

Benchmarking of OEM Hybrid Electric Vehicles at NREL

Kenneth J. Kelly
Arun Rajagopalan

*National Renewable Energy Laboratory
Golden, Colorado*

*Prepared for the DOE
Office of Advanced Transportation Technologies
In fulfillment of August Milestone "Benchmark 2 new production
or pre-production hybrid vehicles with ADVISOR."*



National Renewable Energy Laboratory

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Golden, Colorado 80401-3393

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Kenneth J. Kelly
Arun Rajagopalan

*Center for Transportation Technologies and Systems
National Renewable Energy Laboratory
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*For the
U.S. Department of Energy
Office of Transportation Technologies
Office of Advanced Automotive Technologies
Hybrid Electric Vehicle Propulsion Systems Program*



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Executive Summary

This report describes the National Renewable Energy Laboratory's (NREL) progress and activities related to its Department of Energy FY2001 Annual Operating Plan milestone entitled "Benchmark two New Production or Pre-Production Hybrids with ADVISOR." NREL purchased a 2000 model year Honda Insight and a 2001 model year Toyota Prius for testing and understanding vehicle and component behavior under various test conditions. The Insight was received in April of 2000. The Prius was received in the fall of 2000. NREL's testing of the vehicles has been designed to provide information to three separate program activities, including:

1. Battery Thermal Management
2. Auxiliary Load Reduction
3. Systems Analysis

NREL's vehicles were tested at Environmental Testing Corporation's (ETC) chassis-dynamometer testing test facility near Denver, Colorado. Data collection from the testing includes continuous HEV component, emissions, and fuel usage data (as well as bag emissions and fuel economy) on the vehicle for various drive cycles. The following standard chassis dynamometer tests were performed on both vehicles

- a) FTP-75
- 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

Additional non-standard chassis dynamometer testing and on-road vehicle testing was also conducted to explore battery operation under various conditions.

This report has two focus areas. One is to report on the completion of benchmarking activities with the Honda Insight, which includes final development of an ADVISOR model of the Insight. The second focus area is to report on the results from testing the Prius. The program has achieved several major accomplishments on this activity during the 2001 fiscal year. These are as follows:

- Completion of Insight data analysis
- Significant improvements to the Insight control strategy included in the public release of ADVISOR 3.2
- Incorporation of Insight engine fuel use map from Argonne National Laboratory (ANL) into the ADVISOR model of the Insight
- Prius vehicle mileage accumulation (to age the catalyst) and initial testing with Toyota engineers at ETC
- Instrumentation of the Prius and programming of data acquisition software (completed by NREL's Battery Thermal Management team)
- Completion of chassis dynamometer emissions testing on the Prius
- Initial analysis and reporting of Prius test data

In developing the test plan for these two vehicles NREL set out to answer several questions that it deemed important to the understanding of the vehicle behavior. These questions are listed below with answers based on the work that has been completed so far.

How much does the fuel economy and emissions of high efficiency vehicles like the Insight and Prius suffer when the air-conditioning is used under hot conditions?

The impact of air conditioning on vehicle fuel economy is one of the clearest and most dramatic results from the testing. ETC tested both vehicles using the EPA's procedure for evaluating emissions while using air conditioning (SC03). Two tests were performed: one with the AC on and one with the AC off. The Insight showed a 34% reduction in fuel economy with the air conditioning on. The Prius showed a 30% reduction in fuel economy with the air conditioning on.

In terms of emissions, the Insight showed significant increases in CO₂ and CO emissions with the air conditioning on. Emissions of NO_x and HC were not statistically different between the two tests. The Prius showed substantial increases in CO₂, HC, and CO with the air conditioning on. Emissions of NO_x were actually higher with the AC off than with the AC on. Results for the Insight were verified through repeat testing. Repeat testing of the Prius will be conducted before the end of the fiscal year 2001.

Other effects of air conditioning include:

- the Insight was not able to fully follow the SC03 driving trace with AC on and required significantly more use of the motor assist and therefore battery power
- the Prius was able to follow the SC03 driving trace, but required greater use of the gasoline engine
- for the Insight, electrical energy from the high voltage battery pack used to power auxiliary systems increased from 170 W to 900 W with the AC on
- for the Prius, electrical energy from the high voltage battery pack used to power auxiliary systems increased from 300 W to 800 W with the AC on

When and to what degree do the Insight and Prius use their electric traction motors and batteries to assist the engine and capture regenerative braking?

Utilization of the traction motor and battery pack is a key feature of any hybrid vehicle model. NREL's instrumentation of the Insight and Prius focuses on collection of the appropriate electrical signals to answer this question. Axle torque data was provided by Argonne National Laboratory from their testing of the Honda Insight at Automotive Testing Laboratories in Ohio.

For the Insight, the gasoline engine is the primary motive source and the electrical motor is used to assist in conditions of high load. NREL's analysis indicates that the electric motor kicks in when the driveline torque required exceeds 20 Nm and that it provides a relatively constant torque of approximately 10 Nm (data shows that actual motor torque levels vary from 8 Nm to 12 Nm while assisting). Input power levels to the electric motor during the FTP (city) driving cycle were between 2.5 kW and 4.5 kW. On the more aggressive driving cycles

such as the US06, input power levels peaked at a high of 6.5 kW. The Insight's permanent magnet DC motor has a maximum torque of 50 Nm and a peak power of 10 kW.

The Insight's regenerative braking has two modes of operation. One when the vehicle is "coasting down" with the vehicle in gear, and the other with the driver's foot on the brake. The amount of regenerative braking varies linearly with the amount of torque available through the driveline. The test data indicates that approximately 50% of the braking energy goes into the driveline to be captured by the electric motor. Power levels from the motor/generator on standard driving cycles were often as high as 6 kW on the FTP cycle and 7 kW to 9 kW on the more aggressive US06 driving cycle.

Less analysis has been performed on the data from the Prius, since the testing has not yet concluded. However, the following observations can be made from the existing data. The Prius uses the electric motor in a wider range of modes. The Prius gasoline engine is shut off during a significant portion (46%) of the UDDS (the first two phases of the FTP) driving cycle. Twenty percent of this is while the vehicle has come to a stop. This means that the Prius is running all-electric during 26% of the UDDS cycle. The Prius also uses the electric motor and the planetary gear to reduce the transient operation of the gasoline engine and thereby reduce emissions and fuel use. Test data shows that during certain portions of the driving cycle, when both the electric motor and the gasoline engine are operating, the gasoline engine does not directly follow the speed of the vehicle and therefore experiences fewer transients.

Both vehicles have nickel-metal hydride battery packs with a 6.5 Ah rating. The Insight battery pack has 120, 1.2 V cells for a nominal voltage of 144 V. The Prius battery pack is nearly twice as large with 228, 1.2 V cells for a nominal pack voltage of 273.6. Testing on the dynamometer determined that the Insight maintains control limits on the battery pack that only allow 3.7-3.9 Ah, or between 57% and 60% of the rated capacity. This agrees well with published information that indicates that the Insight maintains its battery state-of-charge (SOC) between 20% and 80% SOC. Testing also revealed that the Prius has control limits of 40% to 80% SOC, so that the Prius battery pack useful capacity is 40% of the rated 6.5 Ah, or 2.6 Ah.

Additionally, the NREL tests showed that while the Insight seems to continually add a small amount of charge to the vehicle over standard drive cycles like the FTP and HWFET, the Prius tends force its battery to within a narrow band around 56% SOC. In testing the Insight over back-to-back cycles it tended to exhibit the same SOC profile no matter independent of the initial SOC. The exception to this is when the Insight pack reaches 80% SOC and no longer accepts regenerative power, or when it reaches about 36% SOC and begins tapering off the amount of available power provide for motor assist. The latter situation was seen both on the dynamometer and during on-road mountain driving conditions in which the vehicle began limiting motor assist long before the top of the grade was reached. By comparison, testing of the Prius showed that it drastically adjusts its use of the battery pack depending on the initial SOC until it reaches the target 56% SOC. For example, when running a city driving cycle with an initial SOC of 40% and the engine already warm, the Prius did not shut off the engine for the first time until it reached the target SOC.

Engine-off operation for the two vehicles is also very different. For the case of the Insight this basically refers to elimination of idling when the engine is warm and has come to a stop or is decelerating at speeds less than 20 mph. For the Prius “engine-off” occurs during low speed, low load conditions during which the vehicle can run in all-electric mode. When conducting a cold-start FTP test the Prius engine is off 46% of the time, while the Insight engine shuts off only 18%. An ADVISOR simulation of the effect of eliminating engine-off operation indicated that this has about a 6% impact on fuel economy. On the HWFET test, which does not have any stops during the cycle, the Prius engine was off during 4% of the cycle while the Insight engine did not shut off. Engine-off operation during the hot US06 cycle occurred 16% of the time for the Prius and only 7% of the time for the Insight.

How do the Insight and Prius battery thermal management systems behave under various ambient temperature conditions?

Although the Insight and Prius both have nickel-metal hydride battery packs with a rated 6.5 Ah capacity, their configurations and thermal management systems have some significant differences that are apparent in the test results. Both vehicles force cabin air through the pack to cool the batteries, but the pack geometries are very different. The Insight pack consists of a set of 20 cylindrical models stacked in rows of 3. The Prius pack consists of a set of 38 prismatic modules stacked side-by-side.

From the tests conducted it appears that the Prius thermal management system is more effective at transferring heat away from the pack than the Insight’s is. However, under relatively mild conditions such as those encountered during standard FTP and HWFET tests, the thermal management systems on both vehicles appear to be adequate. On the FTP cycle the change in average battery pack temperature from the beginning of the test to the end of the test was 2.5°C, and the temperature distribution across the pack was 1.3°C. Compared to the Insight, the Prius used five times more battery energy over the FTP cycle, yet the increase in temperature from beginning to end was only 5°C and the temperature distribution across the pack at the end of the test was 4°C.

Under the more aggressive driving conditions of the US06 cycle where the Prius pack transferred 3x more energy, the change in battery temperature from the beginning to the end of the test cycle was 7.5°C for the Insight and 8°C for the Prius. Temperature distributions across the pack at the end of the US06 cycle were 2°C for the Insight and 4°C for the Prius.

Hard charging of the Insight revealed an apparent control strategy that limits the amount of power available from the battery pack when battery temperatures reach 45°C to 50°C. This power limiting had a significant effect on the Insight’s ability to meet the US06 driving trace when the test procedure was initiated at 40°C. Cold temperature testing of the Insight also showed reduced power available from the battery and a reduced ability to meet the driving trace for the initial 0°C US06 driving cycle. The Prius did not have a problem following the driving trace for any of the US06 tests (0°C, 20°C, 40°C), but analysis of the power availability from the battery pack under these conditions has not yet been completed.

Are the ADVISOR battery models of the Insight and Prius accurate when compared with in-vehicle usage of the pack?

For the Insight, ADVISOR simulations of battery current and voltage over the various test cycles were in very good agreement with the test data. Battery state of charge predictions also agreed well with the test data. At the time this report was written the ADVISOR model of the US Prius had not yet been developed.

Do the ADVISOR Insight and Prius models accurately predict the emissions & fuel consumption of the Insight and Prius vehicle on standard driving cycles?

Using NREL's newly developed Honda Insight control strategy model, the best available vehicle and component information available including an engine fuel use map provided by Argonne National Laboratory, ADVISOR's predictions of fuel economy were fairly consistent with the EPA's fuel economy numbers and with the ETC test results. Comparisons of emissions were not possible since an accurate emissions map from the Insight has not yet been incorporated into the model.

ADVISOR predicted fuel economy of 63.3 mpg on FTP test and 88.3 mpg on the HWFET test within 7% of the unadjusted EPA city fuel economy and within 2% of the unadjusted EPA highway fuel economy values. The fuel economy test results from ETC were 7% lower than the EPA city result and 12% lower than the EPA highway cycle results. When comparing the ADVISOR predictions to the ETC test data, the ADVISOR results were within 1% on the FTP, 12% on the HWFET, 9% on the US06, 0.2% on the SC03 without air conditioning, and 5% on the SC03 with air conditioning. For the cycle with air conditioning the simulation was run with an electrical auxiliary load of 800 W and an additional mechanical load of 3 kW to account for air conditioning.

A comparison of the Prius test results to ADVISOR simulations was not possible at this time, since the US Prius model has not yet been developed in ADVISOR.

Other Findings and Accomplishments

A number of other findings and accomplishments from this testing are described in the report. The report provides a contrast and comparison of many of the features of the first two production HEVs available in the US. A key accomplishment is the inclusion of the new Honda Insight control strategy in the August 2001 public release of ADVISOR 3.2. This is a new parallel vehicle control that, while it is a relatively simple motor assist strategy, it is a popular approach for mild hybrids. The parametric design allows the user to perform "what if" investigations on parameters such as the level of torque contribution from the electric motor, at what point should the motor provide assist, and the level of regen energy available.

Future Work

For the Insight, only a limited amount of additional modeling work is planned. Most notably, NREL plans on incorporating an engine emissions map in ADVISOR based on test data from

ANL. This activity may also include incorporation of catalyst efficiency information and the incorporation of a NO_x trap if this information becomes available.

For the Prius, NREL will complete testing of the Prius at ETC during the end of FY2001. This will include repeat tests on most of the procedures discussed here along with some extended tests such as multiple back-to-back FTP, HWFET, and US06 cycles to determine the thermal behavior of the battery pack over an extended period. Once the testing has been completed additional analysis will be performed and a US Prius model will be developed in ADVISOR. The US Prius model will most likely use the Japanese Prius as the starting point and incorporate new information based on testing at NREL and ANL.

Introduction

The National Renewable Energy Laboratory purchased a 2000 model year Honda Insight and a 2001 model year Toyota Prius for testing and understanding of vehicle and component behavior under various test conditions. The Insight was received April of 2000. The Prius was received in the fall of 2000. NREL's testing of the vehicles has been designed to provide information to three separate program activities, including:

1. Battery Thermal Management
2. Auxiliary Load Reduction
3. Systems Analysis

NREL's vehicles were tested at Environmental Testing Corporation's (ETC) test facility near Denver, Colorado for chassis-dynamometer testing. ETC is a privately owned test laboratory that conducts high-altitude emissions certification tests, vehicle and engine research for many of the automotive manufacturers. A key customer of ETC is Daimler Chrysler, which maintains an on-site testing presence at ETC. NREL's testing was conducted on their 48" electric dynamometer that is within a temperature controlled chassis test cell capable of maintaining temperatures from -29°C to 43°C . Data collection from the testing includes continuous HEV component, emissions, and fuel usage data (as well as bag emissions and fuel economy) on the vehicle for various drive cycles. This data will serve multiple purposes, but primarily will be used to answer the following questions:

- How much does the fuel economy and emissions of high efficiency vehicles like the Insight and Prius suffer when the air-conditioning is used under hot conditions?
- When and to what degree do the Insight and Prius use their electric traction motors and batteries to assist the engine and capture regenerative braking?
- How do the Insight and Prius battery thermal management systems behave under various ambient temperature conditions?
- Are the ADVISOR battery models of the Insight and Prius accurate when compared with in-vehicle usage of the pack?
- Do the ADVISOR Insight and Prius models accurately predict the emissions & fuel consumption of the Insight and Prius vehicle on standard driving cycles?

This report has two focus areas. One is to report on the completion of benchmarking activities with the Honda Insight, which includes final development of an ADVISOR model of the Insight. The second focus area is to report on the results from testing the Prius. Although it was not one of the stated objectives of the test plan, this report also provides comparison and contrast of some of design aspects and test results from the two vehicles. The program has achieved several major accomplishments on this activity during the 2001 fiscal year. These are as follows:

- Completion of Insight data analysis
- Significant improvements to the Insight control strategy included in the public release of ADVISOR 3.2

- Incorporation of Insight engine test data from Argonne National Laboratory (ANL) into the ADVISOR model of the Insight
- Prius vehicle mileage accumulation (to age the catalyst) and initial testing with Toyota engineers at ETC
- Instrumentation of the Prius and programming of data acquisition software (completed by NREL’s Battery Thermal Management team)
- Completion of chassis dynamometer emissions testing on the Prius
- Initial analysis and reporting of Prius test data

In addition to the objectives described above, NREL’s testing has provided NREL engineers with an opportunity to conduct hands-on research with these two production HEVs. While not in itself a reason for doing the testing, this experience provides DOE with the side-benefit of giving National Laboratory staff a deeper understanding of HEV and component technologies and designs. In part, this report serves to disseminate the understanding gained through NREL’s testing to DOE and its clients.

Vehicle Descriptions

The two hybrid electric vehicles that are covered in this report have been available in the United States since the 2000 model year. They are the Honda Insight and the Toyota Prius. The Honda Insight is a small, two-seat vehicle with a parallel HEV configuration. It has the highest rated fuel economy of any car sold in the US (EPA estimates 70 mpg on the highway and 61 mpg in the city) and has achieved a US EPA emissions national certification at the low emitting vehicle (LEV) level and ultra-low emitting vehicle (ULEV) level for sales in California. The Toyota Prius, which also has very good fuel economy ratings (see Table 1), is a dual-mode HEV that combines elements of both the parallel and series configurations. The Prius received a US EPA emissions certification of ULEV under the national low emitting vehicle program (NLEV) and a super ultra-low emitting vehicle (SULEV) rating for sales in California.

Table 1: EPA fuel economy ratings

	<i>EPA Rated Fuel Economy (mpg)</i>	
	Insight	Prius
City	61	52
Highway	70	45
Combined	65	48

* Note EPA city fuel economy ratings are adjusted by EPA 10% below the tested value, and the highway rating is adjusted 22% below the tested value to reflect the actual expected in-use performance.



Figure 1: Photograph of NREL's Honda Insight



Figure 2: Photograph of NREL's Toyota Prius

A great deal has already been written about the design of these vehicles and their control strategies (see references). For this report, a few of the key relevant differences of the two vehicle designs are described in brief. Table 2 provides a side-by-side comparison of some of the important vehicle parameters. Important differences in the size of the two vehicles include the fact that the Insight is a two-seater while the Prius is a 5-passenger sedan, the curb weight of the Insight is approximately 30% lighter than the Prius, and the Prius has a larger engine, electric motor, and battery pack. See Figure 1 and Figure 2 for photographs of NREL’s test vehicles used in this benchmarking.

Table 2: Comparison of vehicle parameters

<i>Dimensions</i>	<i>Honda Insight</i>	<i>Toyota Prius</i>	<i>Units</i>
Length	3.94	4.31	m
Width	1.70	1.69	m
Height	1.33	1.46	m
Frontal Area	1.90	Not available	m ²
Cargo Volume	0.45	0.33	m ³
Passenger Volume	1.34	2.51	m ³
Curb Weight	855.9	1254.2	kg
Coefficient of Drag	0.25	0.29	-
<i>Engine Parameters</i>			
Valve train	SOHC 12 valve	Water-cooled inline DOHC	
Cylinders	3	4	-
Displacement	1	1.5	L
Power data	50 kW @ 5700 rpm	52 kW @ 4500 rpm	
Torque data	89 Nm @ 4800 rpm	111 N-m @ 4200 rpm	
<i>Emissions</i>			
Catalyst	3 way with NOx adsorber	3 way with HC trap	
<i>Transmission</i>			
	manual 5 speed	Electronically controlled CVT (planetary gear)	
<i>Electric Motor</i>			
Type	Permanent magnet dc brushless	3 phase AC synchronous permanent magnet	
Power output	10 kW @ 3000 rpm	33 kW @ 1040-5600 rpm	
Low rpm torque	48 Nm @ 1000 rpm	344 Nm @ 0-400 rpm	
<i>Battery Pack</i>			
Type	Ni-MH	Ni-MH	
Cell voltage	1.2	1.2	V
Cells per module	6	6	-
Number of modules	20	38	-
Total voltage	144	273.6	V
Rated capacity	6.5	6.5	Ah

Comparison of powertrains

The two vehicles also have very different hybrid powertrain configurations. A schematic diagram of the Insight's powertrain is shown in Figure 3. It is a straightforward parallel HEV with an electric motor that assists vehicle propulsion by direct coupling to the output shaft of the engine. The electric motor speed is equal to the engine speed, and the motor cannot spin independent of the engine. The electric motor also acts as a generator to recapture energy during decelerations and to provide power for the auxiliary systems. For the motor to regenerate power during decelerations, the clutch has to be engaged and the transmission in an appropriate gear, to transmit the torque to the motor.

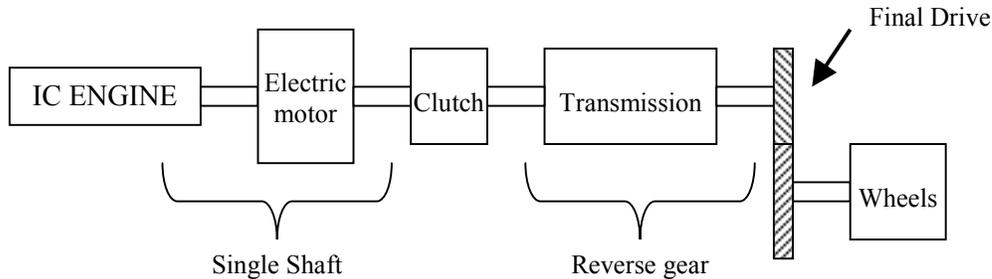


Figure 3: Honda Insight powertrain schematic

The Prius has a much more complex hybrid system known as a dual-mode hybrid (see Figure 4). In the Toyota Prius, a planetary gear set allows for the engine and electric motor to synergistically (in parallel) drive the wheels, or the electric motor to individually drive the wheels (with either the engine on or off). This allows for greater control over the engine and battery usage. Power to the wheels can flow directly from the electric motor (for low speed/load all-electric operation) can come directly from the gasoline engine, or can be a combination of gasoline and electric motor contributions. During decelerations the electric motor is used to regenerate kinetic energy and charge the battery pack. Energy from the gasoline engine can also be used to power the generator and charge the battery. Relative speeds of the gasoline engine, generator, and electric motor are controlled by the gear ratios of the planetary gear set.

