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Battery Usage and Thermal Performance of the Toyota Prius and Honda Insight for Various Chassis Dynamometer Test Procedures

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K.J. Kelly, M. Mihalic, and M. Zolot

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Battery Usage and Thermal Performance of the Toyota Prius and Honda Insight during Chassis Dynamometer Testing

XVII. The Seventeenth Annual Battery Conference on Applications and Advances

Kenneth J. Kelly, Mark Mihalic, Matthew Zolot

National Renewable Energy Laboratory, 1617 Cole Blvd, Golden, CO 80401

ABSTRACT

This study describes the results from the National Renewable Energy Laboratory's (NREL) chassis dynamometer testing of a 2000 model year Honda Insight and 2001 model year Toyota Prius. The tests were conducted for the purpose of evaluating the battery thermal performance, assessing the impact of air conditioning on fuel economy and emissions, and providing information for NREL's Advanced Vehicle Simulator (ADVISOR). A comparative study of the battery usage and thermal performance of the battery packs used in these two vehicles during chassis dynamometer testing is presented. Specially designed charge and discharge chassis dynamometer test cycles revealed that the Insight limited battery usage to 60% of rated capacity, while the Prius limited battery usage to 40% of the rated capacity. The Prius uses substantially more pack energy over a given driving cycle but at the same time maintains the pack within a tight target state of charge (SOC) of 54% to 56%. The Insight does not appear to force the battery to a specific target SOC. The Prius battery contributes a higher percentage of the power needed for propulsion. The study also found that while both vehicles have adequate battery thermal management systems for mild driving conditions, the Prius thermal management is more robust, and the Insight thermal management limits pack performance in certain conditions.

Introduction

The National Renewable Energy Laboratory (NREL) purchased a 2000 model year Honda Insight and 2001 model year Toyota Prius for the purpose of evaluating the battery thermal performance, assessing the impact of air conditioning on fuel economy and emissions, and providing information for NREL's Advanced Vehicle Simulator (ADVISOR). NREL's HEV program consists of three core areas: 1. Battery Thermal Management, 2. Vehicle Systems Analysis, 3. Auxiliary Loads Reduction. The testing featured in this study includes input from and contributes to all three aspects of the program. The focus of this paper is on the results relating to battery usage and battery thermal management in these vehicles.

Hardware Description

The Honda Insight and Toyota Prius were the first two hybrid electric vehicles (HEV) commercially available in the United States. These two vehicles have some very basic similarities – both combine power from a gasoline engine with an electric motor and a nickel-metal hydride (NiMH) battery pack to provide motive force. The differences in the vehicle designs are numerous and are described in detail in a number of publications (1,2). A few important features are described below.

The Honda Insight is a light-weight (856 kg curb weight), two-passenger hatchback powered by a 50 kW gasoline engine with additional assist power provided by a 10 kW electric motor. The Insight has a parallel HEV configuration. The electric motor is coupled directly to the drive shaft of the engine and provides additional power for relatively hard accelerations. It also operates as a generator to recapture kinetic energy during deceleration and helps balance vibrations of the in-line three-cylinder, 1.0-liter engine.

The Toyota Prius is a five-passenger compact sedan powered by a 52 kW gasoline engine and a 33 kW electric motor. It has a curb weight of 1254 kg. The Prius has a more complex dual-mode hybrid configuration where energy to and from the vehicle wheels can travel along several different pathways. Mechanical energy to the wheels passes through a planetary gear set that couples the engine, electric motor, and generator to the final drive. Power to the wheels can be provided solely by the battery pack through the electric motor, directly from the gasoline engine to the wheels, or from a combination of both the motor and the engine. The battery pack can be recharged directly by energy taken from the wheels through the generator (regenerative braking) or from excess energy from the gasoline engine (also turning the generator).

One of the most important components for this study is the battery pack. Both vehicles have nickel-metal hydride battery packs comprised of a number of 1.2 V cells with a 6.5 Ah capacity. The Honda Insight has a smaller pack that consists of 20 modules, each having six D-sized spiral-wound cells (see Figure 1). The total pack nominal voltage is 144 V. The total energy capacity of the Insight Pack is 936 Wh. The ends of the 20 D-sized modules can be seen in Figure 1. Also shown are the fan and the outside of the ducting that directs cabin air across the modules for cooling. The geometry of the module holders directs cooling air between all of the modules (3).

