent on the limitations of NiMH battery power capabilities at very low temperatures. With advanced Li-ion batteries and sophisticated controls, this detriment may be reduced or nullified.

Fuel consumption and electrical energy consumption are strongly correlated to engine-on time and engine temperature, while pollutant emission rates are influenced by these parameters as well as the catalytic converter temperature. Changes in operating mode, and the timing of these changes, may cause temperature to vary from one repeat of a test to another, and this will impact fuel consumption and emissions test results.

The A123 Li-ion pack used in the Hymotion Prius PHEV and the Hymotion Escape PHEV performed well at subfreezing temperatures of -5°C and -7°C. The electrical energy consumption rate was reduced, however, at -18°C and under cold-start conditions at -7°C.

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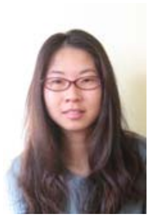

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