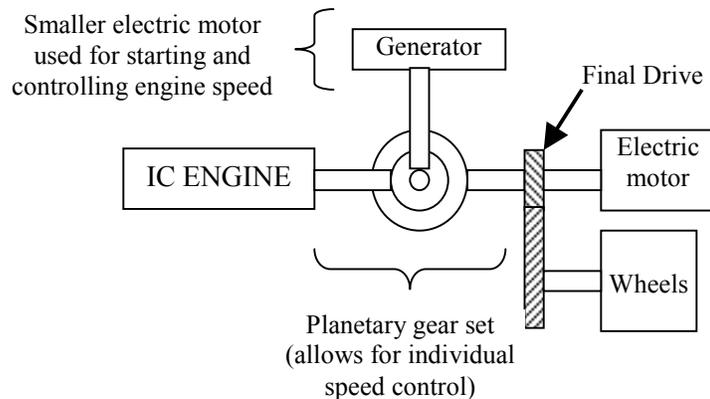


Figure 4: Toyota Prius powertrain schematic

Other key characteristics of the Prius configuration:

- The motor can drive the vehicle all electric (not possible in the Insight).
- The engine can run independent of the vehicle speed (allows for regeneration)
- Engine speed is accurately controlled (not possible in the Insight). This allows for better emissions control, since transient conditions and low efficiency operating points can be avoided.

A qualitative comparison of the two drivetrain configurations is provided in Table 3.

Table 3: Comparison of drivetrains

No	Feature	Honda Insight	Toyota Prius
1.	Drivetrain type	Parallel Starter Assist (Motor helps to start the engine and assists when required)	Electrical Continuously Variable Transmission (E-CVT). Can work as a series as well as a parallel hybrid.
2.	Number of electric motors	1 (assist and start)	2 (Second smaller generator used for starting, and controlling engine speed).
3.	Engine Speed	Dependent on driver / gear ratio/ speed.	Not under the driver's control. Engine speed is controlled to avoid transients.
4	Engine off	Only during slow speed decelerations and vehicle stops.	Engine off at many more instances, including electric start and decelerations.
5.	Electric motor speed	Equal to engine speed. (on the same shaft)	Based on vehicle speed, but different from engine speed.
6.	All electric drive	Not possible, since motor is connected to the engine	Possible, since motor speed is independent of the engine speed.
7.	Reverse	Engine is on. Reverse gear is engaged in the gearbox.	Engine has no effect. Reverse is all electric.

Battery Packs

The vehicles' nickel-metal hydride battery packs play an important role in all three aspects of the NREL testing program (modeling, battery thermal management, and auxiliary loads). As was mentioned previously, the Prius battery pack is larger than the Insight. The Prius has 38 modules that each have 6, 1.2V cells and 6.5 Ah for a total nominal voltage of 273.6 V and energy capacity of 1.8 kWh. The mass of the Prius pack is 53 kg. The Insight Pack has 20 modules that each have 6, 1.2 V cells and 6.5 Ah for a total nominal voltage of 144 V and energy capacity of 0.94 kWh. Both packs are supplied by Panasonic, but the Prius pack is a later generation, prismatic design that more efficiently packs the larger capacity. Figure 5 through Figure 8 show the two battery packs in the vehicle with the covers removed and also after removal from the vehicle for instrumentation and off-board testing.

An important consideration for both packs is the design of the thermal management system. Both vehicle designs force cabin air through the individual modules to cool them. The Insight employs a small "muffin" fan to force air between the modules. Holder geometry varies the flow in different areas of the pack. The Prius utilizes a 12V blower to force air through gaps between the modules. The cross-sectional area of the inlet and outlet plenums vary along the length of the pack. The geometry of the plenums and gaps are used to provide a uniform cooling air velocity across the modules. Detail on the battery thermal management system design and performance is described in several publications by NREL's Battery Thermal Management team^{1,2,7}.

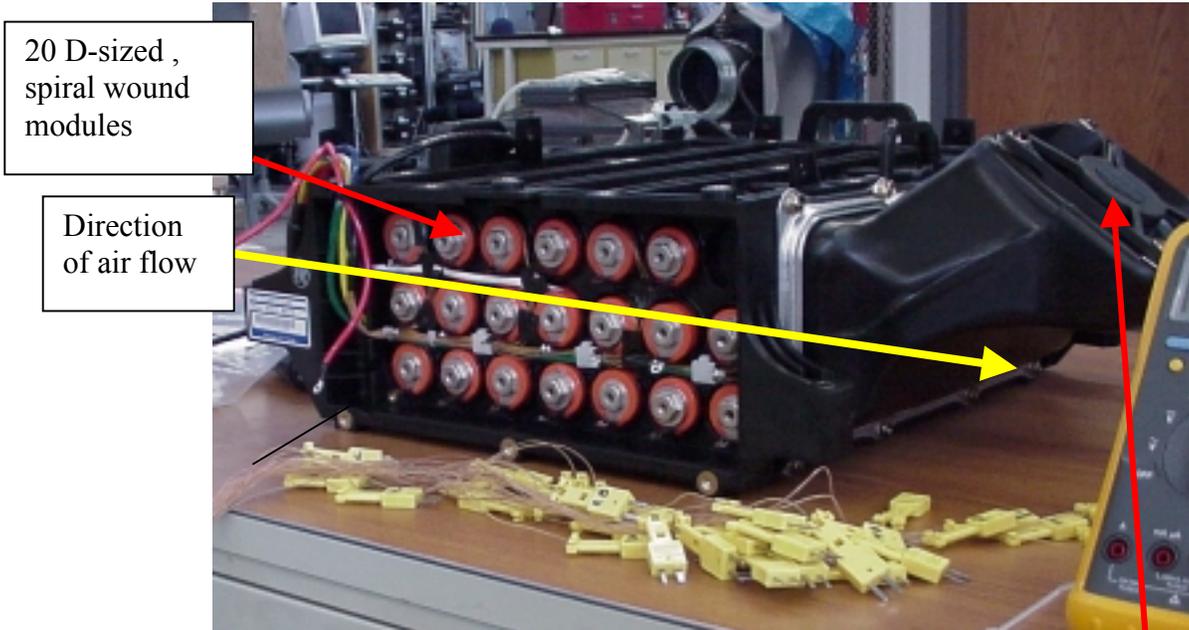


Figure 5: Insight battery pack

Battery Pack with Electronic Controls stored under rear cargo area

Pack Coolant Fan

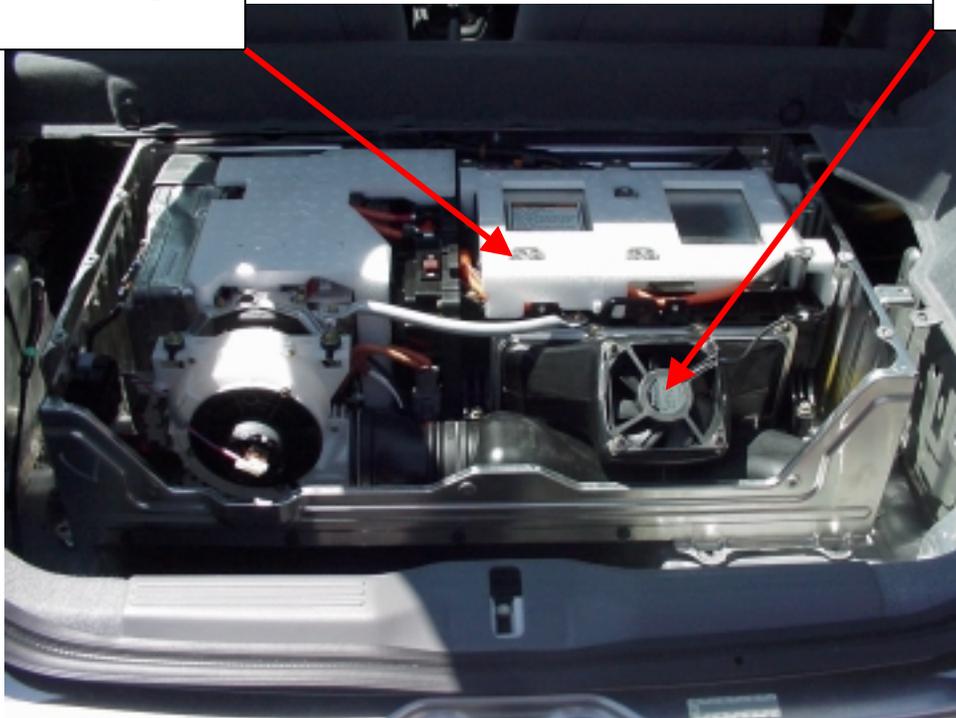


Figure 6: Insight battery pack (in the vehicle)

38 prismatic modules shown removed from vehicle

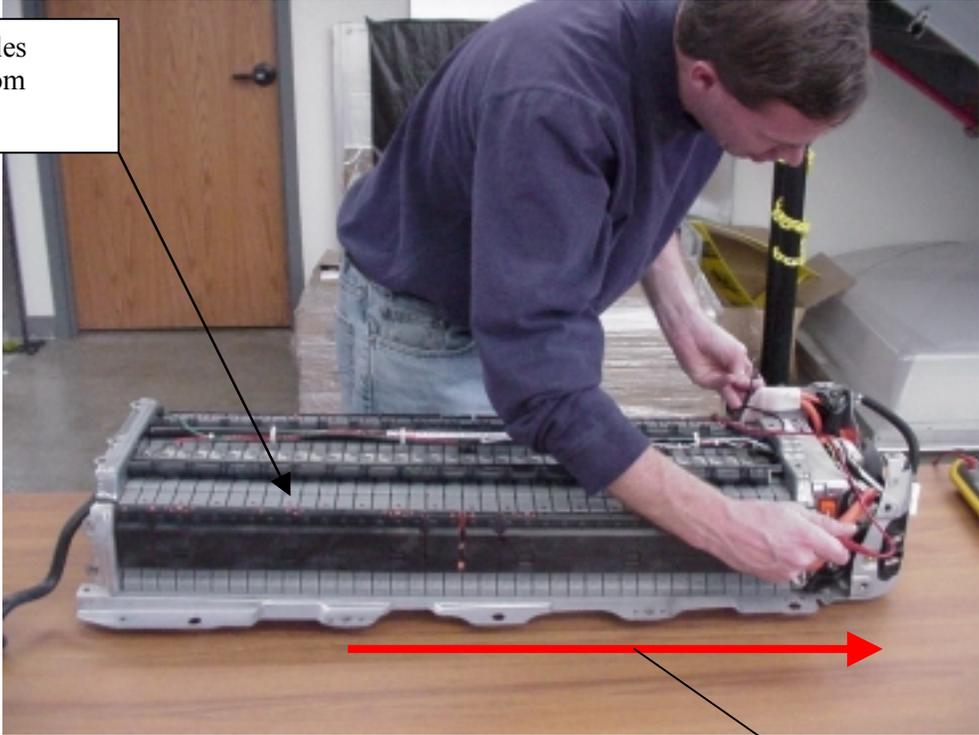


Figure 7: Prius battery pack

Front seats

Direction of air flow

Rear seat removed showing Prius pack with cover

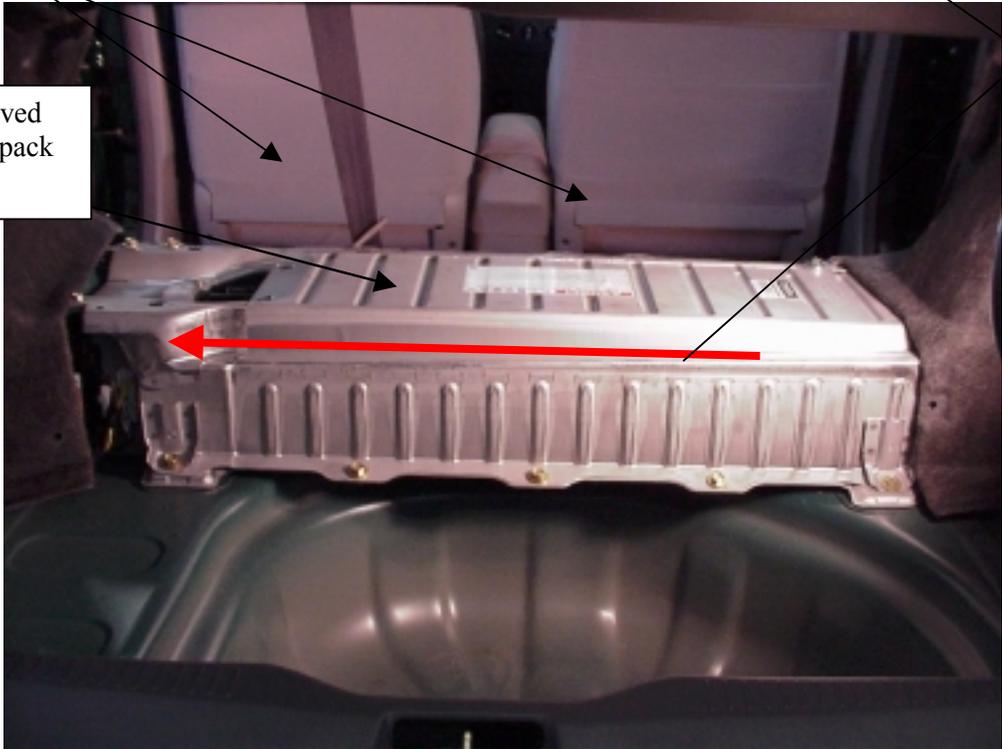


Figure 8: Prius battery pack (in the vehicle)

Emissions

Another area of particular interest is the emissions control systems and resultant emissions levels from these vehicles.

It is important to note that while the hybrid-electric components and control of these vehicles contribute to their ability to achieve low emissions, key technologies other than the hybridization of these vehicles are critical to their success. Both Toyota and Honda have gone to great lengths to improve fuel efficiency and thus reduce overall emissions (including CO₂). Features to reduce weight, friction, and improve efficiency are found throughout both vehicles. Some of the key features that are more directly associated with emissions are described briefly below.

The Honda Insight employs a lean-burn engine with a close-coupled, three-way catalyst (TWC) and a NO_x adsorbing catalytic converter. The exhaust manifold is integrated into the cylinder head (allowing the TWC to be mounted very close to the engine for rapid light-off). The engine design includes increased swirl in the combustion chamber for more complete combustion. The Insight's hybrid control strategy includes an idle stop feature to reduce fuel consumption and emissions during idle operation. The idle-stop is not allowed to engage until the engine has reached a sufficient temperature to avoid repeated cold starts. Honda also states that they use a "precision fuel and spark control augmented by a new honeycombed catalyst and a new secondary air-injection system with an electric air pump."

The Toyota Prius employs a high expansion Atkinson cycle engine with slanted squish area combustion chambers and 12 injector nozzles for increased atomization of the charge fuel. Toyota states that they use a "high-density ceramic catalyst substrate with super-thin walls that heats to catalyzing temperatures faster". While the catalyst is still below temperature the hybrid control system prioritizes engine control to maintain low-level emissions. Also, while the catalyst is below temperature, an HC adsorber is employed to capture HCs and release them after the catalyst lights off. Evaporative emissions are reduced through the use of a fuel bladder in a fuel tank that expands and contracts to reduce the volume available for evaporation depending on the fuel level. Other key emissions related features of the hybrid control system include balancing the use of the electric motor and engine to maintain engine operation within an efficient band, shutting off the engine during idle or deceleration, and electric-only operation under low speed and load conditions. The Prius also controls the use of the electric motor to smooth out transient operation of the engine.

EPA Emissions Certification Test Data

While most people know that the Insight was certified as a ULEV vehicle and the Prius was certified as a SULEV vehicle, the actual certification test results have not been as widely discussed. Certification test results allow for a comparison of the actual vehicle emissions collected by EPA as opposed to a more general comparison of the emissions standards to which the vehicles were certified.

Table 4 summarizes the Honda Insight emissions certification data available from the US EPA, and figures 5-7 show the FTP-75 data graphically.

Table 4: Insight emissions (EPA)

	<i>Useful Life Level (miles)</i>	<i>Test Results (g/mi)</i>		<i>Emissions Standards (g/mi)</i>		<i>Deterioration Factors</i>	
		test1	test2	CA-ULEV	NLEV	Additive	Multiplicative
<i>FTP-75 Test Results</i>							
CO	50K	0.40	0.53	1.70	3.40	0.219	1.0
	100K	0.64	0.77	2.10	4.20	0.458	1.0
NO _x	50K	0.06	0.08	0.20	0.20	0.00	1.0
	100K	0.06	0.08	0.30	0.30	0.00	1.0
NMOG	50K	0.031	0.032	0.040	0.075	0.006	1.0
	100K	0.037	0.039	0.055	0.09	0.012	1.0
HCHO	50K	0.0003	0.0004	0.008	0.015	0.00	1.0
	100K	0.0003	0.0004	0.011	0.018	0.00	1.0
Total HC	50K	0.04			0.41	0.008	1.0
<i>Cold CO Test Results</i>							
CO	50K	1.72		10	10	0.0	2.61

The Honda Insight certification test data shows that this vehicle had emissions that were well below the ULEV emissions standard projected out to 100,000 miles. In fact, the CO emissions were 66% lower, the NO_x emissions were 77% lower, and the NMOG emissions were 31% lower than the ULEV standards. Only the CO emissions were below the SULEV emissions standard.

Table 5 summarizes the Toyota Prius emissions certification data available from the US EPA, and figures 5-7 show the FTP-75 data graphically. The Toyota Prius certification test data shows that this vehicle had emissions that were well below the SULEV emissions standards projected out to 100,000 miles. In fact, the CO emissions were 57% lower, the NO_x emissions were 55% lower, and the NMOG emissions were 71% lower than the respective SULEV standards.

Table 5: Prius emissions (EPA)

	<i>Useful Life Level (miles)</i>	<i>Test Results (g/mi)</i>		<i>Emissions Standards (g/mi)</i>		<i>Deterioration Factors</i>	
		Test1	Test2	ULEV	CA-SULEV	Additive	Multiplicative
FTP-75 Test Results							
CO	50K	0.14		1.70		0.05	1.0
	100K	0.21		2.10		0.11	1.0
	120K	0.43			1.00	0.35	1.0
NO _x	50K	0.010		0.200		0.000	1.0
	100K	0.010		0.300		0.000	1.0
	120K	0.009			0.020	0.002	1.0
NMOG	50K	0.0024		0.040		0.000	1.0
	100K	0.0024		0.055		0.000	1.0
	120K	0.0029			0.010	0.004	1.0
HCHO	50K	0.000		0.008		0.000	1.0
	100K	0.000		0.011		0.000	1.0
	120K	0.000			0.004	0.000	1.0
Cold CO Test Results							
CO	50K	1.70		10.0		0.07	1.0
	50K	1.80			10.0	0.14	1.0
US06 Test Results							
CO	-	0.09		8.0	8.0	-	-
NMHC+ NO _x	-	0.011		0.140	0.140	-	-
SC03 Test Results							
CO	-	0.13	0.52	2.70	2.70	-	-
NMHC+ NO _x		0.000	0.024	0.200	0.200		

Figure 9 through Figure 11 illustrate several interesting points. First the figure shows how far each vehicle was below the relevant standard, the difference between the two standards, and shows the relative difference between the two vehicles. Going from ULEV to SULEV certification decreases HC emissions by 82%, NO_x emissions by 93%, and CO emissions by 52%. Compared to the Insight certification data projected to 100K miles, the Prius had 94% lower HC emissions, 86% lower NO_x emissions, and 70% lower CO emissions. The Insight and Prius were both certified to the Cold CO standard of 10 grams per mile. Emissions from both vehicles were well below (83%) this standard.

Additionally the Prius was certified to the EPA’s standards for aggressive driving (US06) and air conditioning (SC03) standards. Emissions certification results for these tests were also well below the standards. The results and the standards for the US06 and SC03 are included in Table 5.