The larger Prius battery pack is a later generation NiMH design that consists of 38 prismatic modules, each having six, 1.2 V cells. The total pack nominal voltage is 273.6 V. The total energy capacity is 1778.4 Wh. Figure 2 shows the Prius pack with the 38 prismatic modules as they are arranged in the pack. Forced cabin air flows around and between the modules in air spaces between each module.

Variable cross-sectional area air plenums are used to maintain constant air flow rates to all the modules (4).

Figure 1 – Honda Insight Battery Pack

Figure 2 – Toyota Prius Battery Pack

Additional specifications for the Insight and Prius battery packs are summarized in Table I below.

Table I – Battery Pack Specifications

	Insight	Prius	Units
Battery Type	Ni-MH	Ni-MH	-
Nominal Cell voltage	1.2	1.2	V
Rated capacity	6.5	6.5	Ah
Cells per module	6	6	-
Number of modules	20	38	-
Total voltage	144	273.6	V
Nominal energy storage	936	1778	Wh
Module Mass	1.09	1.04	kg
Pack mass*	35.2	53.3	kg

** Note that the pack mass includes the enclosure and packaged power electronics.*

Test Procedures

The tests covered in this paper were conducted with the vehicle on a chassis dynamometer following standard EPA test procedures (5). The chassis dynamometer test procedures included the following:

a) FTP-75 (EPA urban emissions certification test procedure – also used for city fuel economy estimate)
b) Highway Fuel Economy Test (HWFET)
c) US06 aggressive driving cycle performed at 0°C, 20°C, and 40°C
d) SC03 air conditioning cycle performed at 95°F with and without air conditioning.

In addition to the procedures listed above, a dynamometer procedure for charging and discharging the battery pack was also conducted (6). All of the tests were performed at Environmental Testing Corporation (ETC) in Aurora, CO, using its 48-inch electric chassis dynamometer.

Vehicle and component instrumentation included measurement of battery module temperatures, module voltages, pack current, air coolant temperatures, interior cabin temperatures, vehicle speed, and pack fan power. Vehicle speed, torque, and analysis of exhaust gases were measured continuously by ETC. Data was collected continuously over the cycle at a rate of 20 Hz. Additional detail on the vehicle instrumentation is provided in several previously published reports (3,4,6).

Discussion of Results

Charge and discharge cycles - As mentioned previously, a special procedure was designed for charging and discharging the battery pack while onboard the vehicle. This procedure used the motoring capability of the electric dynamometer to charge the batteries by spinning the vehicles' wheels at 50 mph to simulate coasting down a long descending grade with the vehicle in gear. Discharging was achieved by attempting to overcome the dynamometer loading while accelerating at full throttle. This is somewhat similar to attempting to climb a steep incline at high speed.

For both the Insight and the Prius, the charge/discharge procedure quickly revealed the control limits and useful battery capacity for each vehicle. In these tests, the Prius limited the battery usage to approximately 40% of the rated capacity, and the Insight limited the battery usage to approximately 60% of the rated capacity.

The discharge cycle (Figure 3) was started with the pack at the full usable SOC. During the discharge cycle, the Prius pack provided between 15 and 19 kW to the motor to quickly discharge 2.65 Ah (40.1% of the rated capacity). After this point was reached, the vehicle control system no longer allowed current to be drawn from the pack to power the electric motor. Using the same discharge procedure, the Insight pack provided a constant 6 kW to the motor for the first 200 seconds of the cycle, when the battery SOC had reached approximately 36%. At this point, power to the motor tapered down to less than 1 kW until 3.7 Ah (57% of the rated capacity) was removed from the pack.

The charge cycle was started with the battery at the minimum useable SOC. During the charging cycle, the Prius generator supplied 6.4 kW to the pack for nearly 500 s to charge the pack by 2.92 Ah (45% of rated capacity). The Insight charged the battery at a constant power 4.8 kW for 528s.

A total charge of 3.78 Ah (58% of rated capacity) was added to the pack. When the maximum SOC was reached in both vehicles, the control systems cut-off charge current to the pack. In the case of the Insight, when the charge and discharge cycle was repeated, additional power limiting was observed, which is apparently tied to battery pack temperatures (6). The same charge and discharge characteristics were later observed during on-road testing involving steep highway ascents and descents.