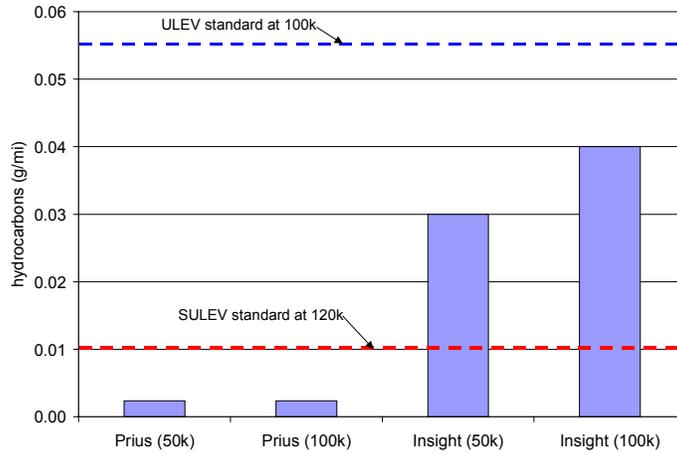


Figure 9: HC emissions

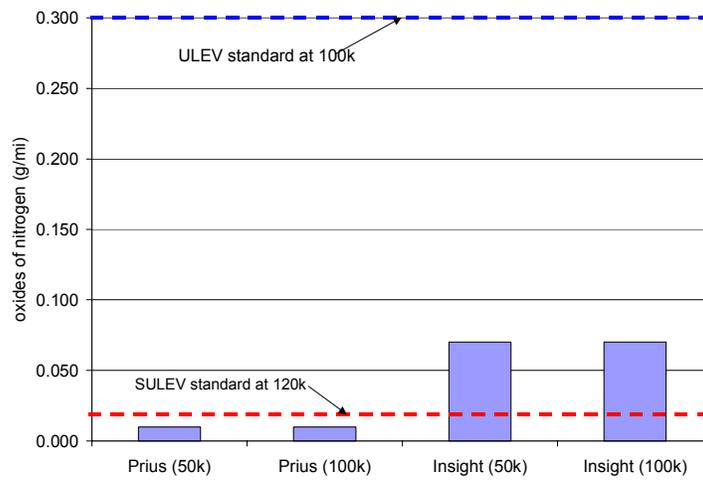


Figure 10: NO_x emissions

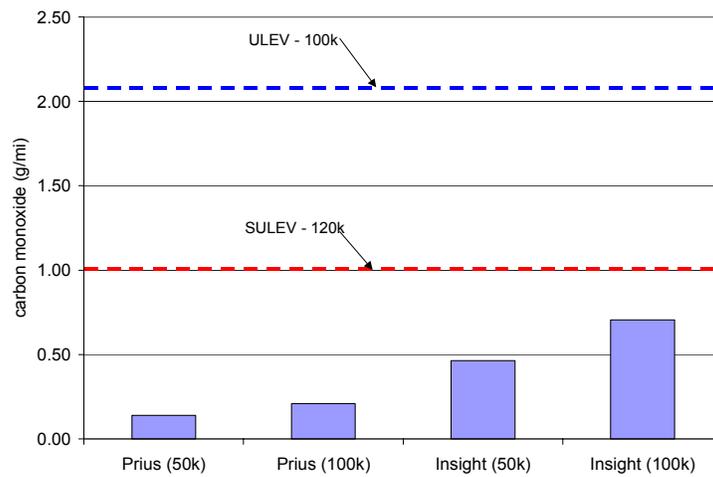


Figure 11: CO emissions

Test Procedures

The chassis dynamometer test plan was designed to address the following:

- a) effect of air conditioning on fuel economy and emissions of high efficiency vehicles
- b) assess performance of the vehicles' batteries and battery thermal management systems under different ambient conditions and vehicle driving cycles
- c) obtain vehicle and system level performance data needed to develop and validate an ADVISOR model
- d) obtain battery performance data to validate battery models.

To do this, Environmental Testing Corporation in Aurora, Colorado was subcontracted to perform the following tests on the vehicle.

- e) FTP-75
- f) Highway Fuel Economy Test (HWFET)
- g) US06 aggressive driving cycle performed at 0°C, 20°C, and 40°C
- h) SC03 air conditioning cycle performed at 95°F with and without air conditioning

Figure 12 and Figure 13, respectively, show the Prius and Insight on the dynamometer in the temperature controlled test cell at ETC.

At least two repeats of each test procedure were conducted to help validate the results. The driving cycles for each of the tests listed above are shown in the appendix. In all cases, standard testing procedures as detailed in the Code of Federal Regulations⁵ were followed. This included the appropriate vehicle prep procedures called out for in the procedures. For example, an official FTP-75 requires an initial prep-driving cycle performed 12-36 hours before the test, followed by a 12-36 hour of temperature controlled soak period. The vehicle must then be pushed onto the dynamometer and the engine is not started until the "official" test begins. In this case, the test is a "cold start" procedure. The other three procedures (HWFET, US06 and SC03) are "hot" procedures that require a warm-up driving cycle before the "official" cycle is run. In all cases, ETC ran the given test driving cycle (HWFET, US06, SC03 respectively) as the warm-up (as allowed for in the CFR). A side benefit of these procedural requirements is that NREL received data from its on-board system for both the warm-up and the official portions of the test procedure. In standard emissions certification work, data is not normally collected during the warm-up cycle. The CFR also defines procedures and requirements for emissions measurement equipment, air and exhaust handling, calibration of the dynamometer, gas recovery rates, record keeping and more. Since ETC runs certification tests for automotive manufacturers, the US EPA, the state of Colorado, and others they are thoroughly versed and experienced in the application of whole range of procedures required in the EPA. Further, as part of its alternative fuels program, NREL worked with EPA to conduct an on-site audit of the ETC facility, equipment, procedures, and record keeping.



Figure 12: Prius on the chassis dynamometer at ETC



Figure 13: Insight on the chassis dynamometer at ETC

The tests listed above are hereby referred to as the standard test procedures. Before starting testing on the standard procedures NREL engineers worked with ETC staff to run a series of “shakedown” tests on the dynamometer to work out any problems with the data acquisition and to better understand the vehicle operation and controls. These tests were less controlled in nature, but were very informative.

Most notably, NREL developed a relatively simple procedure for charging and discharging the vehicle battery packs using the motoring capability of ETC’s electric dynamometer. A more detailed description of this procedure is covered along with a discussion of the results in a later section. For pack charging, the procedure basically simulates coasting down a long grade by using the dynamometer to motor the vehicle wheels at a constant speed of 50 mph with the vehicle in gear and the operator’s foot off the accelerator. For discharging, the same constant-speed control of the dynamometer is used, but now the operator shifts the vehicle into high gear and maintains a full throttle acceleration to attempt to overcome the dynamometer loading. This is similar to accelerating up a long grade. The battery pack is thereby discharged as the vehicle pulls power from the pack for use by the electric motor. These procedures allowed NREL engineers to determine the battery control limits, or useful battery pack Ah capacity. For the Insight, this information was then used to develop a SOC preconditioning procedure used to set the battery near 50% SOC before the start of each test. This was done by first fully charging the vehicle and then discharging by 50% of the useful Ah capacity. In cases where the vehicle required a prescribed temperature-controlled soak period, the SOC preconditioning was performed prior to the soak period.

For the Prius, use of the charging and discharging cycles quickly led to the determination that the vehicle maintains SOC control limits between 40% and 80% SOC. Toyota engineers had indicated that, under normal driving conditions, the vehicle sets the battery SOC at around 50%. NREL performed repeated city (LA4 - first phase, 505 seconds, of the FTP drive cycle) and highway (HWFET) cycles using the charge and discharge cycles to set various initial SOC values. From this testing it was determined that the vehicle tends to quickly bring the SOC to a target value of around 56% no matter what the initial SOC was. This information led to the determination that running an LA4 drive cycle prior to the start of testing (or required soak period) is sufficient for setting an initial SOC.

Instrumentation and Data Acquisition

NREL’s Battery Thermal Management team performed the instrumentation and programming of data acquisition software for the Honda Insight. NREL’s on-board data acquisition includes the following measurements

- 33 battery cell temperatures
- inlet and outlet battery coolant (air) temperatures
- pressure drop across the pack
- 10 battery cell voltages
- 5 interior cabin temperatures
- inverter current
- DC/DC converter current
- GPS coordinates, altitude, and speed

Additional signals were also collected from the vehicle's on-board diagnostics (OBDII) system and from ETC's data acquisition system. Details on the instrumentation and data acquisition systems for the Honda Insight were provided in two previous FY2000 milestone reports.^{1,3} For both vehicles, special attention was paid to instrumentation of the battery pack for determination of battery performance and in-vehicle thermal characteristics. Figure 14 shows the basic location of the battery pack (red numbers) and interior cabin thermocouples (yellow dots), and the location of the current measurements.

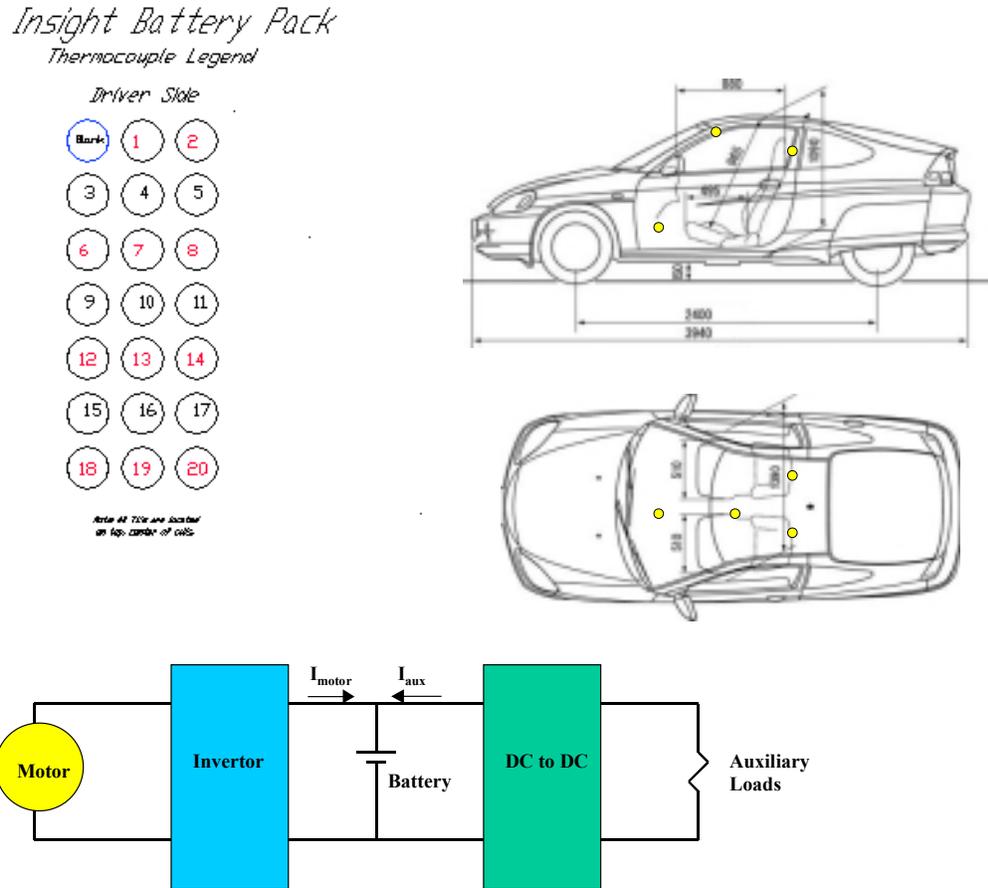


Figure 14: Insight thermocouple and current measurement locations

The Insight battery pack thermocouple legend shows an end view of the Insight pack modules (see also Figure 5). Modules with red numbering were each instrumented with three thermocouples – one on each end and one in the middle along the length of the module.

NREL's Battery Thermal Management team also performed the instrumentation and programming of data acquisition software for the Toyota Prius. An overview of the key points of the instrumentation is provided below. Additional details are contained in the Battery Thermal Management milestone for the Prius pack evaluation². Although many of the measurements are the same as on the Insight, substantial improvements were made to the system for the Prius. Most notably, the data acquisition rate and number of data signal was

increased. For the Prius, a National Instruments SCXI (signal conditioning extended interface) chassis was used that multiplexes the signals and feeds them to a PCMCIA DAQ card at aggregate rates of up to 20 kHz. NREL's on-board data acquisition for the Prius includes the following measurements

- 38 battery module temperatures
- 18 battery skin temperatures
- 19 battery module voltages
- high voltage battery pack current
- battery cooling air inlet and outlet temperatures
- pack fan current and voltage
- pressure drop across the pack
- DC/DC current
- 6 interior temperatures
- vehicle speed from on-board signal
- vehicle speed and torque from ETC
- radiator fan current
- A/C clutch current

Data from all channels are stored at a rate of 20 Hz. The SCXI cards also provide isolation between the vehicle common chassis and the instrumentation ground. The SCXI chassis is shown in the trunk of the vehicle just behind the battery pack (see Figure 15).



Figure 15: Prius instrumentation

For the battery pack, thermocouples were located in thermal wells in all 38 modules of the pack. Additional thermocouples were mounted at six points on the face of three separate modules. Figure 16 shows the location of the battery thermocouples.

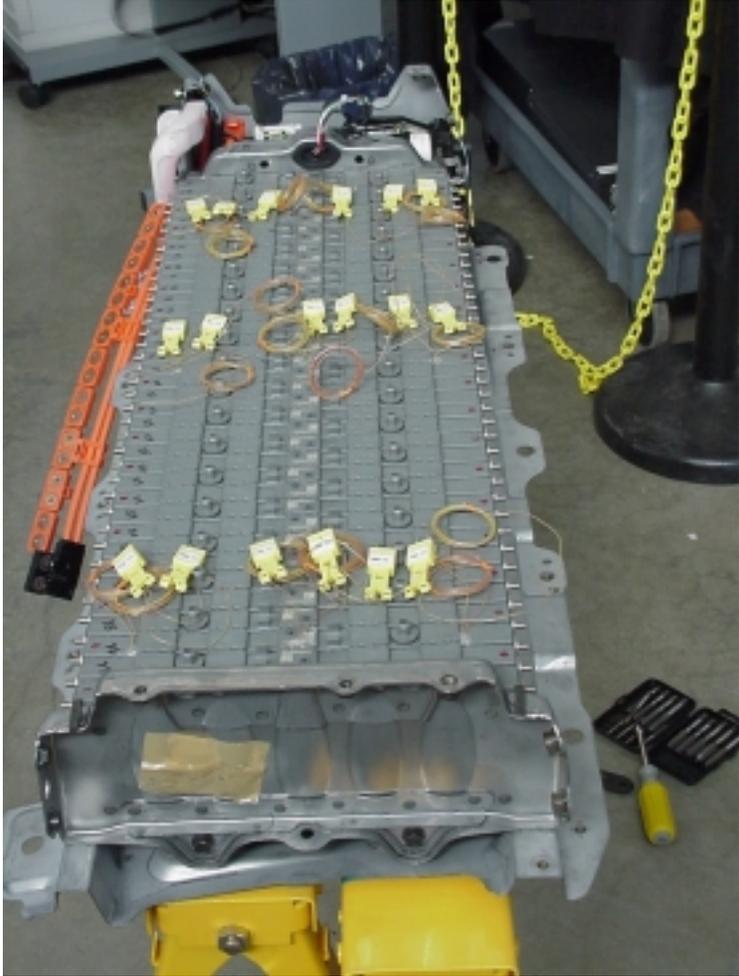


Figure 16: Thermocouples on the Prius battery pack

The data acquisition program was developed using National Instruments LabView software. The program includes an interface that allows users to view the data as it is being collected. This feature is important when setting up the system and verify signals as tests are being run. Figure 17 shows the position of the laptop that has the data acquisition program and temporarily stores incoming data before it is archived.



Figure 17: Prius data acquisition

In addition to the on-board instrumentation, several signals are obtained from the vehicle's OBDII system. These include:

- time (min)
- speed (mph)
- engine load (%)
- engine coolant temperature (C)
- intake manifold air pressure (kPa)
- intake air temperature (C)
- air flow rate (g/s)
- throttle position (%)

Data from ETC's test equipment was logged at 20Hz and includes the following channels:

- | | |
|-------------------------------------|---------------------------|
| - Time | - HC (ppm) |
| - Distance | - HC (grams) |
| - Speed | - CO (ppm) |
| - Torque | - CO (grams) |
| - Exhaust Flow Rate | - NO _x (ppm) |
| - Exhaust Volume | - NO _x (grams) |
| - Ambient Volume | - CO ₂ (%) |
| - Dilution Rate | - CO ₂ (grams) |
| - NO _x Correction Factor | - Motor Current |
| - Absolute Humidity | - Auxiliary Current |
| - Temperature | - Battery Voltage |
| - Barometric Pressure | - Cabin Temperature |

The laboratory also reported results from the analysis of exhaust samples collected over the entire cycle and for individual test phases (referred to as bag analysis). Several key signals are exchanged between the vehicle's on-board data acquisition and the ETC system. These include:

From vehicle on-board to ETC

- Hardware time
- Motor Current
- Auxiliary Current
- Battery Voltage
- Cabin Temperature

From ETC to vehicle on-board

- Vehicle Speed
- Dynamometer torque

These signals (in particular the time and vehicle speed) allow for the two data sets to be readily aligned.

Vehicle Performance on Standard Test Drive Cycles

Fuel Economy and Emissions

Results from the standard chassis dynamometer tests of the Honda Insight are shown in Table 6. Results from the standard tests performed on the Toyota Prius are summarized in Table 7. A side-by-side comparison of the results from the two vehicles is shown graphically in Figure 18 through Figure 23.

Table 6: Insight emissions (Lab tests)

ETC Test Number	Test Date	Test Type	Test Temp (F)	Fuel Economy (mpg)	ΔAh	Emissions (g/mi)			
						HC	CO	NO _x	CO ₂
2698	01-Aug-00	FTP75	75.2	65.7	-0.049	0.023	0.133	0.022	135.0
2699	02-Aug-00	FTP75	74.1	64.2	0.032	0.022	0.144	0.025	138.1
2714	10-Aug-00	FTP75	74.8	62.4	-0.090	0.024	0.159	0.020	142.1
			Average	64.1	-0.036	0.023	0.145	0.022	138.4
2684	28-Jul-00	HWFET	75.0	78.8	-0.003	0.001	0.161	0.031	112.5
2685	28-Jul-00	HWFET	74.9	79.8	-0.013	0.001	0.162	0.040	111.1
2709	09-Aug-00	HWFET	75.2	78.5	0.027	0.003	0.146	0.037	113.0
2710	09-Aug-00	HWFET	74.8	78.8	-0.008	0.001	0.117	0.045	112.5
			Average	79.0	0.001	0.002	0.147	0.038	112.3
2692	31-Jul-00	SC03 with AC off	94.9	63.5	-0.145	0.005	0.255	0.094	139.5
2693	31-Jul-00	SC03 with AC off	96.8	65.6	-0.039	0.004	0.171	0.078	135.2
2721	11-Aug-00	SC03 with AC off	95.4	63.4	0.029	0.010	0.206	0.043	139.8
2722	11-Aug-00	SC03 with AC off	95.6	58.5	0.457	0.006	0.244	0.044	151.6
			Average	62.7	0.075	0.006	0.219	0.065	141.5
2696	31-Jul-00	SC03 with AC on	95.7	42.8	-0.070	0.004	0.663	0.024	206.7
2697	31-Jul-00	SC03 with AC on	95.2	42.3	-0.138	0.009	0.880	0.095	209.4
2723	14-Aug-00	SC03 with AC on	95.0	40.5	-0.091	0.006	0.658	0.100	218.3
2733	15-Aug-00	SC03 with AC on	95.0	41.2	-0.050	0.007	0.694	0.071	214.7
			Average	41.7	-0.087	0.007	0.724	0.073	212.3
2687	28-Jul-00	US06	75.0	52.7	-0.799	0.014	3.014	0.008	163.8
2688	28-Jul-00	US06	75.5	53.1	-0.721	0.009	3.070	0.007	162.5
2689	31-Jul-00	US06	81.1	52.7	n/a	0.009	2.705	0.076	164.4
2716	10-Aug-00	US06	74.5	51.8	-0.242	0.009	2.670	0.005	167.4
2739	16-Aug-00	US06	77.9	51.4	-0.130	0.006	3.740	0.006	166.9
			Average	52.3	-0.473	0.009	3.040	0.020	165.0
2691	31-Jul-00	US06	103.2	52.7	n/a	0.015	2.831	0.241	164.1
2729	14-Aug-00	US06	105.7	51.4	-0.169	0.013	3.720	0.004	167.1
2736	15-Aug-00	US06	105.0	52.6	-0.327	0.008	3.112	0.002	164.0
			Average	52.2	-0.248	0.012	3.221	0.082	165.0
2743		US06	32.0	49.7	-0.405	0.008	3.382	0.004	173.5
2750		US06	32.0	49.8	-0.339	0.007	3.146	0.008	173.5
			Average	49.7	-0.372	0.008	3.264	0.006	173.5

Table 7: Prius emissions (Lab tests)

<i>ETC Test Number</i>	<i>Test Date</i>	<i>Test Type</i>	<i>Test Temp (F)</i>	<i>Fuel Economy (mpg)</i>	<i>ΔAh</i>	<i>Emissions (g/mi)</i>			
						<i>HC</i>	<i>CO</i>	<i>NO_x</i>	<i>CO₂</i>
101104	02-Aug-01	FTP75	69.9	54.7	n/a	0.007	0.095	0.008	162.6
101121	03-Aug-01	FTP75 (3 bag weighting)	77.3	57.3	0.457	0.009	0.120	0.003	155.3
		FTP75 (4 bag weighting)		56.3	0.634	0.009	0.116	0.003	158.0
<i>Average</i>				56.0		0.009	0.116	0.003	158
10868	29-Jun-01	HWFET	72.7	54.9	n/a	0.002	0.168	0.002	161.8
101105	02-Aug-01	HWFET	74.5	59.1	-0.038	0.001	0.036	0.015	150.5
<i>Average</i>				57.2		0.001	0.091	0.008	155.7
101153	07-Aug-01	SC03 with AC on	98.9	37.0	0.237	0.004	0.152	0.002	240.3
101154	07-Aug-01	SC03 with AC off	94.8	53.3	0.085	0.002	0.028	0.025	167.1
101123	08-Aug-01	US06	75.6	41.8	0.068	0.006	0.243	0.003	212.6
101165	08-Aug-01	US06	31.5	36.6	0.078	0.004	0.563	0.005	242.2
101155	07-Aug-01	US06	99.8	40.3	0.063	0.004	0.260	0.006	220.3

For the Prius, a “4 bag” FTP was run to study the impact of running a second “stabilized phase”. Typically in an FTP three separate phases are run (see appendix for a graph of the drive cycle). The complete test includes a fourth phase, which is simply a repeat of the phase 2 driving cycle conducted at the end of the test. Phase 4 is not usually run because it is assumed that the results would be identical to bag 2. This may not be the case for HEVs since the battery SOC may be different at the beginning of the two phases (2 and 4). Table 7 shows results from a 3 bag test and a 4 bag test. The fuel economy during the fourth phase of this test (65.4 mpg) was substantially lower than fuel economy during the second phase (70.3 mpg). Therefore, the overall fuel economy is 1.0 mpg lower when the results from the fourth bag are included compared to when they are assumed to be identical to the third bag.

Table 8 shows a side-by-side comparison of ETC measured city and highway fuel economy along with the “unadjusted” EPA test certification test results. For the Insight, the ETC measured fuel economy over the HWFET cycle was 12% lower than that published by EPA, while the city fuel economy was within 6% of the EPA value. The Prius measured fuel economy was only slightly lower than the EPA numbers for both the city (FTP – 3% lower than EPA) and highway (HWFET – 0.9% lower than EPA) cycles.

Table 8: Comparison of fuel economy test results (mpg)

	<i>Insight</i>			<i>Prius</i>		
	<i>ETC Test</i>	<i>EPA Cert (unadjusted)</i>	<i>% difference</i>	<i>ETC Test</i>	<i>EPA Cert (unadjusted)</i>	<i>% difference</i>
<i>City</i>	64.0	67.8	5.6%	56.0	57.8	3.1%
<i>Highway</i>	79.0	89.7	12.0%	57.2	57.7	0.9%
<i>Combined</i>	70.8	77.7	8.9%	56.5	57.7	2.1%

From the graph below (Figure 18), we can see that the Insight had better fuel economy on all the cycles tested, but that the Prius typically had lower emissions for all but CO₂ (which is proportional to fuel use). The Insight exhibited a greater range of fuel economy results from one test type to another – i.e. comparing how it performed on the various cycles FTP, HWFET, US06, and SC03. The Insight fuel economy ranged from 79.0 mpg on the HWFET to 41.7 mpg on the SC03 with air conditioning (a range of 37.3 mpg). The Prius fuel economy ranged from a high of 57.2 mpg on the HWFET to a low of 37.0 mpg on the SC03 with air conditioning (a range of 20.2 mpg). The difference between the city and highway fuel economy for the Prius was less than 1 mpg, but for the Insight was 15 mpg.

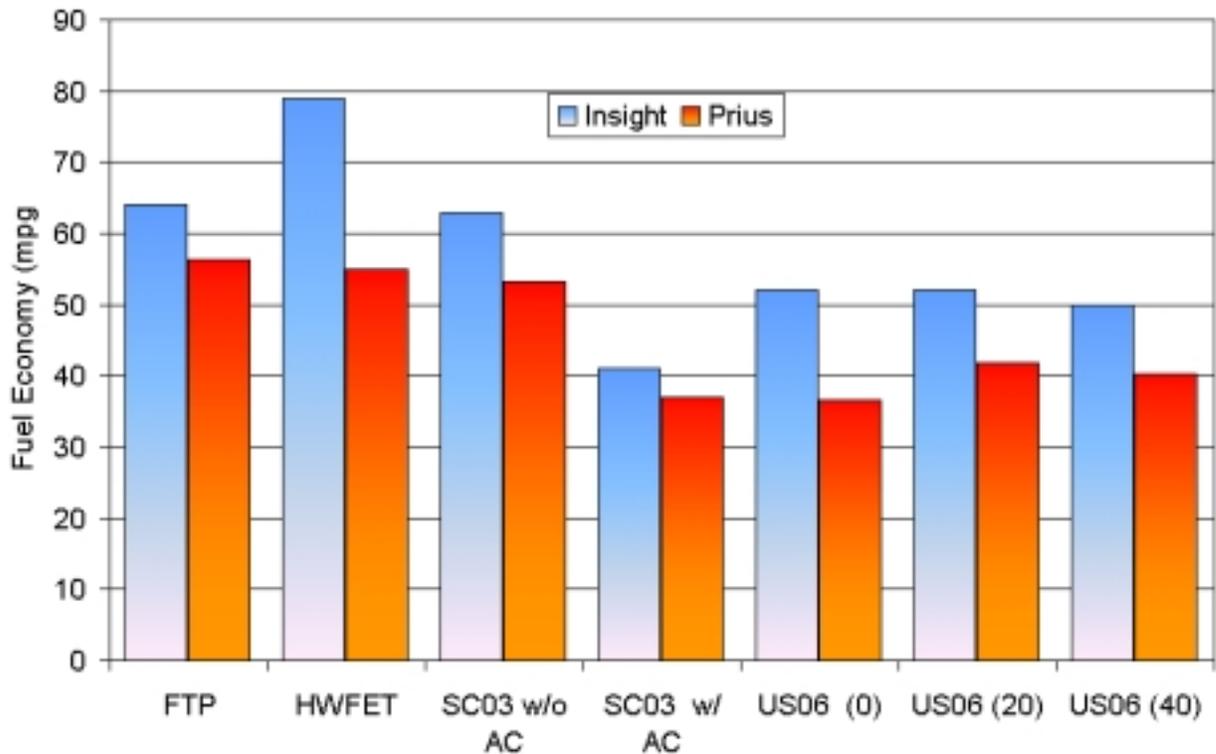


Figure 18: Comparison of fuel economy from NREL testing

Figure 19 simply shows that along with better fuel economy (lower fuel use) comes lower CO₂ emissions. This, at least partially answers a question that typically arises when discussing the Insight and Prius – “how can the Prius use more fuel but have lower emissions”. The answer (in part) is that the emissions standards do not apply to CO₂, which accounts for the majority of exhaust emissions (note the scale on this graph compared to HC, CO, and NO_x). The other part of the answer has to do with the drastic differences in how the vehicles use their engines, batteries, and motors, and also in the differences in emissions control devices as explained previously.

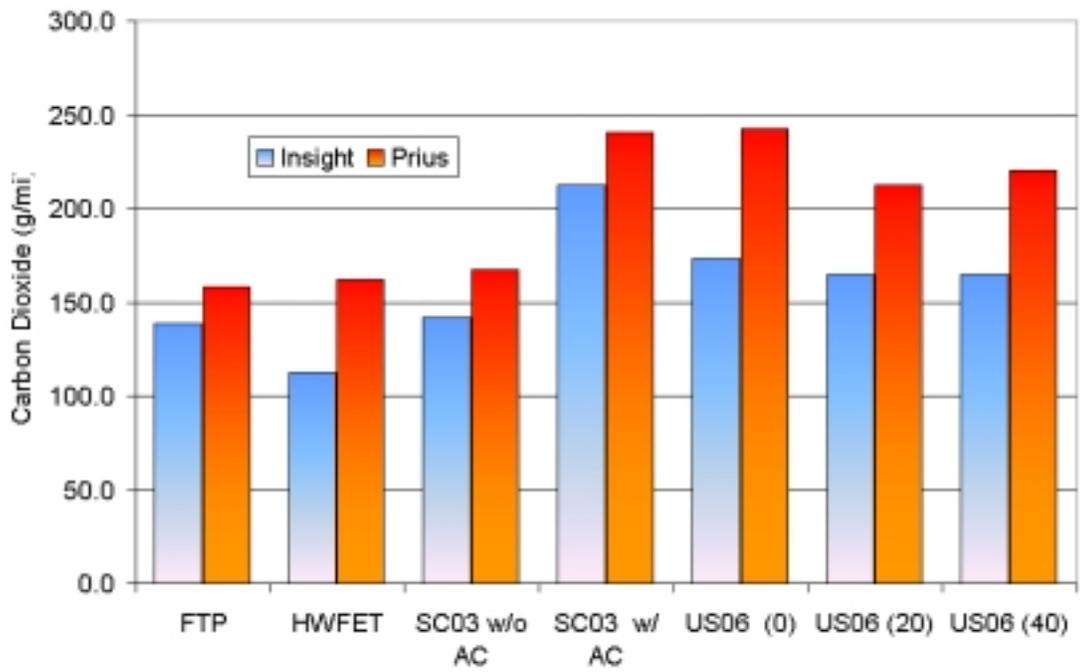


Figure 19: Comparison of CO₂ Emissions from NREL testing

Figure 20 shows that both the Insight and the Prius had higher HC emissions (the ULEV and SULEV emissions standards are shown on the emissions graphs as a point of reference) on the FTP cycle (the only cycle that includes a cold start of the engine). This is expected, but the difference between HC emissions for the FTP and other cycles is greater for the Insight than for the Prius. Figure 18 provides evidence that this may be due to the Prius’ HC adsorber technology that traps HC during while the catalyst is cold and releases back into the catalyst later in the cycle after it has reached light-off temperatures.

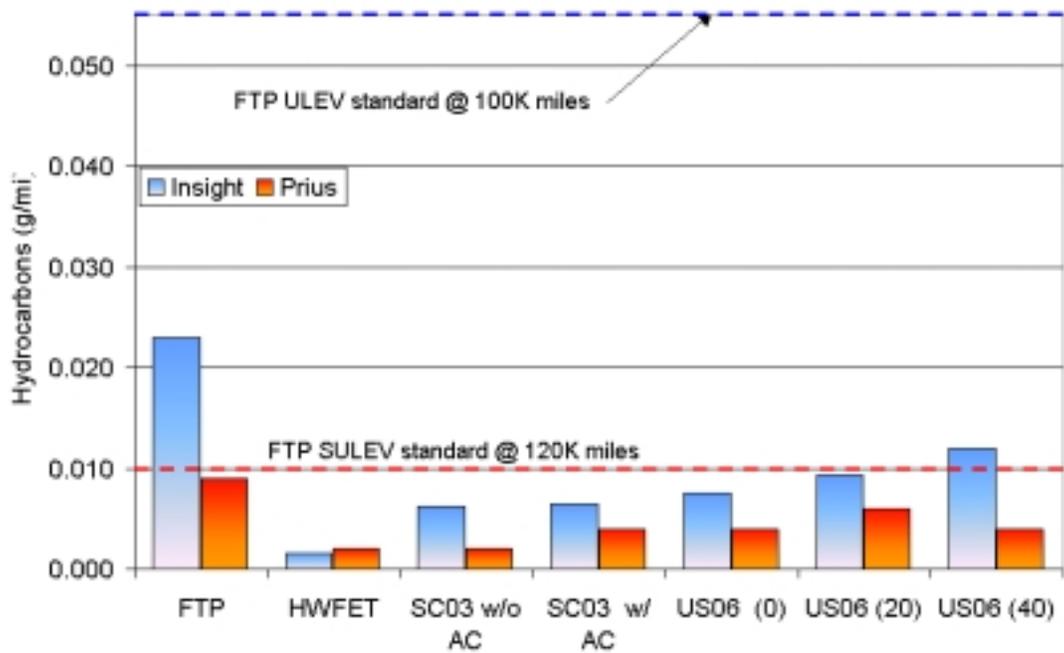


Figure 20: Comparison of HC Emissions from NREL testing

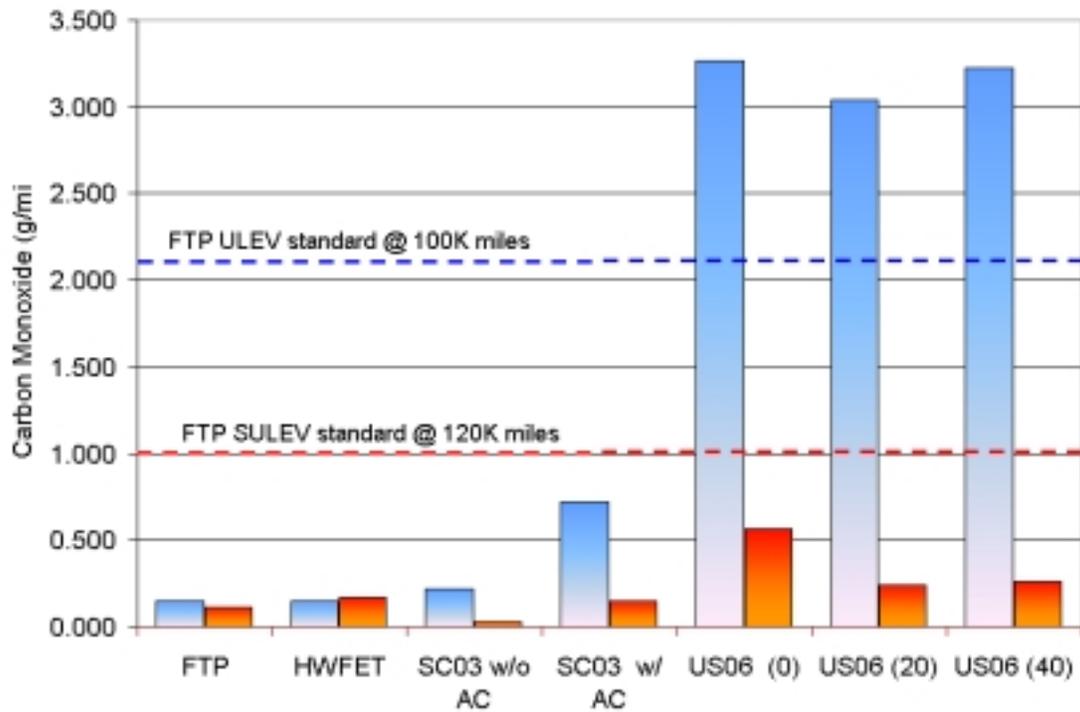


Figure 21: Comparison of CO Emissions from NREL testing

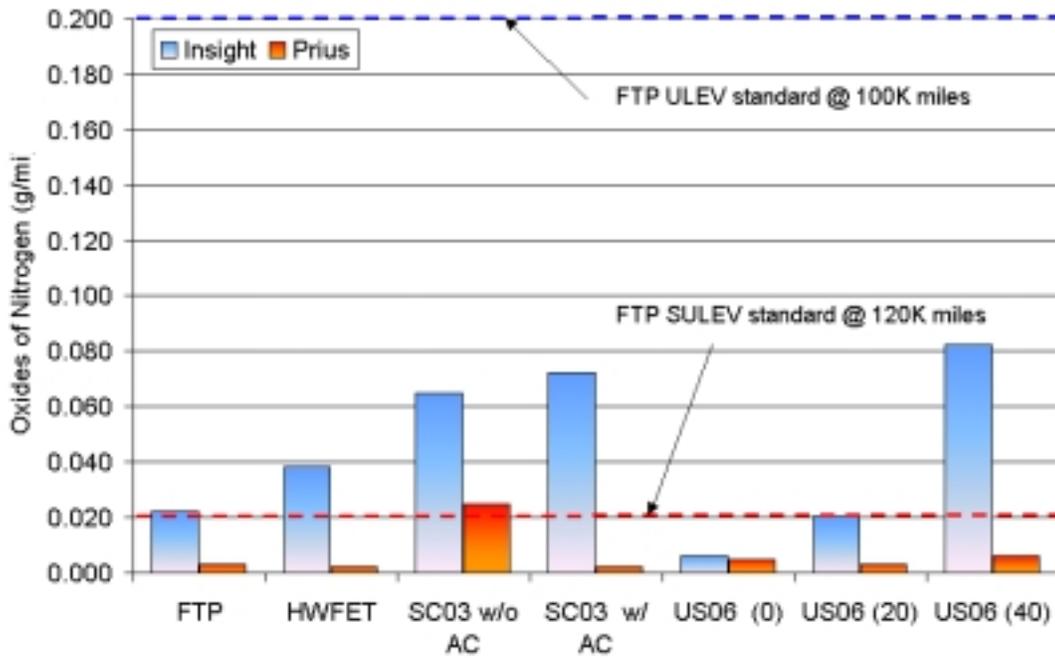


Figure 22: Comparison of NO_x Emissions from NREL testing

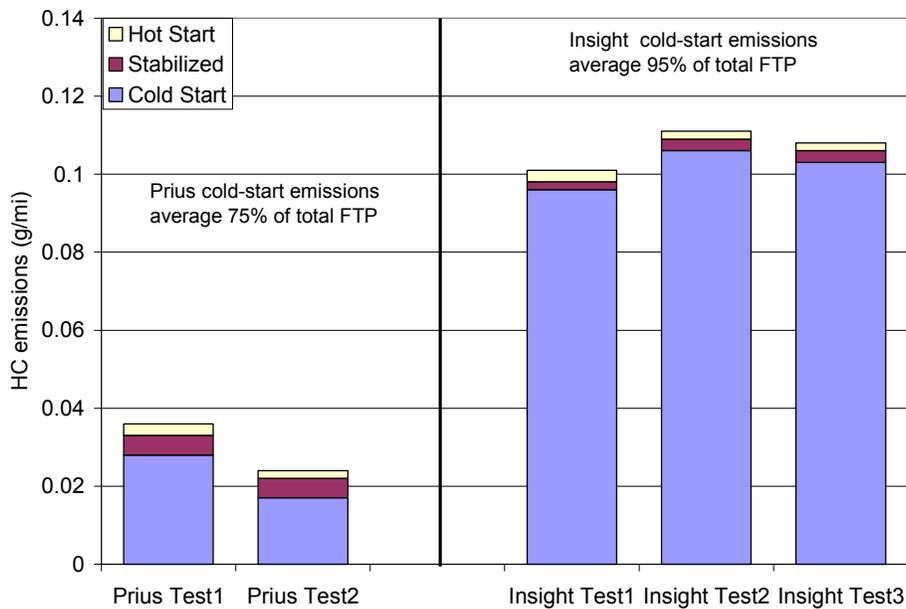


Figure 23: Emissions (Cold / Hot starts)

Figure 23 shows that while the Insight has higher hydrocarbon emissions, the majority of these emissions occur during the cold start phase of the FTP cycle. The Insight's cold start HC emissions make up 95% of the total cycle emissions, while the Prius' cold start

emissions were between 70-77%. HC emissions from Insight during the stabilized and cold start phases of the test are as low or lower than that of the Prius.

Figure 16 shows that the Insight had a dramatic increase in CO emissions during the US06 tests compared to the FTP. The Prius also showed an increase in CO emissions for the US06, but the increase was not nearly as great. One possible explanation is that the Prius' hybrid drivetrain and control system allow the gasoline engine to be operated in efficient regions and to dampen out the effects of transients. The US06 cycle is an aggressive driving cycle with very hard accelerations. The Insight's engine operation is directly tied to the vehicle speed. It should be noted that although the Insight was not certified on the US06 test, the NREL measured emissions of 3.26 g/mi were well below the US06 emissions standard of 8 g/mi for US06 certification.

The Insight also had higher levels and greater test-to-test variations in NO_x emissions. This was especially evident for the hot temperature tests such as the SC03 (performed at 35°C) and the hot US06 (performed at 40°C). Both of these tests include hard accelerations at high speeds, which may lead to high combustion temperatures and increased NO_x formation. Use of the hybrid system to better control engine transients during both of these cycles is likely to have helped the Prius maintain lower NO_x levels. One surprising result is that the NO_x was actually higher for the SC03 test without air conditioning for the Prius – an increase in NO_x is expected with the AC on. This conclusion will be verified with repeat tests during the coming weeks.

Vehicle Performance

The US06 is an aggressive driving cycle used by the EPA to account for certain real-world driving conditions such as hard accelerations, hard decelerations, and higher speeds. Compared to the FTP, the US06 has much harder acceleration rates (12.2 ft/s² max on the US06, compared to 4.8 ft/s² max on the FTP) and includes a portion of high speed operation (top speed on the US06 is 80 mph with a substantial portion above 60 mph, top speed on the FTP is 57 mph). Figure 24 & Figure 25 show how the Insight and Prius performed on this cycle. As described previously in the "Test Procedures" section, the US06 test procedure defined in the Code of Federal Regulations⁵ includes a warm-up cycle, followed by the "official test cycle". The cycle shown in the figures below is the "official cycle". Figure 25 shows that the Prius was able to follow this trace very closely. The Insight, on the other hand, missed the trace over significant portions of the cycle. The power deficiency appeared to have been exacerbated during the high temperature (40°C) tests. This appears to be related to high temperature limiting of battery power by the control strategy. The improved performance on the cold temperature (0°C) test is somewhat misleading, as the test shown here is the official phase, or 2nd cycle, of the US06. By this time the battery has warmed from an initial 0°C to approximately 12°C while the battery temperatures from the 20°C and 40°C tests have heated to a point where their performance may be limited by the vehicle's controls. This phenomenon is covered in greater detail in the FY2000 battery thermal management report¹ and in a paper presented at the 36th Intersociety Energy Conversion and Engineering Conference⁷.