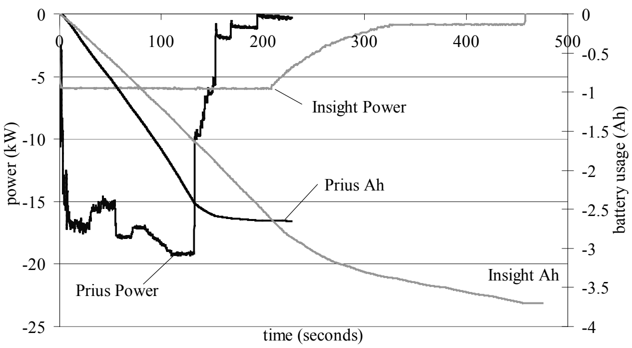

Figure 3 – Current and Ah during discharge cycle

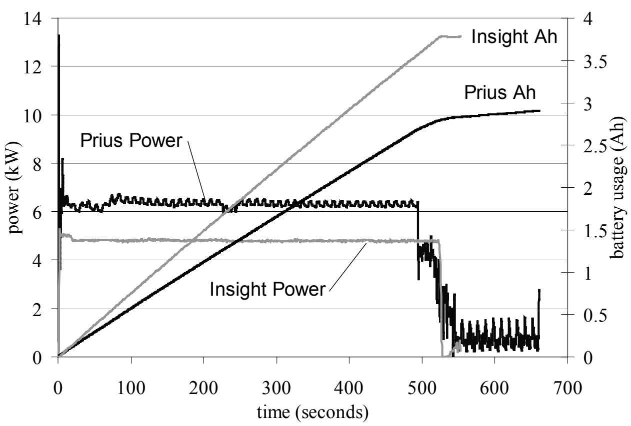

Figure 4 – Current and Ah during charge cycle

SOC control and target SOC – A striking difference in how the two vehicles are controlled was revealed from battery SOC information taken over various chassis dynamometer drive cycles. Figures 5 and 6 show SOC data for the Insight and Prius, respectively, while driving over the EPA's Urban Dynamometer Driving Schedule (UDDS), which is the first two phases of the FTP-75. The light gray line on both graphs is the vehicle speed for the cycle. The other three lines are the SOC profiles for three different initial SOCs. In the case of the Insight, the SOC profile is the same (parallel SOC profiles) regardless of the initial SOC. This means the vehicle behaved the same way in battery/motor usage despite different initial SOC values.

The Prius' behavior was much different. Figure 6 shows that the Prius tended to control battery usage in such a way that the SOC is forced to a target value of approximately 56% during the drive cycle. When starting at an SOC of 80%, the Prius tended to use the electric motor and discharge the battery much more than when the SOC is started within the target band. On the other hand, when starting at an SOC of 40%, the vehicle did not use the electric motor until the battery SOC reached the targeted SOC band (approximately 400 s into the cycle). During typical city or highway driving, the Prius tends to maintain the battery SOC within the narrow band shown here. It is only when the vehicle encounters aggressive driving conditions that it wanders outside of this target area.