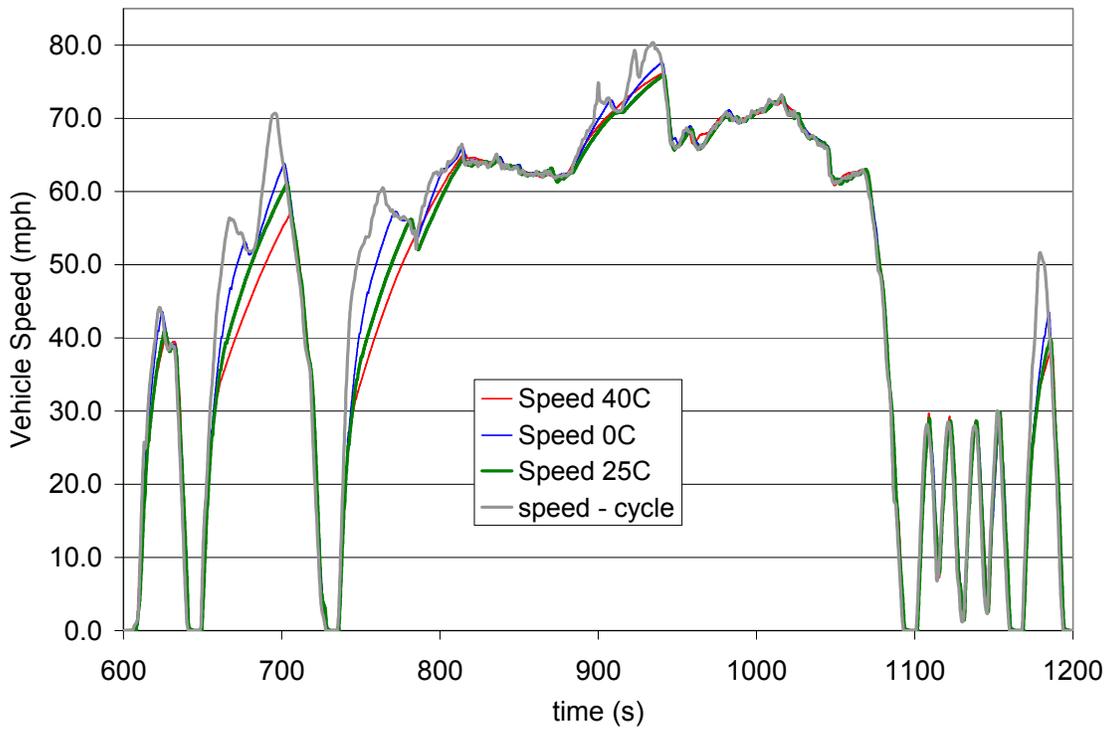


Figure 24: Insight on the US06

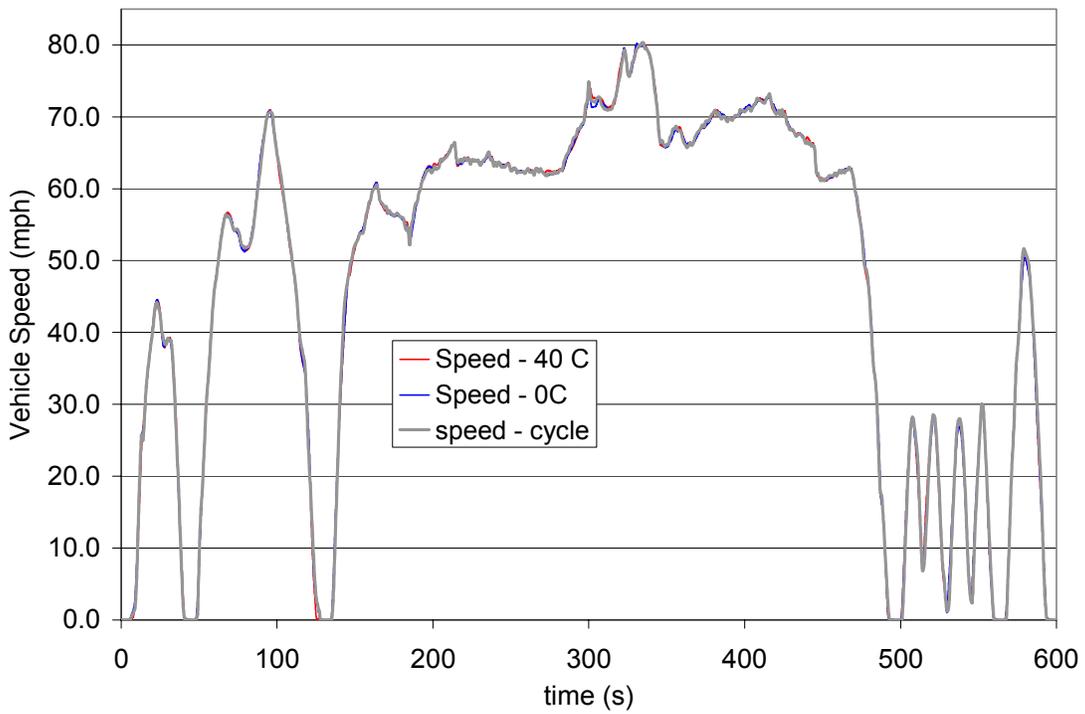


Figure 25: Prius on the US06

Engine speed control

The engine speed control in the Toyota Prius is independent of the vehicle speed (unlike the Insight). Figure 26 and Figure 27 depict the Insight and Prius engine speed for portions of the UDDS drive cycle. The Prius engine speed appears to be more dependent on vehicle acceleration than vehicle speed.

In Figure 26, it is seen that the engine in the Prius goes through relatively fewer transients, and can be steady even though vehicle speed varies. In the Insight, since the engine is connected through a discrete-ratio gearbox, the engine speed is dependent on vehicle speed and the current gear ratio.

In Figure 27, it is seen that the Prius engine shuts down more frequently than the Insight engine, for the same driving conditions. The Insight engine shuts down only if the engine is warm, gear is put in neutral, and the vehicle speed is approximately below 10 mph. One would expect the Insight engine to shut down only during idle and when the vehicle is stopped, since the engine has to be spinning for the motor to regenerate during decelerations. Shutting down the Insight engine during most decelerations would deprive the electric motor of its regenerative capacity.

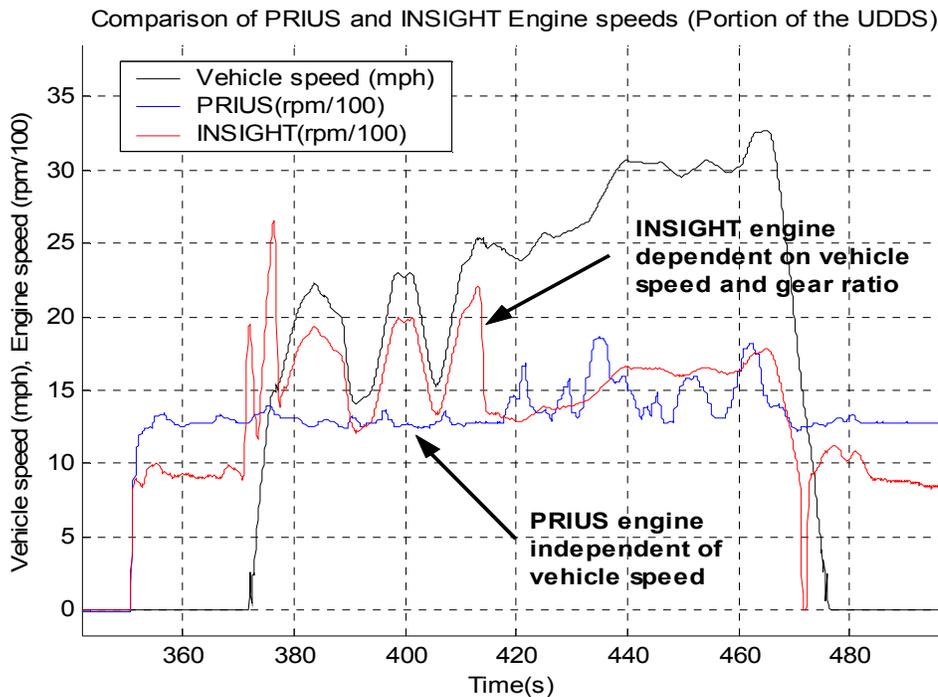


Figure 26: Engine speeds of Prius and Insight on the UDDS

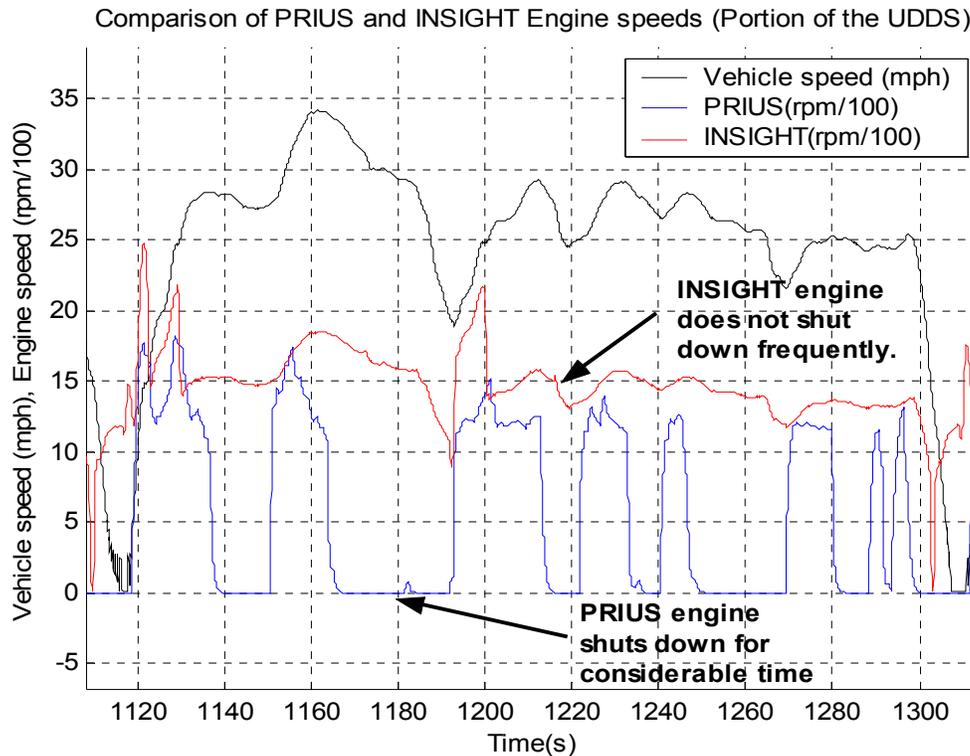


Figure 27: Engine speeds of Prius and Insight on the UDDS

One of the important aspects and differences in the vehicle control is the amount of time that the vehicle operates with engine off. Figure 28 shows the Prius engine speed and vehicle speed during the cold start and hot start phases of the FTP cycle. For both vehicles, the engine will not shut off until it has warmed up. Figure 28 shows that during the cold start phase of the FTP the Prius engine does not shut off until approximately 5 minutes into the driving cycle, when the engine coolant temperature has reached 83°C. Over the first two phases of the FTP drive cycle, the Prius engine is off 46% of the time (20% of the time is during vehicle stops). This is compared to the Insight where the engine only shuts off only when the engine is hot and the vehicle is stopped or decelerating below 20 mph, which accounts for 18% of the same time period .

On the HWFET test, which does not have any stops during the cycle, the Prius engine was off during 4% of the cycle while the Insight engine did not shut off. Engine-off operation during the hot US06 cycle occurred 16% of the time for the Prius and only 7% of the time for the Insight.

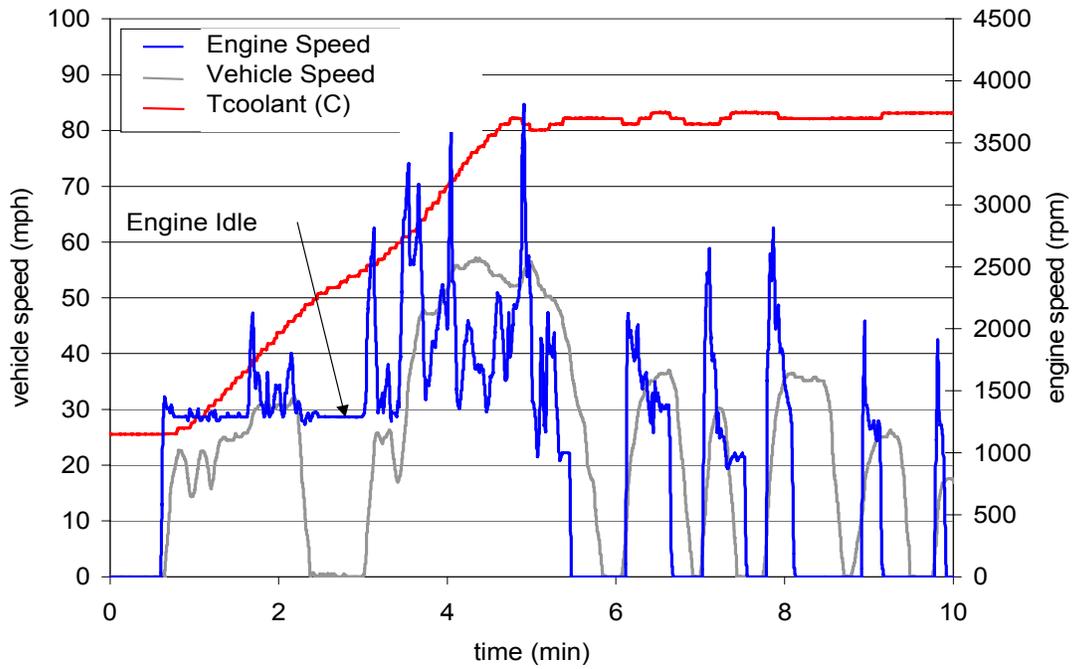


Figure 28: Engine-off characteristics (Prius)

Battery Pack Performance on Standard Drive Cycles

Pack Energy Use

An important consideration for HEVs is the extent to which they utilize the battery pack. Table 9 and Figure 29 provide several insights into how the battery is used for each of the vehicles over the standard test cycles. The basic parameters used to make these comparisons include:

- fuel energy used over the cycle, which was calculated from the amount of fuel used multiplied by a fuel energy content of 31.5 kJ/L
- delta Ah is based on the Ah integration of the battery current data
- regen, assist, and auxiliary energies were calculated by integrating the power (voltage x current) over the cycle
- net pack energy is the amount of energy stored in the battery pack minus the amount drawn over a given cycle (regen – assist – auxiliary)
- total energy transferred to and from the pack over a given cycle is the regen, plus the assist, plus the auxiliary energies combined (Shown in Figure 29 and Figure 30)

Table 9: Battery pack usage – average energy analysis

<i>Test Type</i>	<i>Fuel Economy (mpg)</i>	<i>Fuel Energy (kJ)</i>	<i>Delta Ah</i>	<i>Net Pack Energy/ Fuel Energy</i>	<i>% of Ah Capacity</i>	<i>Average Aux Power (W)</i>
<i>Honda Insight</i>						
FTP	64.1	2.05E+04	-0.04	0.12%	-0.55%	113.7
HWFET	79.0	1.55E+04	0.00	0.12%	0.03%	218.5
US06 0°C	49.8	1.92E+04	-0.37	-0.49%	-5.73%	200.4
US06 20°C	52.1	1.83E+04	-0.36	-0.81%	-5.61%	264.8
US06 40°C	52.0	1.83E+04	-0.25	-0.45%	-3.81%	425.6
SC03 no AC	62.5	6.85E+03	0.15	1.65%	2.29%	165.7
SC03 with AC	40.2	1.06E+04	-0.21	-0.43%	-3.20%	894.5
<i>Toyota Prius</i>						
FTP 4bag	56.3	3.16E+04	0.63	0.63%	9.75%	209.0
HWFET	59.1	2.07E+04	-0.04	-0.99%	-0.58%	259.2
US06 0°C	36.6	2.61E+04	0.23	0.90%	3.56%	389.1
US06 20°C	41.8	2.28E+04	0.07	0.38%	1.05%	284.8
US06 40°C	40.3	2.37E+04	0.06	0.06%	0.97%	334.0
SC03 w/o AC	53.3	8.01E+03	0.08	-0.18%	1.30%	323.0
SC03 with AC	37.0	1.15E+04	0.24	-0.99%	3.65%	807.4

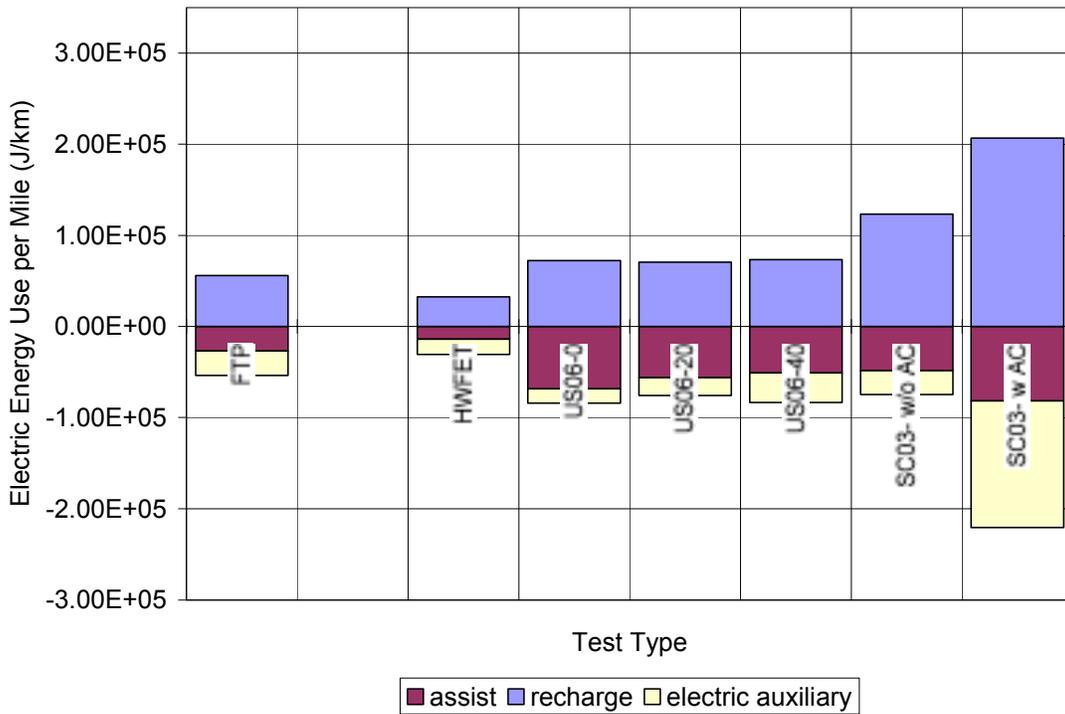


Figure 29: Electrical energy usage per mile (Insight)

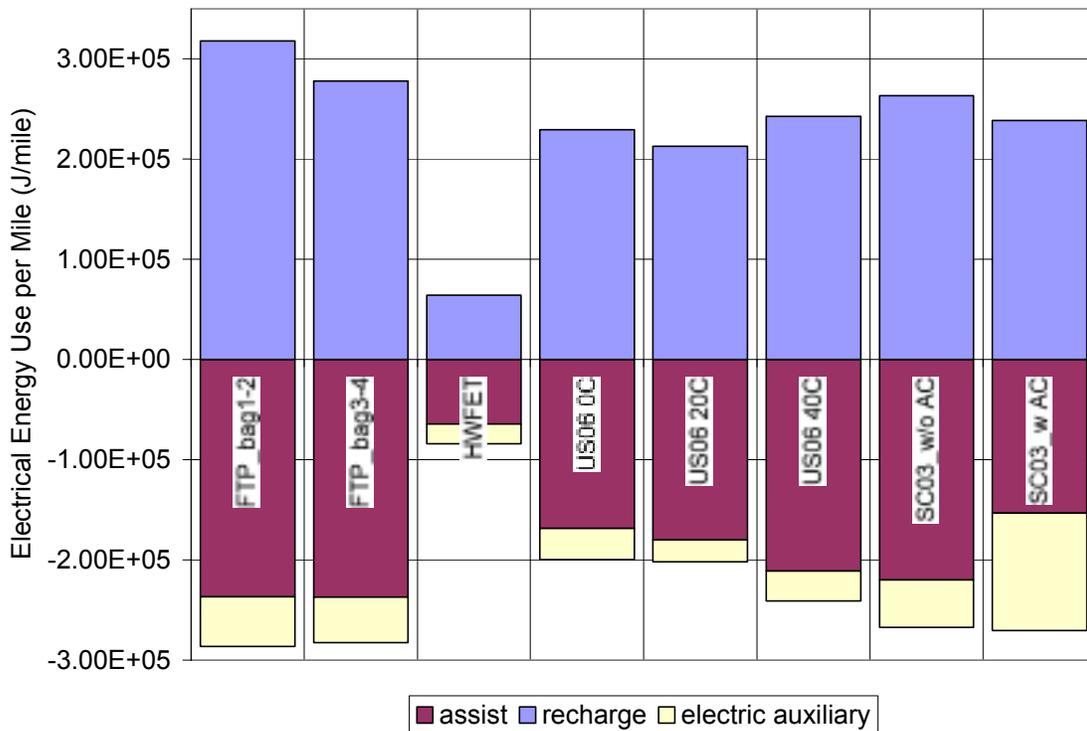


Figure 30: Electrical energy usage per mile (Prius)

Examination of Figure 30 shows that the Prius uses 3x-5x more electrical energy than the Insight depending on the driving cycle. This is expected since the Prius' electric motor has three times the power of the Insight, and the Prius utilizes the all-electric mode of operation, where the Insight cannot. The amount of energy used by the electric motor and auxiliary systems (shown as negative reddish and yellow bars respectively) is typically similar in magnitude to the amount returned to the pack through regenerative braking or charge currents (positive blue bars). The graph shows how the amount of energy used varies for different driving cycles. For both the Insight and the Prius, the least amount of battery energy used occurs during the HWFET. This is expected since this drive cycle is the least transient (the average acceleration rate is only 0.63 ft/s^2). The HWFET has only one acceleration from stop and one complete stop at the end. The remainder is fairly steady driving at highway speeds.

Compared to the HWFET, the Insight used about 2x more electrical energy used for motor assist on the FTP, 4x more on the US06, 3.5x more on the SC03 without AC, and nearly 6x more assist on the SC03 with the AC on.

By contrast the Prius used 3.6x more energy for the motor on the FTP compared to the HWFET, between 2.6x and 3.3x more on the US06, 3.4x more on the SC03 without AC, and only 2.4x more on the SC03 with the AC on.

For the Insight, use of the AC during the SC03 cycle appears to put enough of a mechanical load on the engine to require much more electric motor assist in order to meet the driving trace. This is shown graphically in Figure 31 below. This does not appear to be the case for the Prius. The average auxiliary power supplied over the SC03 cycle (see Table 9) with AC on was relatively similar for both the Prius (807 W) and the Insight (894 W), and was much higher than the 100-300 W used in auxiliary loads on other driving cycles. The Insight also showed higher auxiliary loads on the US06 cycle at 40°C . This is partially due to the battery pack cooling fan that remained on constantly during this hot cycle.

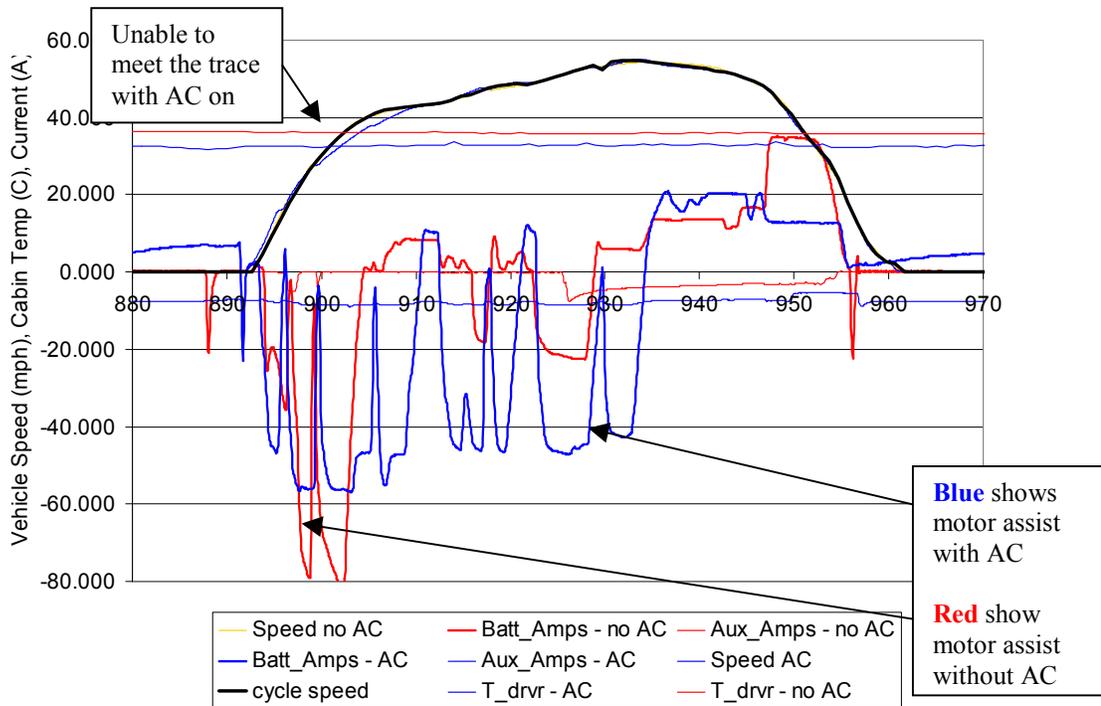


Figure 31: Performance with and without AC (Insight)

Table 9 also shows battery usage expressed as change in Ah over the cycle. For the Insight the delta Ah's ranged from 0.15 (net increase in charge) on the SC03 without AC to -0.37 (net decrease in charge) on the US06 cycle tested at 0°C. When expressed as a percentage of battery pack rated capacity (6.5 Ah) this range is from a 2.3% increase in charge to a -5.7% decrease in charge. Another way to look at battery usage is to express it as a percentage of the fuel energy used as is done by SAE J1711 HEV test procedure. When looking at the energy use in this way, net pack energy usage is generally low in comparison to the fuel energy used over the cycle. For the Insight the net pack energy use was as low as 0.12% of fuel energy use on the FTP and HWFET tests to 1.65% of fuel energy used on the SC03 cycle.

As has been described the Prius uses more battery pack energy. This is due to the larger electric motor, higher voltage battery pack, and the control strategy/drivetrain configuration that allows significantly more contribution from the electric machine. On the other hand, the Prius tends to tightly control the battery SOC under most driving conditions. On an average, the change in Ah for 4 out of the 7 tests run was less than 0.1 Ah, including the HWFET, US06 at 20°C and 40°C, and the SC03 without AC. For the US06 at 0°C and the SC03 at with AC there was a net increase in charge by 0.23 and 0.24 respectively. Surprisingly the FTP (4 bag) showed a 0.63 Ah increase. The net pack energy used on the Prius was less than 1% of the total fuel energy used for all the driving cycles.

SOC Control

Figure 32 through Figure 34 contrast how the Insight and Prius control the use of the battery pack. In Figure 32, the Insight battery usage (expressed in Ah) is shown for 5 back-to-back repeat cycles of the FTP driving trace. Over these cycles the Insight pack is continually charged. The Ah profile from cycle to cycle is nearly identical. Figure 33 shows the profile of SOC for the first two phases of the FTP cycle for several initial starting SOC levels. As long as the battery SOC remains between 20% and 80% SOC the general shape of this profile does not change. In the case of the Prius, Figure 34 shows the battery SOC for three separate LA4 cycle that were started at different SOC levels (80%, 50%, and 40%). This figure illustrates how the Prius rapidly brings the battery SOC to its target of approximately 56% during the LA4 cycle. The battery usage in the Prius is dramatically affected by the SOC whenever it strays from its target. Therefore, for the Prius, it is very important to start a test procedure near the SOC target. Otherwise, the vehicle will spend the first portion of the test correcting the SOC level towards the target. As an example, for the case when the LA4 was started at 40% SOC, even though the engine was already hot, the vehicle controls did not allow the engine to shut off for the first time until it reached the target SOC (around 400 seconds into the cycle).

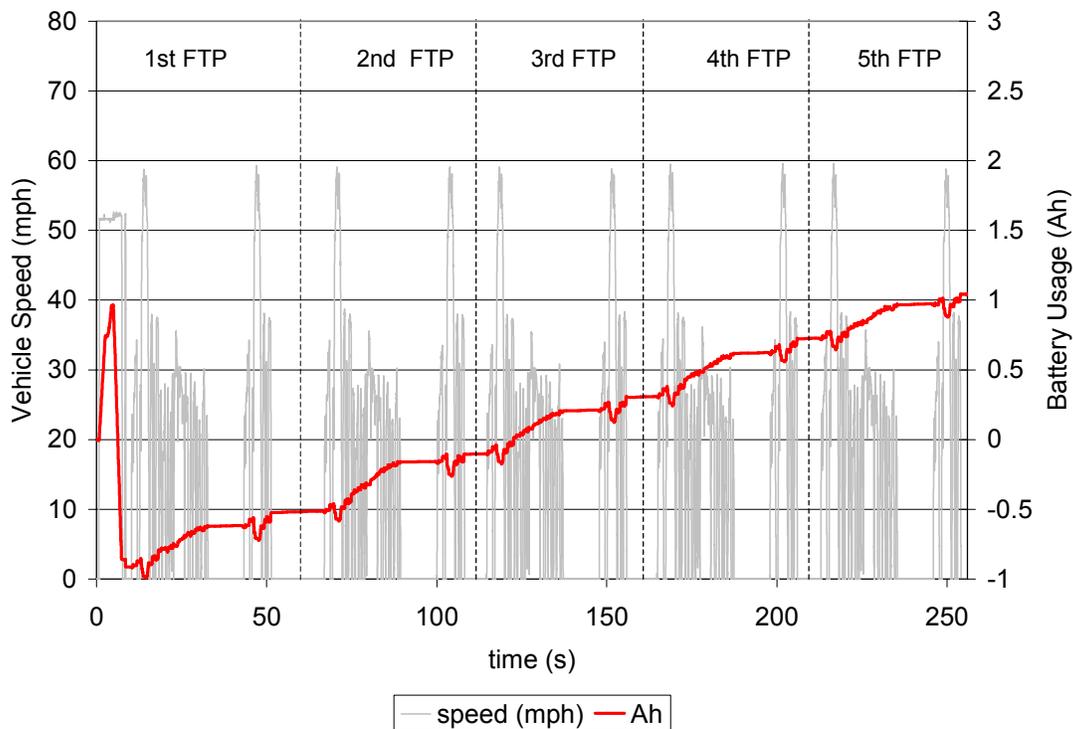


Figure 32: Battery SOC over 5 UDDS cycles (Insight)

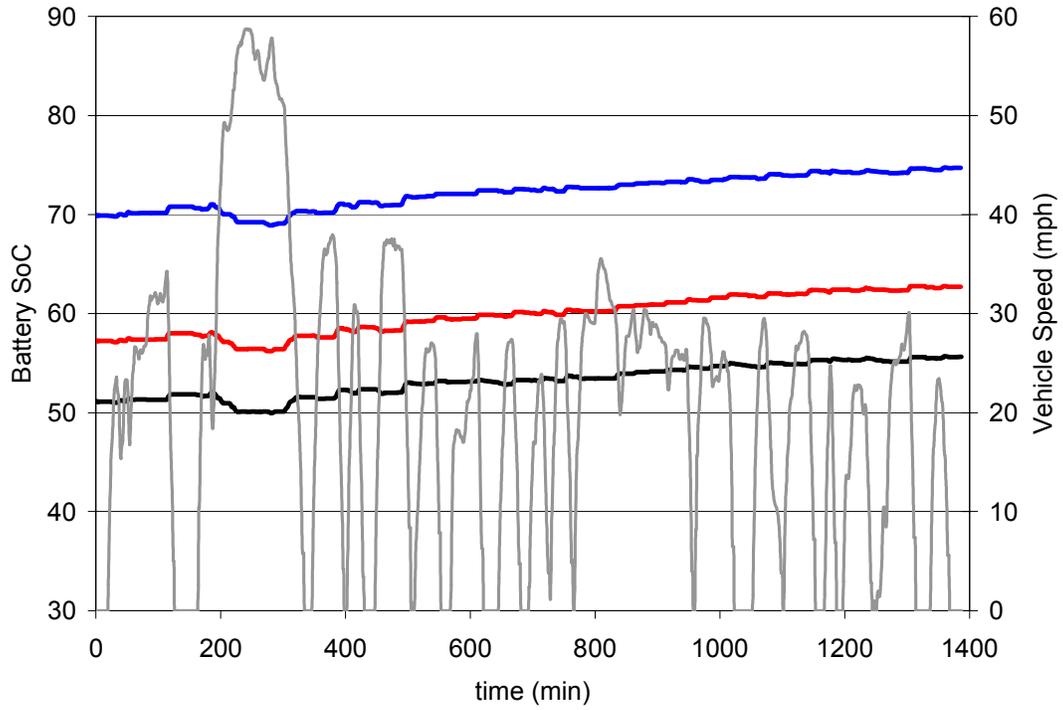


Figure 33: Battery charge over the UDDS (Insight)

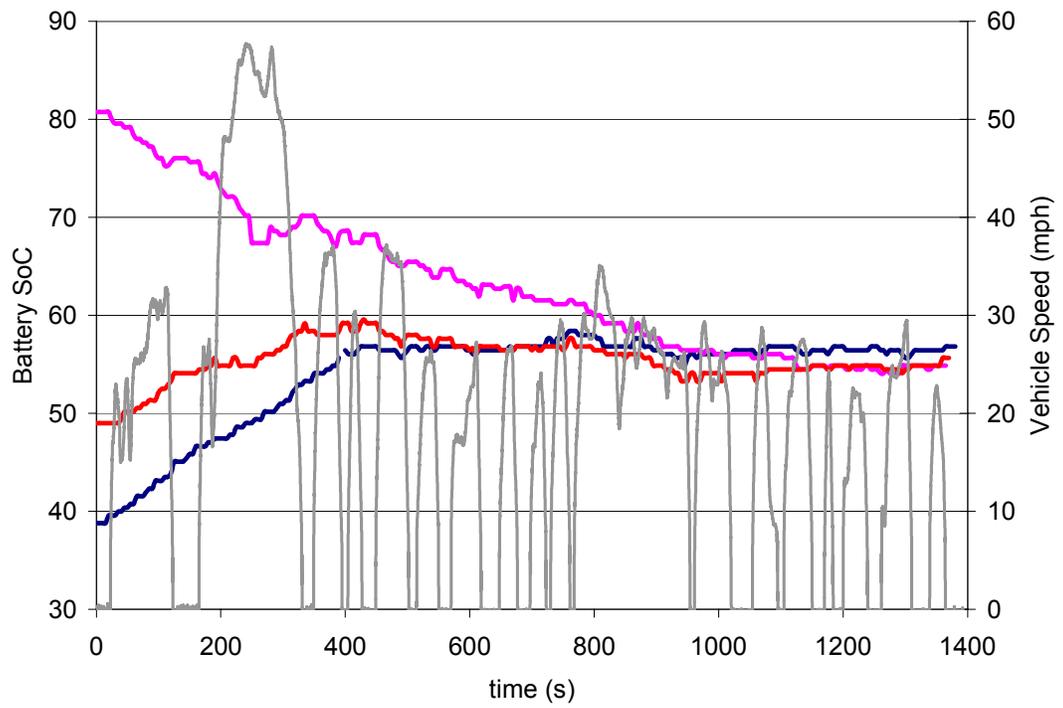


Figure 34: Battery SOC over the UDDS (Prius)

Battery Pack Temperatures

Figure 35 through Figure 38 provide a comparison of battery pack temperature distributions for the Insight and Prius over the FTP, US06 at 0°C, and US06 at 40°C. These figures show a temperature distribution along the length of the pack during various stages of the test procedure. In Figure 35 and Figure 36, the battery temperatures are shown for the Insight and Prius at the beginning (thick blue) and end (thick red) of the FTP procedure. Intermediate temperatures are also shown at the end of the first and second phase (cold start and stabilized phases). T_delta denotes the difference from the beginning to the end of the FTP. Battery air coolant inlet and outlet sides are denoted on the graphs for reference. For the FTP tests, the vehicles were soaked overnight at approximately 27°C to 28°C.

For the Insight, the average pack temperature at the beginning of the test 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 3 bag 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 average temperature at the beginning of the test was 26.6°C with a difference across the pack of 2.3°C. By the end of the three-bag FTP cycle, the average pack temperature had risen to 31.2°C with a difference of 4.2°C across the pack.

So, for the FTP 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. 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.

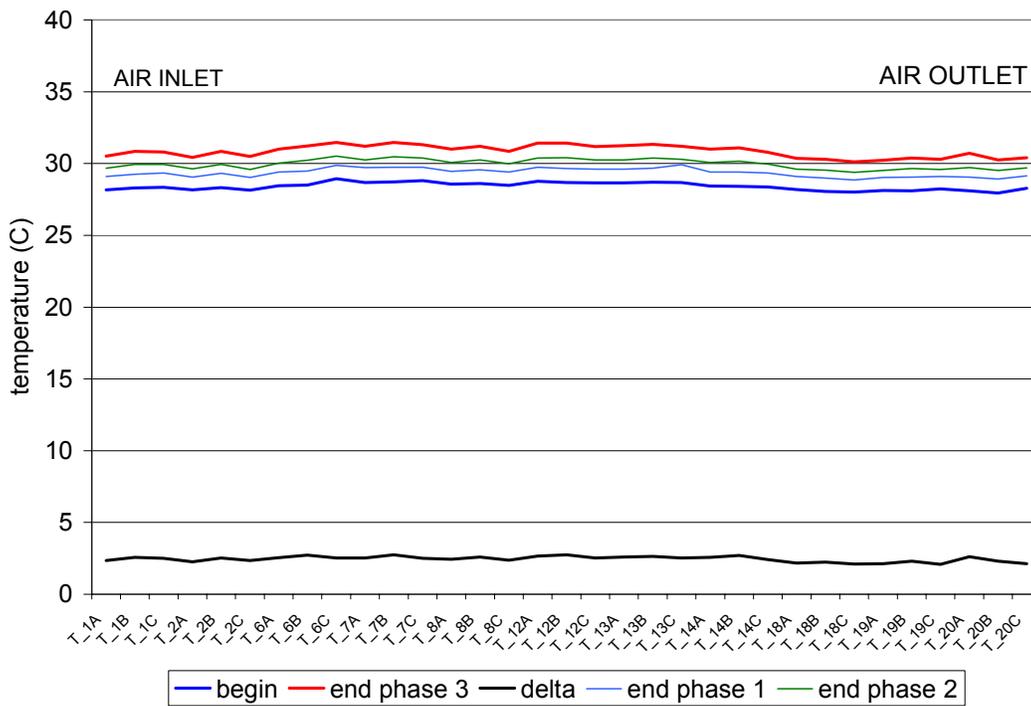


Figure 35: Battery pack temperatures during the FTP (Insight)

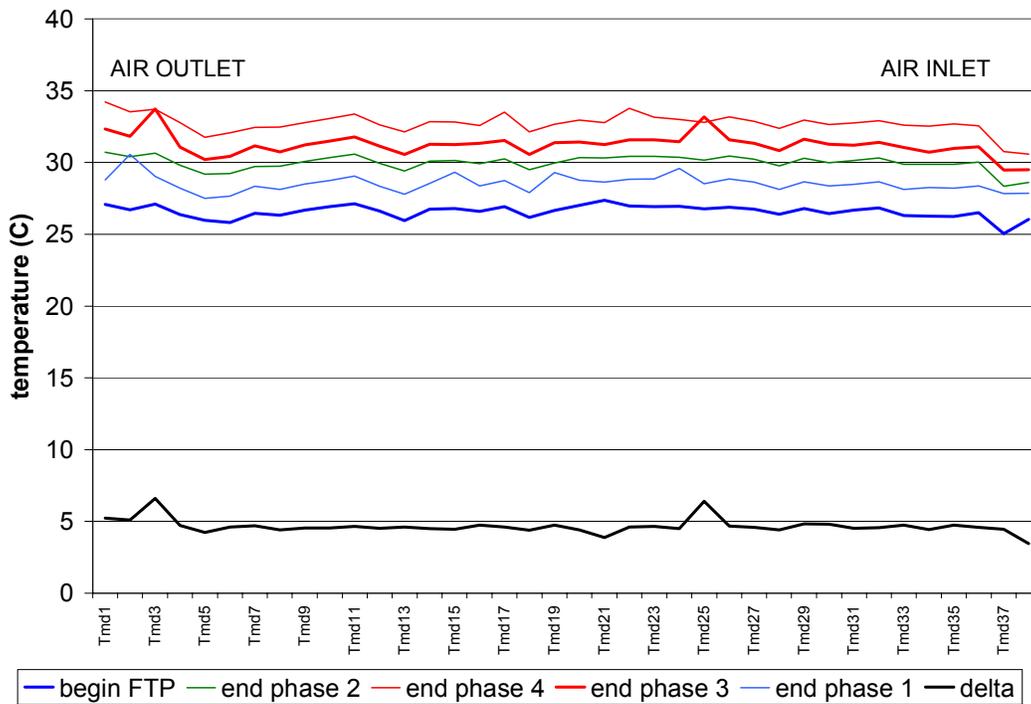


Figure 36: Battery pack temperatures during the FTP (Prius)

As expected with the more aggressive US06 test, the changes in battery pack temperature were higher for both vehicles (see Figure 37 and Figure 38). Data from these tests includes temperatures at the beginning of test procedure and at the end of two back-to-back US06 cycles. The first cycle is started at the soak temperature, and the second cycle follows immediately after the first. Summary data is shown in Table 10 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, it appears that 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 at dissipating heat energy.