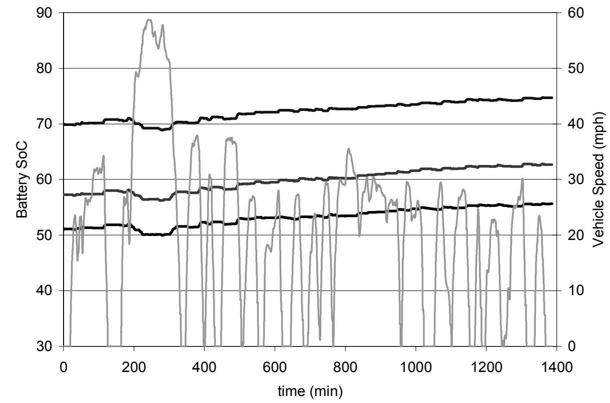

Figure 5 – Honda Insight SOC over the UDDS cycle with several initial SOCs

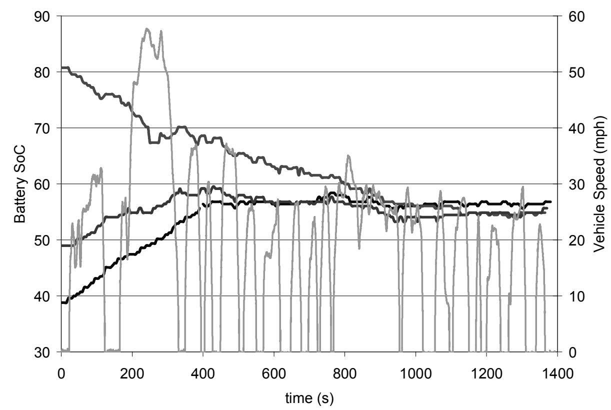

Figure 6 – Toyota Prius SOC over the UDDS cycle with several initial SOCs

Battery Energy use over various test cycles – For both vehicles, a resistive shunt was used to measure the amount of current in and out of the battery pack. Battery pack voltages were also measured. The total amount of energy transferred to and from the battery pack was found by integrating the power (voltage x current) over the cycle time. Table II shows the amount of energy drawn from the battery for vehicle propulsion (assist) and electrical auxiliaries, along with the amount of recharge energy returned to the pack, and the net pack energy for the various cycles. Negative values represent energy drawn from the pack. Also shown for each drive cycle is the cycle distance, measured fuel economy, fuel energy used (volume of fuel

Table II – Battery energy use data for the Honda Insight and Toyota Prius

Test Type	*Battery Energy (kJ)*				*Cycle distance (miles)*	*Fuel economy (mpg)*	*Fuel energy used (kJ)*	*Net energy / Fuel energy*	*Assist energy / Fuel energy*
	Assist	*Electric auxiliary*	*Recharge*	*Net*					
Insight									
FTP-75	-296.1	-296.0	615.7	23.6	11.1	64.0	2.07E+04	0.12%	1.45%
HWFET	-136.7	-170.9	325.8	18.2	10.3	79.0	1.55E+04	0.12%	0.88%
US06 0C	-547.7	-124.6	577.8	-94.5	8.0	49.8	1.92E+04	-0.49%	2.86%
US06 20C	-480.8	-160.9	495.1	-146.6	8.0	52.1	1.83E+04	-0.81%	2.63%
US06 40 C	-407.6	-260.5	585.6	-82.4	8.0	52.0	1.83E+04	-0.45%	2.22%
SC03 no AC	-181.5	-101.1	401.2	118.6	3.6	62.5	0.69E+04	1.65%	2.65%
SC03 with AC	-318.3	-534.6	804.7	-48.2	3.6	40.2	1.06E+04	-0.43%	3.00%
Prius									
FTP-75	-2468.3	-531.0	3232.3	232.9	11.1	53.1	2.52E+04	0.92%	9.78%
HWFET	-661.2	-202.4	659.2	-204.4	10.3	59.1	2.10E+04	-0.97%	3.15%
US06 0C	-1348.2	-249.8	1833.6	235.6	8.0	36.6	2.64E+04	0.89%	5.10%
US06 20C	-1440.5	-173.3	1701.3	87.5	8.0	41.8	2.32E+04	0.38%	6.22%
US06 40 C	-1689.2	-237.7	1941.5	14.6	8.0	40.3	2.40E+04	0.06%	7.03%
SC03 no AC	-788.1	-168.0	941.9	-14.2	3.6	53.3	0.81E+04	-0.17%	9.70%
SC03 with AC	-548.1	-419.9	853.6	-114.3	3.6	37.0	1.17E+04	-0.98%	4.68%

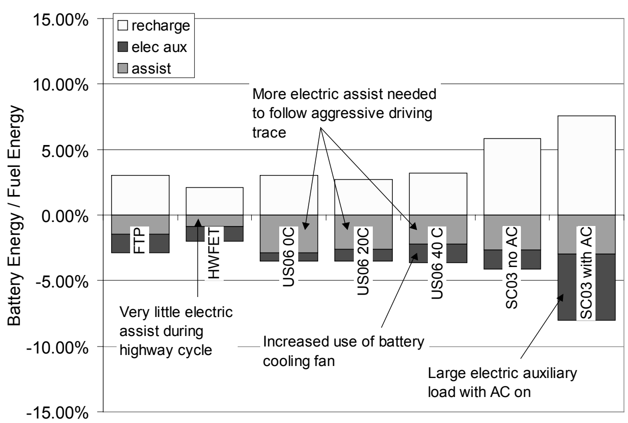

Figure 7 – Insight battery energy / fuel energy used (%)

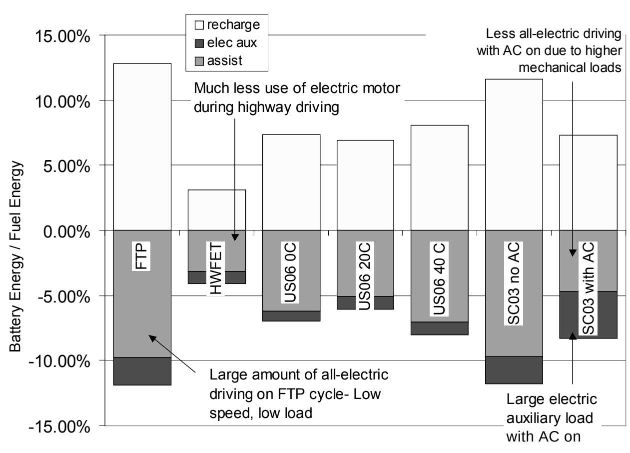

Figure 8 – Prius battery energy / fuel energy used (%)

used times the energy content of the fuel - Lower Heating Value = 31960 kJ/liter), net energy expressed as a percentage of fuel energy used, and assist energy expressed as a percentage of fuel energy used.

One way of displaying this information that combines many of the factors is shown in Figures 7 and 8 for the Insight and Prius, respectively. These figures show the battery energy (assist, auxiliary, and recharge) expressed as a percentage of total fuel used for each of the driving cycles. This calculated value takes into account the battery energy, fuel efficiency of the vehicle, and the driving distance of the different cycles. The dark negative bars in these figures represent the amount of energy drawn from the pack to power electric auxiliaries, the lighter gray portion of the negative bar is energy drawn from the pack to provide motive power, and the white positive bar is the amount of energy returned to the pack from regenerative braking and charging from the gasoline engine.

Comparing the two graphs, we see that the Prius battery contributes a higher percentage of the power needed for propulsion. Over the seven different cycles tested, the average assist energy was 6.7% of fuel energy for the Prius and 2.2% for the Insight. The Prius battery provided motive energy in the range of 3.1% of the fuel energy on the highway cycle and 11.0% on the city cycle. For the Insight, the battery provided a range of 0.9% of the fuel energy used on the highway cycle to 3.0% on the SC03 with the AC on.

These graphs also show how the battery energy changed for the different cycles. For both vehicles, the lowest amount of energy transferred to and from the pack occurred on the HWFET. This is expected since the highway cycle is primarily a cruising cycle at an average of 48 mph.

For a cycle-to-cycle comparison, the amount of energy transferred in and out of the pack was compared to the HWFET cycle on a per-mile basis (energy/miles). The Insight used 2x more pack energy on the FTP cycle than HWFET cycle, 3x more pack energy on the US06 cycles, 3.5x more energy on the SC03 without AC, and nearly 6x more energy on the SC03 with the AC on. The Prius used 3.6x more pack energy on the FTP cycle, between 2.6 and 3.3 times more energy on the US06 cycles, 3.4x more on the SC03 without AC, and only 2.4x more with the AC on.

The differences between how the two vehicles used pack energy on the different cycles point to important differences in the control strategies. The Prius has the capability to run all-electric during low-speed, low-torque conditions. During the FTP cycle, the Prius gasoline engine is shut off for 46% of the cycle time (20% of this is while the vehicle is stopped). The Insight only shuts the engine off during vehicle stops or at low-speed (below 20 mph) decelerations. This is one reason why the Prius uses much more battery energy on the FTP cycle than the Insight. Both vehicles have mechanically driven AC. For the Insight, when the AC is on, the extra mechanical load on the engine requires additional assist power in order to follow the driving trace; thus more battery energy is used for vehicle propulsion on the SC03 with AC than without AC. In contrast, the Prius operates in all-electric mode during the SC03 cycle with the AC off, but when the AC is on the engine is always operating – thus more battery energy is used for vehicle propulsion when the AC is off.

Battery thermal performance over the test cycles – An important aspect of the NREL testing was to gain an understanding of the effectiveness of the thermal management of the battery pack. As explained earlier, both vehicles use forced cabin air to help maintain battery temperature. The geometry of the battery casings and structures are used to direct cabin air across the individual modules. Specific elements of this structure are designed to direct flow in certain areas or to maintain a given flow rate (3,4). For both vehicles, NREL's battery thermal management team disassembled the pack and instrumented it with multiple thermocouples on each module. The effectiveness of these systems for keeping the pack within desired operating temperatures and maintaining an even distribution of temperature across the pack was evaluated by looking at the temperatures for the various cycles.