Table 10: Battery pack temperatures

	<i>Insight</i>		<i>Prius</i>	
	T_{avg}	T_{dist}	T_{avg}	T_{dist}
0°C soak tests				
begin 0°C	-1.0	2.1	3.2	4.2
end 1 st cycle	9.3	1.5	9.1	4.3
end 2 nd 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 1 st cycle	42.2	2.0	44.5	3.8
end 2 nd cycle	44.6	1.2	47.9	4.3

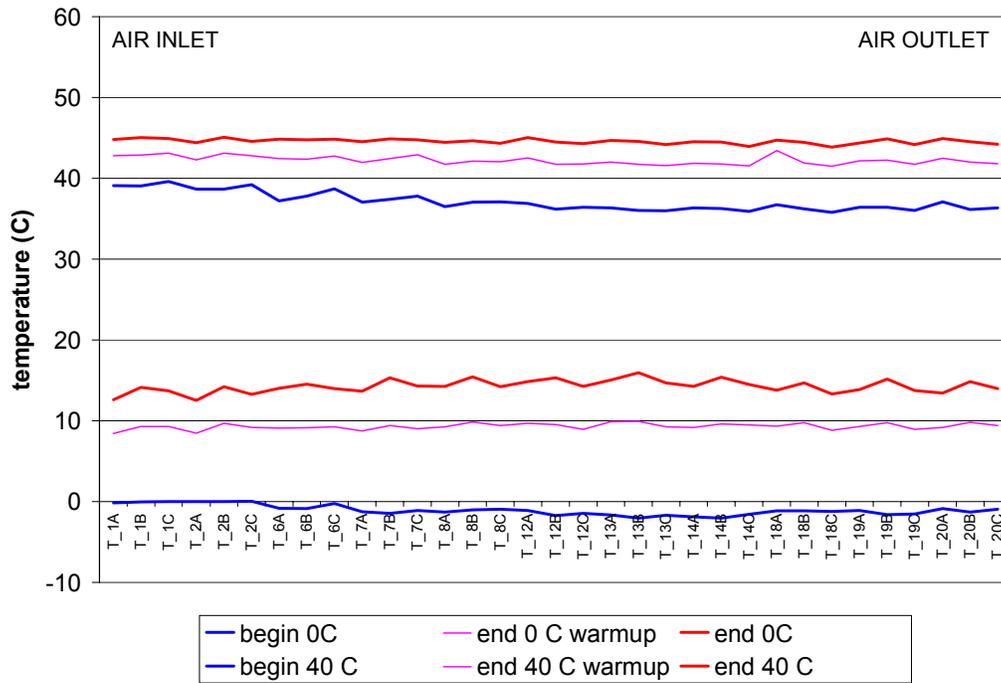


Figure 37: Battery pack temperatures during the US06 (Insight)

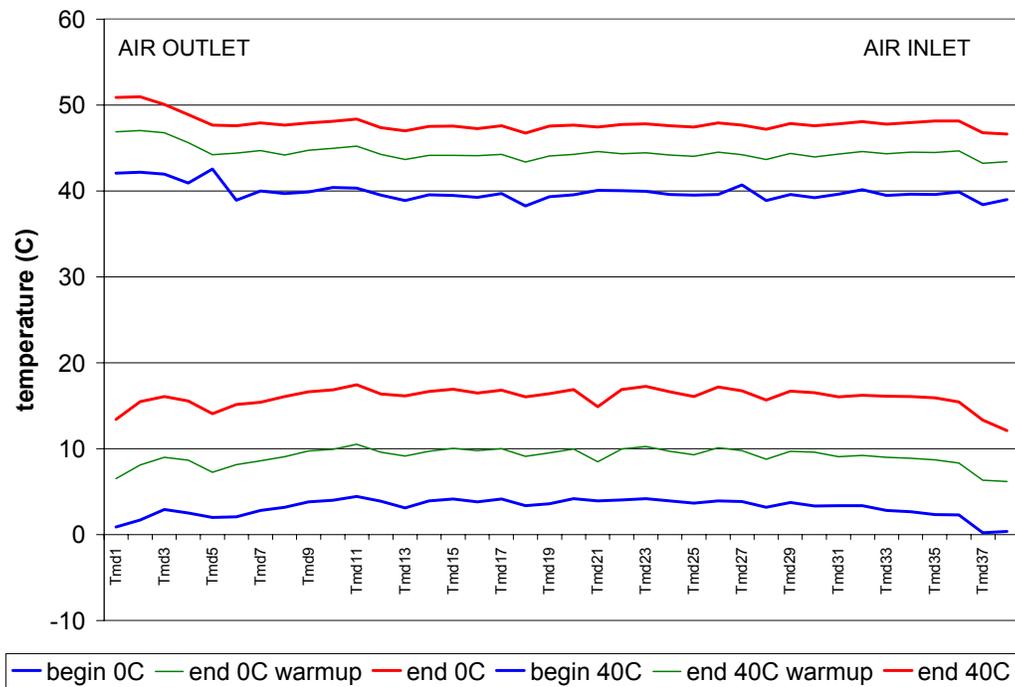


Figure 38: Battery pack temperatures during the US06 (Prius)

Battery Pack Behavior under non-standard Test Conditions

One of the first elements of testing for both vehicles was to understand the control limits of the battery pack. Both packs are rated at 6.5 Ah, but it was discovered that the two vehicles use this capacity differently. One fairly simple test that can be performed on the electric dynamometer at ETC is to fully charge the vehicle and fully discharge the vehicle. Charging was accomplished by using the dynamometer to motor the vehicle's wheels and send current to the pack. Discharging was accomplished by attempting to overcome inertia and loading applied by the dynamometer. This procedure was repeated for both vehicles. The results are described below.

Honda Insight

Using the procedure described above, it was determined that the Insight allows approximately 60% of the rated capacity to be utilized under hard charge and discharge conditions. Additionally, we found that these conditions tend to add a significant amount of heat to the battery pack, and that the vehicle seems to compensate by limiting the amount of current available from and to the pack.

Figure 39 shows a typical charge cycle on the Insight. The figure shows that during charging from the low limit to the high limit, approximately 3.78 Ah (or 58% of the rated 6.5 Ah capacity) were added to the pack at a rate of between 24 A and 28 A. Once the high limit is reached, the vehicle control strategy quickly cuts off further charging by dropping the input current to 0 A. Maximum, minimum, and average battery module temperatures indicate that during this cycle the average temperature of the pack was increased by approximately 8°C, and the distribution of temperatures across the pack increased from about 2.5°C to 5.0°C.

Subsequent to charging, the vehicle was then shifted into high gear and the driver gave it full throttle to attempt to overcome the dynamometer loading and thereby discharge the pack. Figure 40 shows the results. During this procedure approximately 3.7 Ah, or about 57% of the rated capacity was drawn from the pack. Initially the current draw ranged from about 39 to 46 A. Then, after about 2.6 Ah (with the SOC at approximately 40%) the current allowed for motor assist quickly tapered down to approximately 6 A and remained there until the SOC dropped to 20%. At that point, no additional current draw from the battery was allowed. During the discharge cycle the average battery pack temperature increased by approximately 7°C (from 46.5°C to 53.3°C). Once the current was limited to 6 A, the battery temperatures began to decrease. The temperature distribution across the pack went from 5°C at the beginning of the cycle to 7°C at the end.

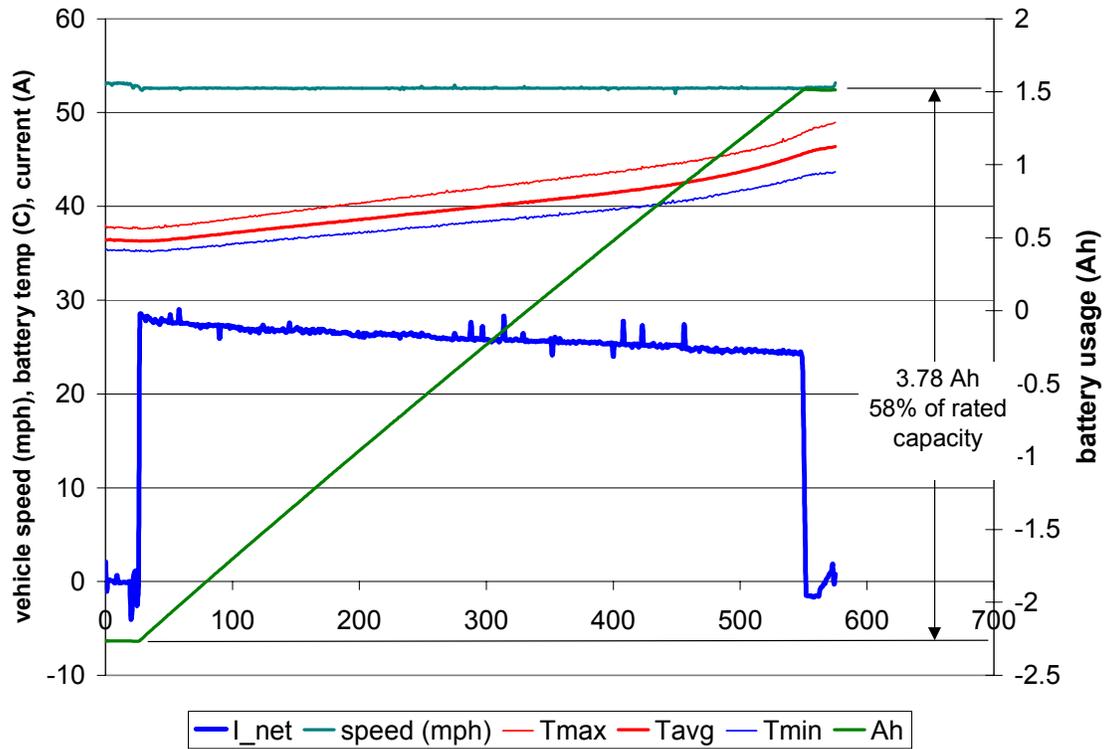


Figure 39: Charging the battery (Insight)

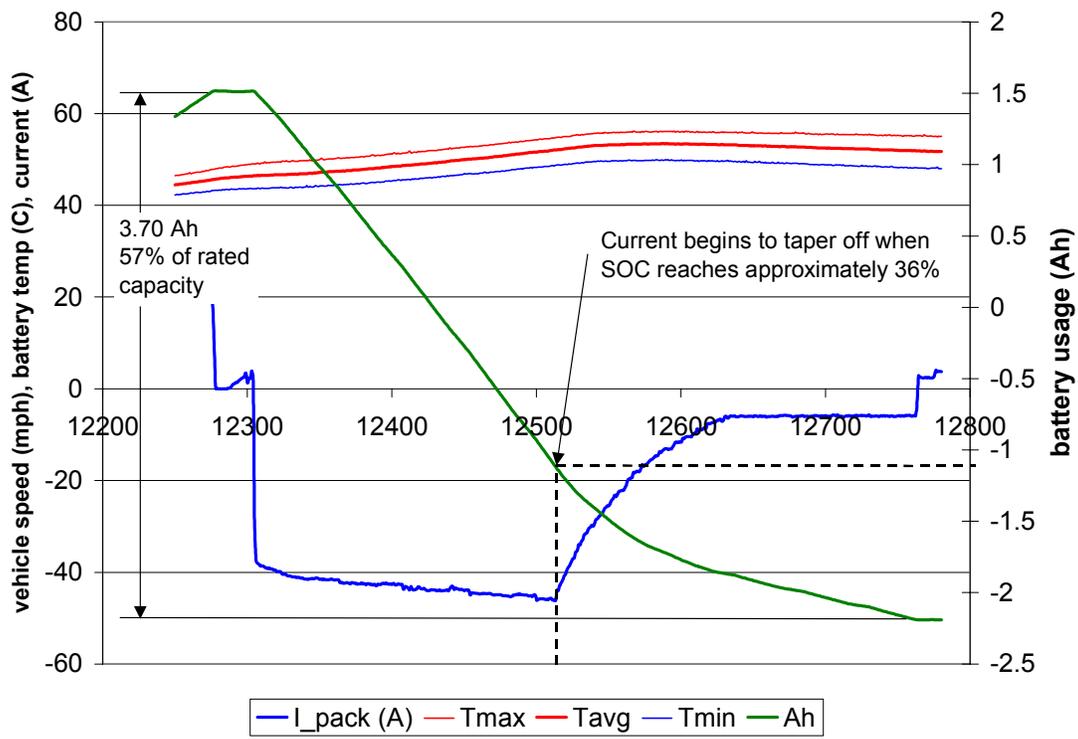


Figure 40: Discharging the battery (Insight)

A very similar controlled response was observed while driving the vehicle on the highway near Golden, CO. The Insight was driven west from NREL on I-70 up a long, steady incline (2040 feet in 8.8 miles) at speeds between 60 – 70 mph. While this type of driving, which included traffic and changing road conditions (there are a couple of relatively level areas along the grade), a plot of current, Ah and battery temperatures vs. time shows some very similar behavior compared to the dyno discharge cycle. Maximum current levels ranged between 39 A and 44 A until an SOC of 36% was reached then the amount of available electric assist tapered off to around 6 A until the low state of charge of 20% was reached. Note that the SOC at the bottom of the grade was 64%, the vehicle began limiting electric assist after only 3 miles up the 8-mile grade. Finally, electric assist was completely cut out 0.5 miles from the top.

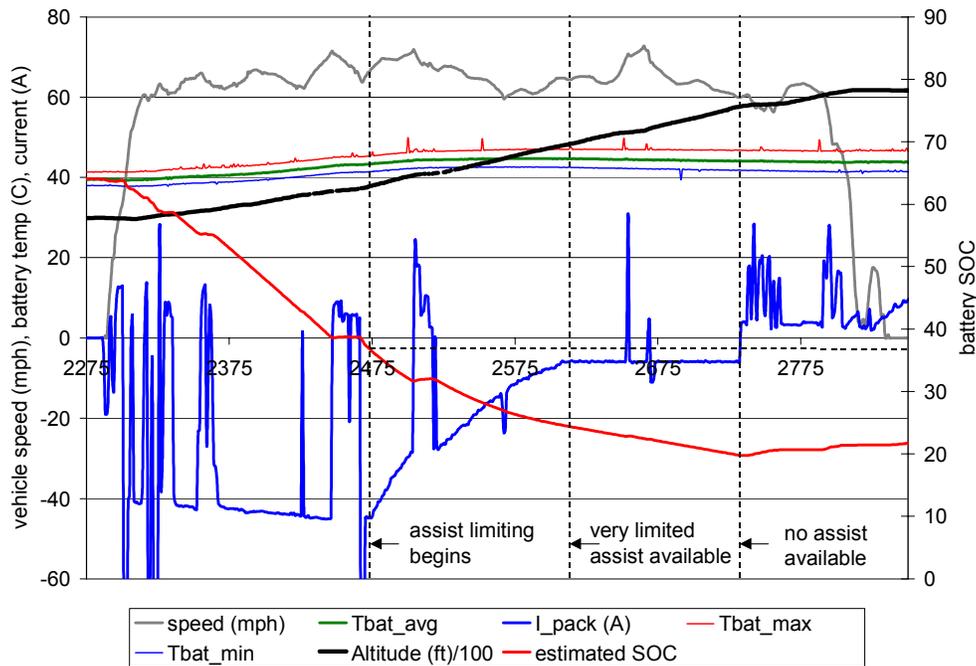


Figure 41: Real world mountain driving on the Insight

Figure 42 shows the power delivered to the motor (current x voltage) as a function of battery SOC during the period where the assist is tapering off. In the region below 36% SOC, the power available from the electric motor decreases linearly from 6kW to around 800 W. This particular example is for the on-road data collection. A very similar relationship was observed for the dynamometer discharging cycles.

Another characteristic that was observed during the charge and discharge cycling is shown in Figure 43. This figure shows the behavior of the current supplied to the electric motor when the discharge cycle was followed by a second charging cycle. By the end of the discharge cycle the battery temperature had exceeded 50 C, and when a second charging was attempted, it was noticed that the pack would not accept the same level of charge. The stair-stepping, or limiting, of charge current shown in Figure 43 appears to

be a method for controlling battery temperature by limiting the power allowed to the pack.

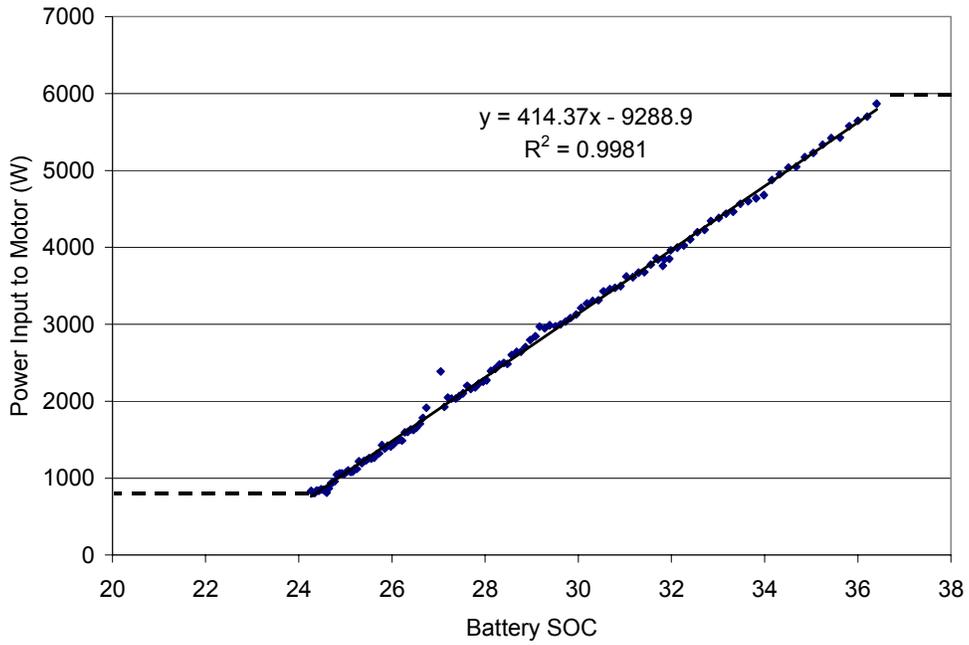


Figure 42: Battery limiting characteristics for low SOC (Insight)

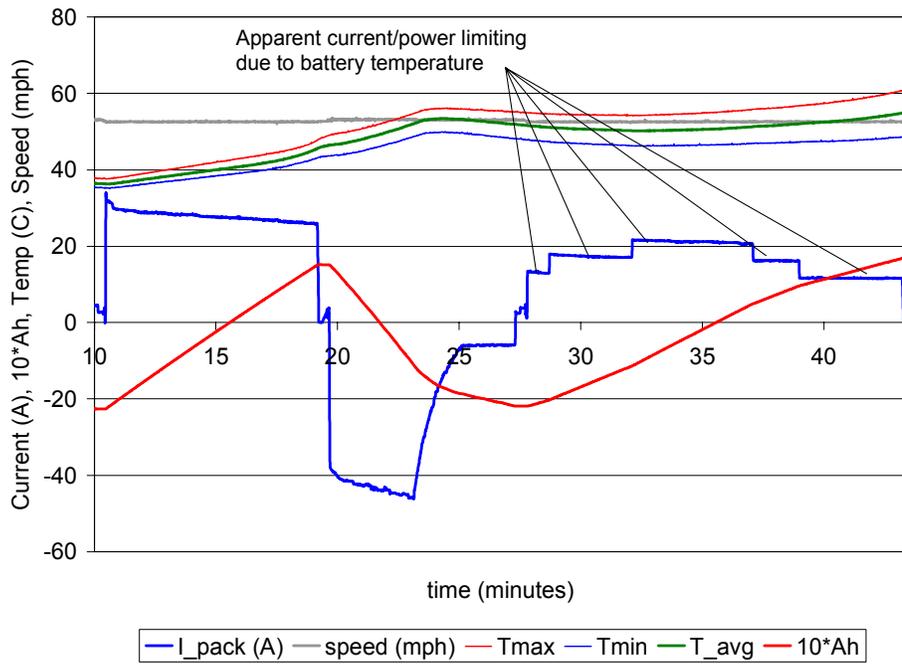


Figure 43: In-vehicle charge and discharge on the Insight pack

Toyota Prius

Through the use of the hand-held Scantool and the previously described charge/discharge procedure, it was quickly determined that while the Prius attempts to maintain a target SOC of 56% during normal driving conditions. It also apparently has control limits of 40% and 80% SOC that are employed under harder charging and discharging conditions (such as climbing or descending a long grade). Results from a sample charging cycle are shown in Figure 44. While motoring the vehicle wheels with the dynamometer at a constant 51 mph, the battery pack was charged at a relatively constant rate of approximately 20 A for 8 minutes. This resulted in an increase in battery charge of 2.61 Ah, or 40.1% of the rated 6.5 Ah capacity. Without changing the demand, the vehicle's control system then limits the charge current to approximately 2 A until the battery was charged to 2.9 Ah, or 45% of rated capacity. During the charge cycle the average battery temperature rose 6.6°C from 27.8°C to 34.4°C, while 3.4 M-Joules of electrical energy were added to the pack.

During the discharge cycle the discharge current increased from about 60 A to nearly 80 A over a period of only 2.0 minutes. During this time the Ah decreased by 2.45 Ah or 37.7% of the rated capacity. After this point the discharge current was rapidly stepped down until 2.65 Ah (40.1 % of rated capacity) were removed. During the charge cycle, the average battery temperature rose 9°C from 34.7°C to 43.8°C, while 3.4 M-Joules of electrical energy was removed from the pack.