Figures 9 and 10 show individual module temperatures at different stages during the FTP-75 cycle (at the beginning of the test and at the end of the various test phases). For the Insight, the average pack temperature at the beginning of the FTP-75 was 28.4°C and the difference between the maximum cell temperature and the minimum was less than 1°C. By the end of the three-phase FTP the average temperature had risen to 30.9°C with a difference of 1.3°C across the pack.

For the Prius, the average pack temperature at the beginning of the test was 26.6°C with a difference of 2.3°C across the pack. By the end of the three-phase FTP cycle, the average pack temperature had risen to 31.2°C with a difference of 4.2°C across the pack.

For the FTP-75 cycle, we see that the Prius pack average temperature showed an increase of nearly 5°C, while the Insight average pack temperature rose by only 2.5°C. This is somewhat expected since the total energy exchanged, including charge and discharge energies, was about 5x higher for the Prius than the Insight. The energy provided per unit module in Prius is higher than the Insight. Thus, even for the same energy efficiency, more heat is generated in the Prius battery and thus slightly higher temperatures. For both vehicles, the battery temperature rise was fairly even from test phase to test phase during the procedure. In other words, the battery temperature did not increase dramatically during any given phase.

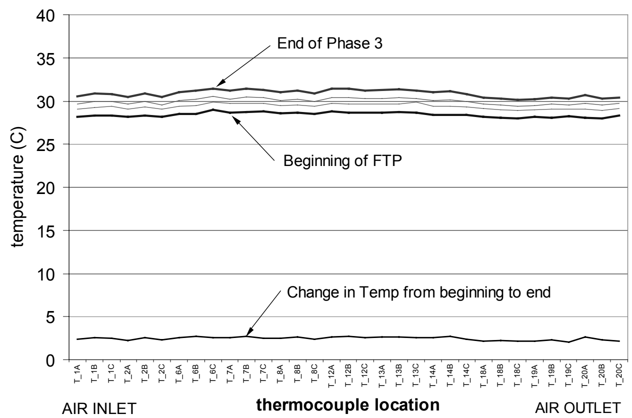

Figure 9 – Insight battery temperatures during FTP-75

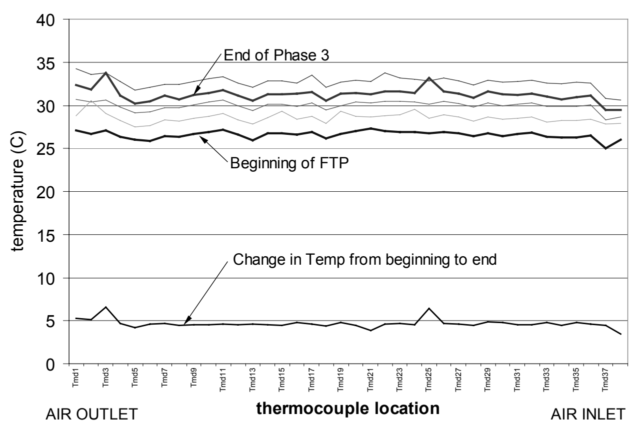

Figure 10 – Prius battery temperatures during FTP-75

As expected with the more aggressive US06 test (the US06 cycle includes much harder accelerations, decelerations, and higher speeds than the FTP-75), the changes in battery pack temperature were higher for both vehicles. Data from these tests include temperatures at the beginning of test procedure and at the end of two back-to-back US06 cycles. The first cycle was started at the soak temperature (0° C, 25° C, or 40° C), and the second cycle followed immediately after the first. Summary data is shown in Table III where T_{avg} is the average temperature across the pack, and T_{dist} is the difference between the maximum and minimum temperatures across the pack. For the 0°C tests, the increase in average temperature after the two cycles was higher for the Insight (15.3°C) than for the Prius (12.8°C). This is despite the fact that the Prius transferred 3x more energy than the Insight during the US06 cycle. For the Insight the temperature distribution across the pack increased by 1.3°C and for the Prius there was an increase of 1.1°C over the two cycles.

For the 40°C tests, the Insight average battery temperature increased by 7.5°C and the Prius temperature increased by 8°C. The temperature distribution across the pack actually decreased on the Insight from 3.8°C to 1.2°C, while the Prius pack temperature distribution remained the same (4.3°C) from beginning to end.

For the more aggressive US06 tests, the Prius battery thermal management system maintained about the same or lower pack temperature rises as the Insight despite using nearly 3x more energy than the Insight. This indicates that the battery thermal management system on the Prius is doing a good job dissipating heat energy.

Table III – Battery thermal performance on US06 cycle

	Insight		*Prius*	
	T_{avg}	T_{dist}	T_{avg}	T_{dist}
0°C soak tests				
Begin 0°C	-1.0	2.1	3.2	4.2
End 1st cycle	9.3	1.5	9.1	4.3
End 2nd cycle	14.3	3.4	16.0	5.3
40°C soak tests				
Begin 40°C	37.1	3.8	39.9	4.3
End 1st cycle	42.2	2.0	44.5	3.8
End 2nd cycle	44.6	1.2	47.9	4.3

Measurement of the battery pack fan power was added as an improvement to NREL's instrumentation of the Prius but was not included on the Insight. During NREL's off-board testing of the Prius pack, the battery thermal management team determined that the Prius pack fan has four distinct operating modes – off, low, medium, and high (4). During the chassis dynamometer testing, three of these modes were observed – off, low, and medium. For the FTP-75 testing of the Prius, the pack fan did not turn on at all. For the 0° C US06 cycles, the pack fan did not turn on. The fan came on low power (4-5 W) during warm-up phase of the 25° C US06 and switched to medium power (17 W) near the end of the test. During the 40° C US06 test, the pack fan was on low from the beginning of the test, then switched to medium power within 30 seconds and remained on medium through the rest of the test.

Conclusions

In this study, NREL's testing of the Honda Insight and Toyota Prius has revealed or quantified the results of a number of design differences that affect battery usage and thermal performance. These differences are due in part to the geometry and design of the packs but also in large part to the design of the vehicle and control systems. Both vehicles have 6.5 Ah NiMH battery packs, but the Prius pack is a later-generation prismatic design that is also significantly larger to account for the greater use of the car's electric motor. The Prius' 33 kW electric motor is used in a wider range of applications including all-electric propulsion under low-load, low-speed conditions. Testing showed that the Insight limited pack usage to approximately 60% of the rated 6.5 Ah capacity, while the Prius was limited to 40%. The Prius control strategy features a target SOC of approximately 56%. Use of the battery and electric motor are strongly influenced by this target. The Insight apparently has a much broader range in which the SOC is controlled and no single target SOC. The Prius uses substantially more battery energy over a given driving cycle. For the Prius, the amount of propulsion energy supplied by the battery was nearly 10% of the gasoline fuel energy used by the engine on the FTP cycle. The highest level of pack energy used by the Insight was 3% of the fuel energy for the SC03 cycle with AC. While both vehicles have an adequate battery thermal management system for mild driving conditions, the Prius design appears to be more robust and is capable of transferring larger amounts of heat away from the pack. The higher voltage in the Prius pack may also help reduce heat generation by reducing the current required to achieve a given power level. Follow-up testing is planned for the Prius during which a number of back-to-back repeats of the cycles described will be conducted to see how the battery performs during extended (two hour) cycles.

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13. ABSTRACT *(Maximum 200 words)*
This study describes the results from the National Renewable Energy Laboratory's (NREL) chassis dynamometer testing of a 2000 model year Honda Insight and 2001 model year Toyota Prius. The tests were conducted for the purpose of evaluating the battery thermal performance, assessing the impact of air conditioning on fuel economy and emissions, and providing information for NREL's Advanced Vehicle Simulator (ADVISOR). A comparative study of the battery usage and thermal performance of the battery packs used in these two vehicles during chassis dynamometer testing is presented. Specially designed charge and discharge test cycles revealed that the Insight limited battery usage to 60% of rated capacity, while the Prius limited battery usage to 40% of the rated capacity. The Prius uses substantially more pack energy over a given driving cycle but at the same time maintains the pack within a tight target state of charge (SOC) of 54% to 56%. The Insight does not appear to force the battery to a specific target SOC. The study also found that while both vehicles have adequate battery thermal management systems for mild driving conditions, the Prius thermal management is more robust, and the Insight thermal management limits pack performance in certain conditions.

14. SUBJECT TERMS
Honda Insight; Toyota Prius; hybrid-electric vehicles; ADVISOR; battery; thermal performance

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