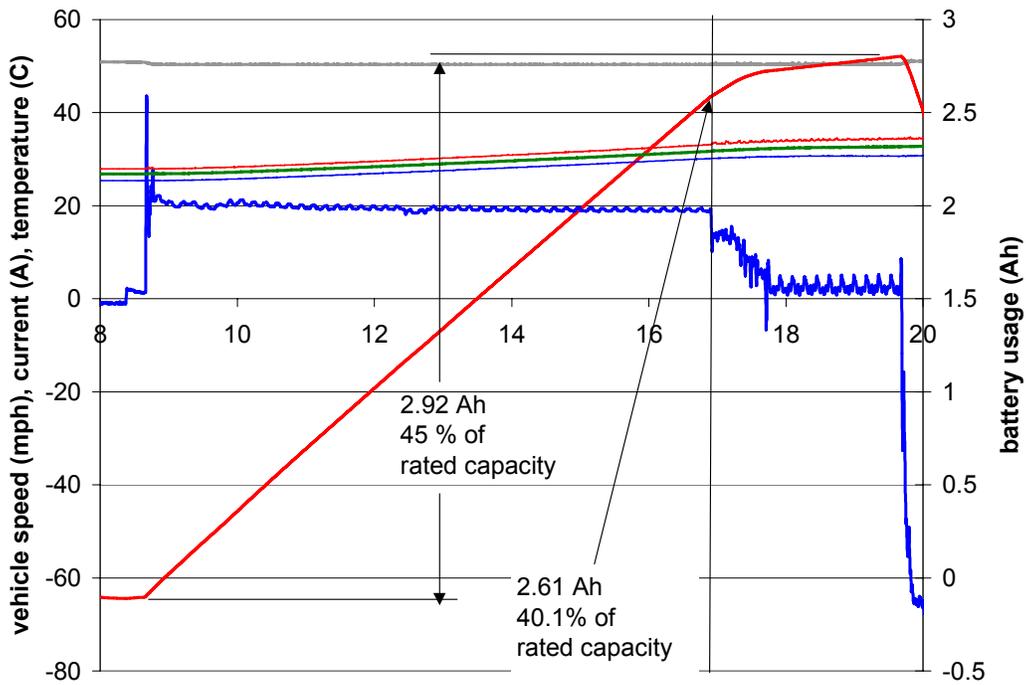


Figure 44: In-vehicle charge of the Prius battery pack

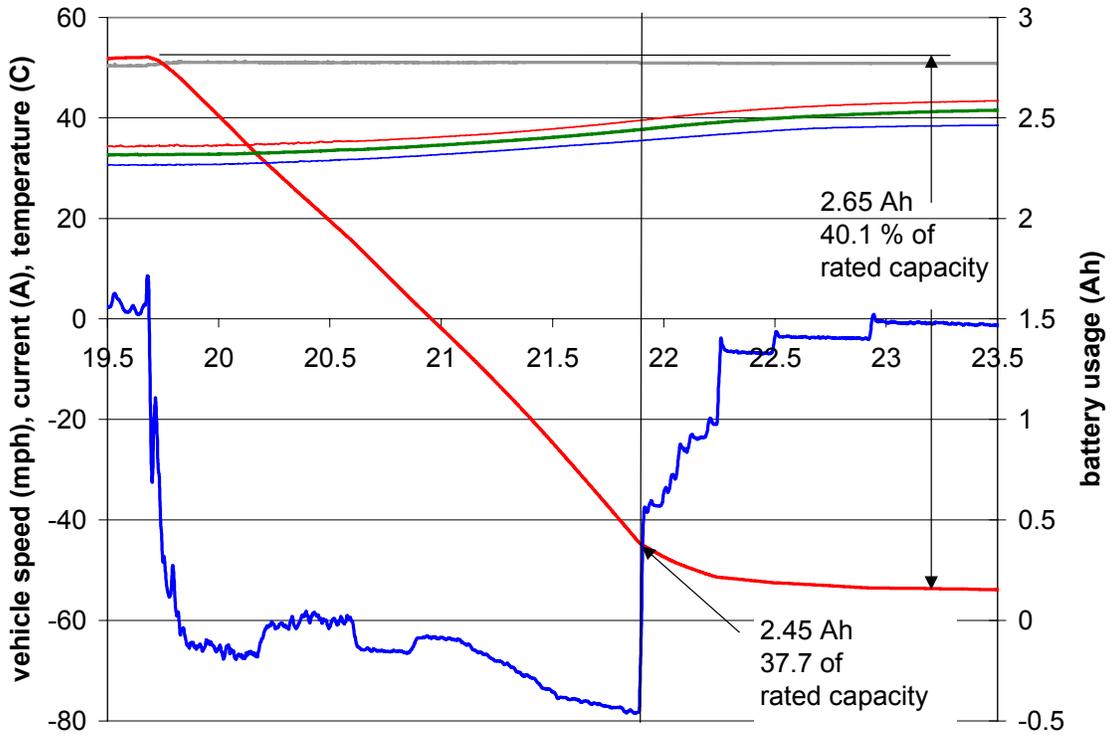


Figure 45: In-vehicle discharge of the Prius battery pack

Impact of Air Conditioning

Several points concerning the effect of air conditioning (AC) have already been mentioned in previous sections about battery and vehicle performance on standard driving cycles. The most notable result from the AC testing is that testing of the Insight on the SC03 cycle at 95°F showed a 34% reduction in fuel economy from 62.7 with the AC off to 41.1 with the AC on. The same testing on the Prius showed a 30% reduction in fuel economy – from 53.2 with the AC off to 37.0 with the AC on. While the two vehicles showed similar reductions in fuel economy, the behavior of their HEV systems was somewhat different. The Insight had a difficult time meeting the driving trace during portions of the SC03 cycle with the AC on, and had to use the electric motor for assisting. The Prius, with its larger engine and motor, did not have a problem following the trace.

Table 11 shows a summary of the Honda Insight data collected over the SC03 driving cycle tests. Figure 46 through Figure 49 shows this information graphically with the ULEV emissions standards for the SC03 shown as a reference point (note that the Insight was not certified by EPA under the SC03 standards). Along with the dramatic decrease in fuel economy with the AC on, the Insight showed large increases in CO₂ (proportional to fuel use) and CO emissions, but no measurable difference in HC or NO_x.

Table 11: SC03 test summary (Insight)

<i>ETC Test Number</i>	<i>Date</i>	<i>Test Temp (F)</i>	<i>Fuel Economy</i>	<i>Emissions (g/mi)</i>			
				<i>HC</i>	<i>CO</i>	<i>NO_x</i>	<i>CO₂</i>
<i>AIR CONDITIONING OFF</i>							
2692	31-Jul-00	94.9	63.5	0.005	0.255	0.094	139.5
2693	31-Jul-00	96.8	65.6	0.004	0.171	0.078	135.2
2721	11-Aug-00	95.4	63.4	0.010	0.206	0.043	139.8
2722	11-Aug-00	95.6	58.5	0.006	0.244	0.044	151.6
		<i>AVG</i>	62.7	0.006	0.219	0.065	141.5
<i>AIR CONDITIONING ON</i>							
2696	31-Jul-00	95.7	42.8	0.004	0.663	0.024	206.7
2697	31-Jul-00	95.2	42.3	0.009	0.880	0.095	209.4
2723	14-Aug-00	95.0	40.5	0.006	0.658	0.100	218.3
2724	14-Aug-00	95.0	38.9	0.008	1.023	0.042	226.8
2733	15-Aug-00	95.0	41.2	0.007	0.694	0.071	214.7
		<i>AVG</i>	41.1	0.007	0.784	0.066	215.2
Percent Change							
(ACon-ACoff)/ACoff			-34.4%	8.8%	257.8%	2.5%	52.0%
negative is a decrease with AC on							

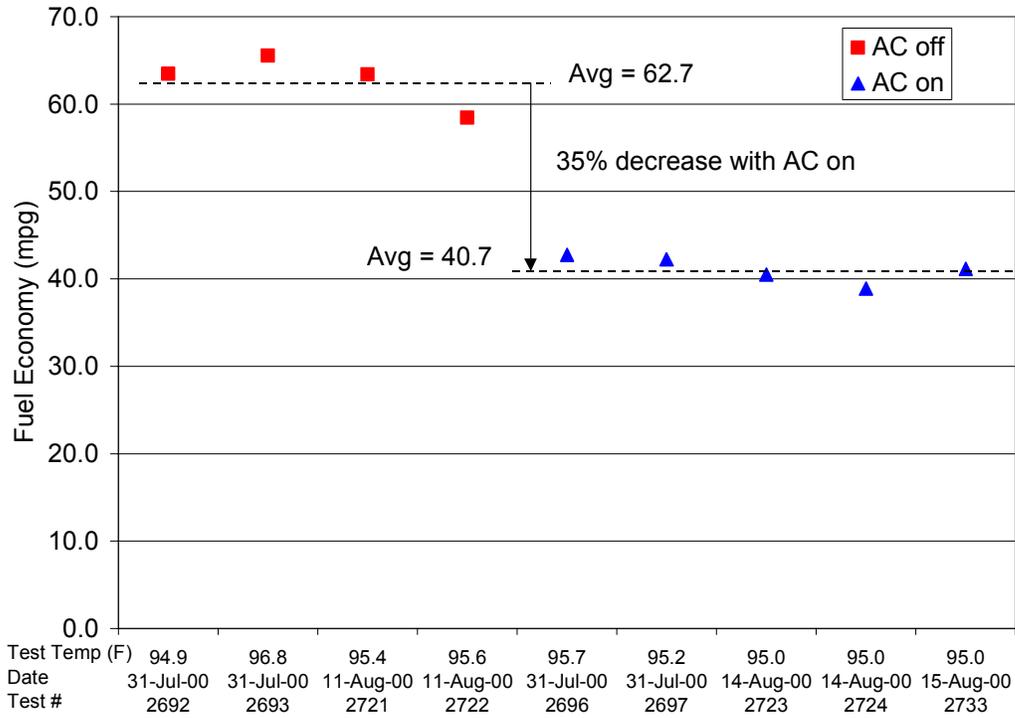


Figure 46: Fuel economy for the SC03 (Insight)

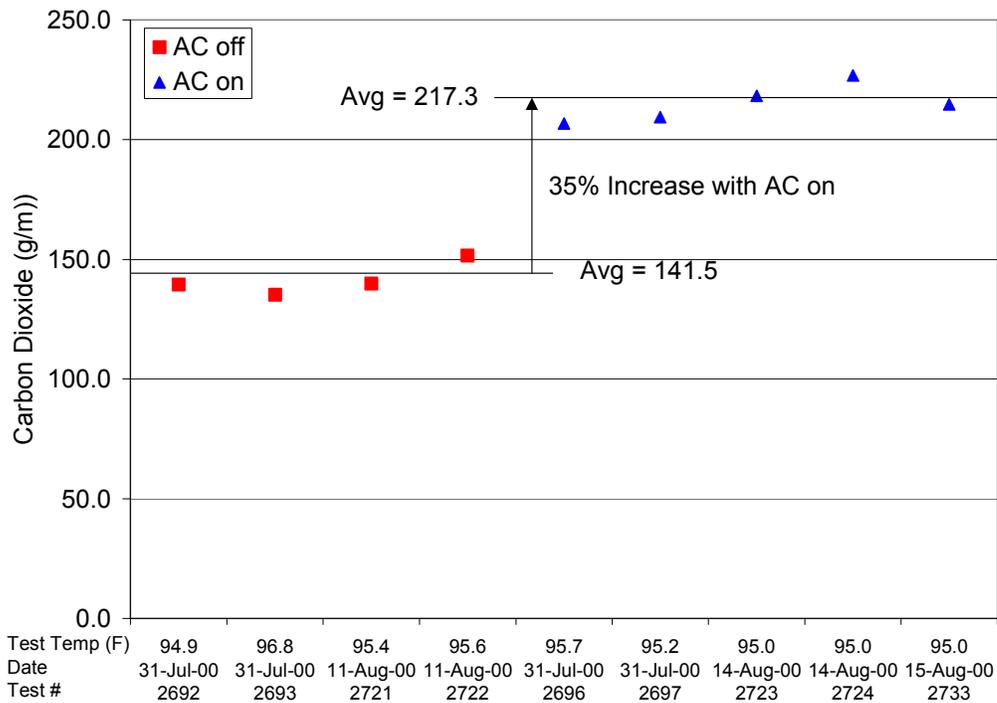


Figure 47: CO₂ emissions over the SC03 (Insight)

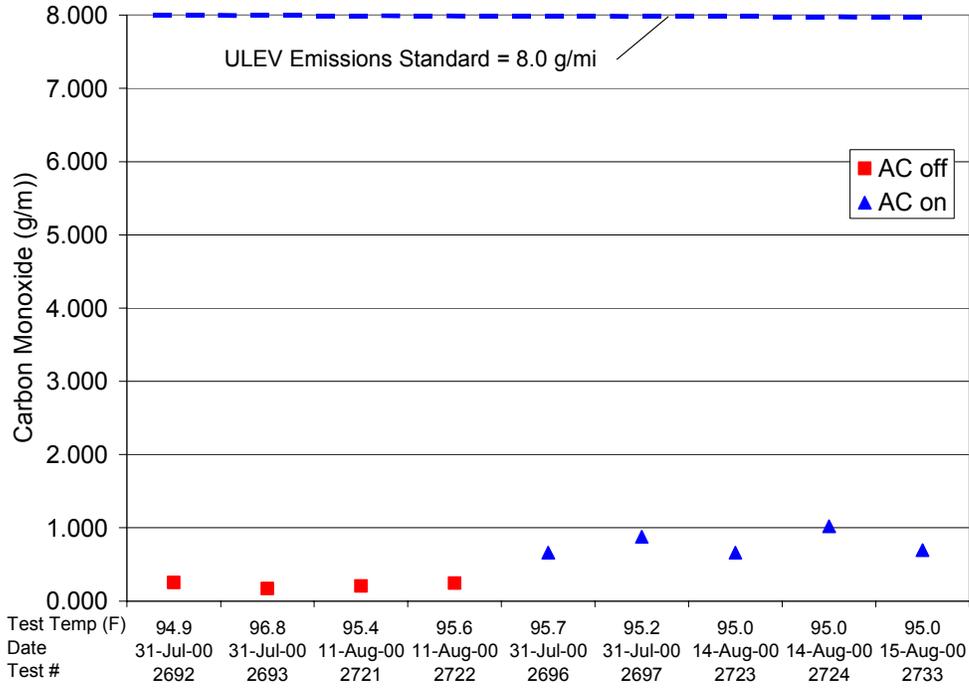


Figure 48: CO emissions over the SC03 (Insight)

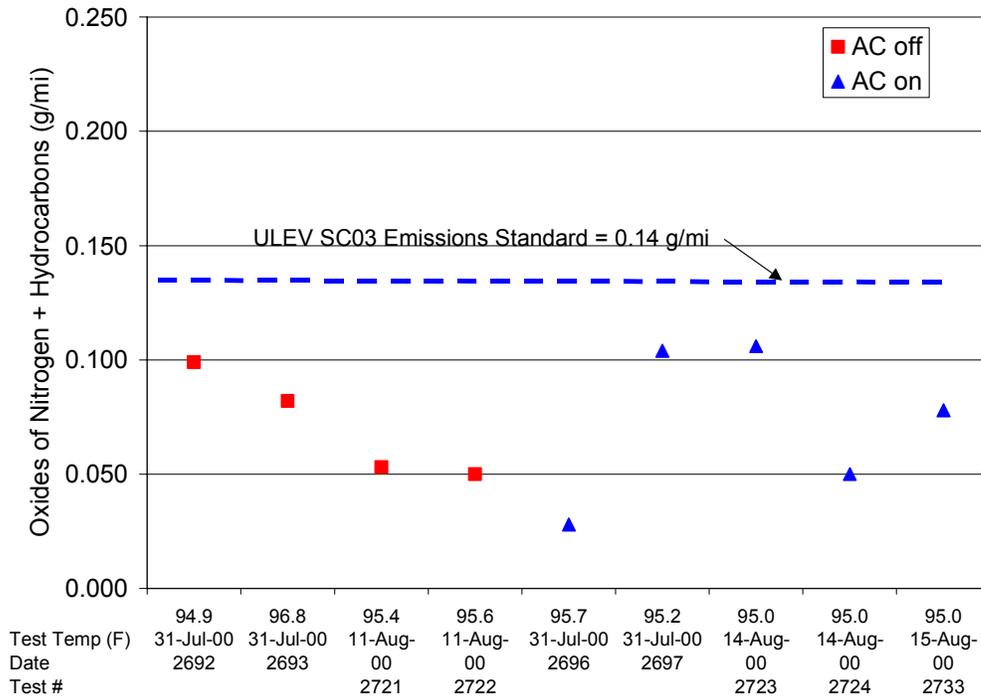


Figure 49: NO_x emissions over the SC03 (Insight)

Figure 24 that was previously discussed in the section titled “Battery Pack Performance on Standard Drive Cycles - Pack Energy Use” showed that the Insight had some difficulty following the SC03 driving trace with the AC on and had to use more electrical assist than for the same cycle with the AC off. For the SC03 driving cycles, there was a net increase in power used by the auxiliary electrical loads of approximately 61% (from 165 W to 822 W) and a net power increase in battery usage of 80% (from 288 W to 745 W) when the AC was on.

At the time this report was written only the first round of SC03 tests on the Prius had been conducted. The results from these tests are shown in Table 12. During the first round of SC03 testing the Prius exhibited a 30.5% reduction in fuel economy with the AC on. In the case of emissions, the Prius showed an increase in emissions of HC, CO, and CO₂ with the AC on. Surprisingly, the NO_x emissions were actually higher with the AC off. The results shown in this table will be verified with a second round of tests in the coming weeks.

Table 12: Fuel economy of the Prius over the SC03

	<i>Fuel Economy (mpg)</i>	<i>Emissions (g/mi)</i>				
		<i>HC</i>	<i>CO</i>	<i>NO_x</i>	<i>CO₂</i>	<i>NO_x + HC</i>
SC03 w/o AC	53.25	0.002	0.028	0.025	167.1	0.027
SC03 w/ AC	37.02	0.004	0.152	0.002	240.3	0.006
Percent Change						
(ACon-ACoff)/ACoff	-30.5%	100.0%	442.9%	-92.0%	43.8%	-77.8%

Figure 50 below shows the battery pack current usage during a portion of the SC03 test with and without AC. It appears from this data that the Prius allows greater use of the electric motor with the AC off. Another way of saying this is that the Prius requires greater use of the engine with the AC on. This would tend to increase fuel use and emissions with the AC on. The Prius uses the electric motor quite differently than the Insight, which uses the motor for additional power when needed. The Prius uses the electric motor to help control the use of the gasoline engine and maintain efficient operation.

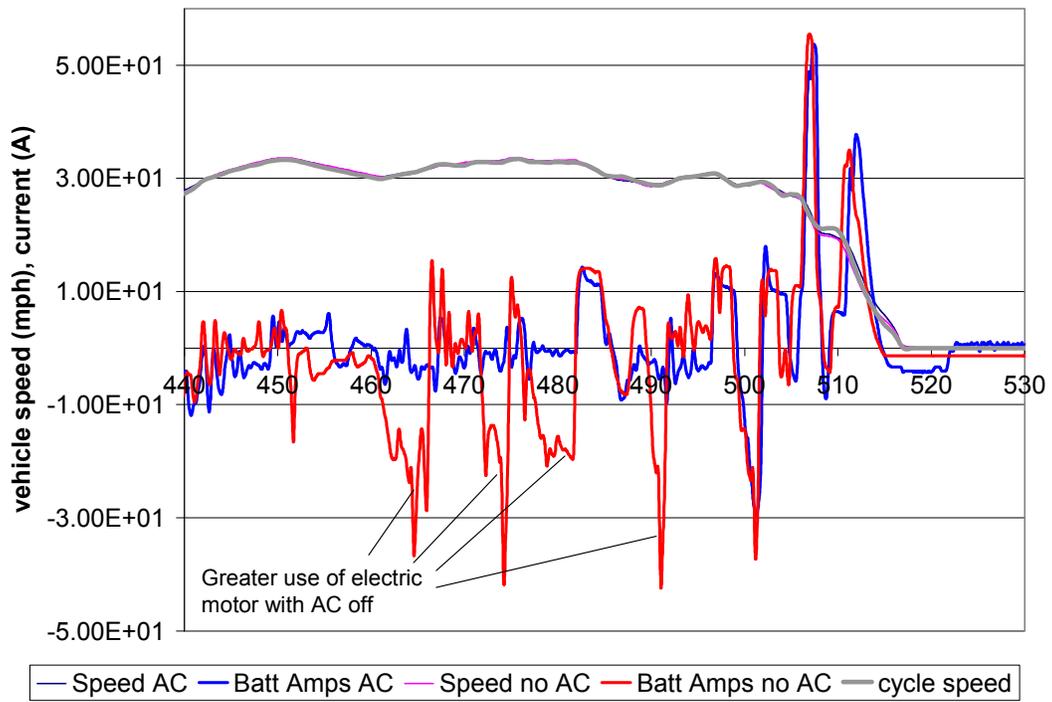


Figure 50: Prius battery currents for the SC03

MODELING

Introduction

This chapter describes test-data analysis and modeling of the Honda Insight. The testing of the Toyota Prius is not complete yet, and the Prius model will be updated from the Japanese Prius reference model in ADVISOR, after testing and analysis is complete. The modeling of the Honda Insight required analysis of the test data, and personal experience driving the vehicle. Basic vehicle information from published sources was previously incorporated into the model and is described in the FY00 milestone report. Both the National Renewable Energy Laboratory (NREL) and Argonne National Laboratory (ANL) have collected test data, which have been compared and used to understand how the vehicle works.

A key difference between the NREL and ANL data is that ANL instrumented their vehicle to include torque sensors on the axles. This data was instrumental in developing the relationships that determined when the electric motor provides assist for accelerations and how much regenerative energy is taken up by the motor during decelerations. NREL had planned to include torque data from the dynamometer, but problems occurred with the lab's torque signal, and this data was not available. The problem with the dynamometer torque signal was corrected for Toyota Prius testing by NREL and is being collected.

Data pertaining to the drivetrain have allowed for a determination of the working of the electric motor under different driving conditions. Test data exist for different driving conditions, and driving cycles. Based on the observations, a model in Simulink was developed and incorporated into ADVISOR. Test data have been analyzed for correlation with the ADVISOR model.

Electric Motor contribution

A critical area of study for modeling is the vehicle's usage of the electric motor: to determine when the electric motor is used, and the factors that determine how much assist is provided, such as torque, throttle position, braking/coasting etc.

Figure 51 to Figure 54 show the relation between the torque contribution from the electric motor, and the total torque demanded from the driveline for various driving cycles.

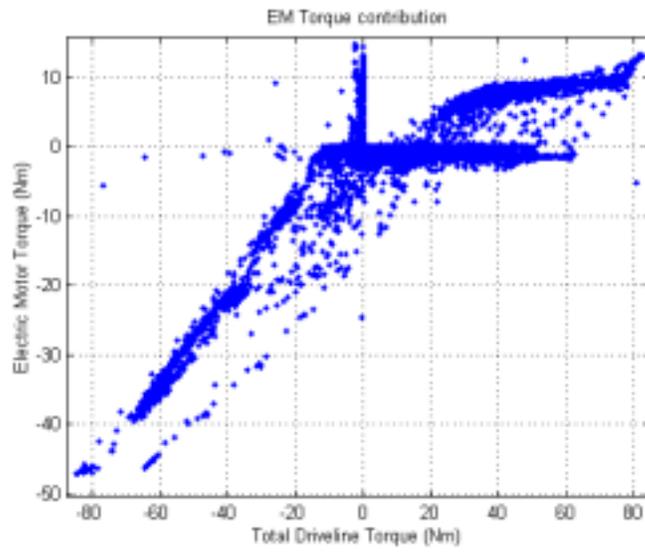


Figure 51: Electric motor contribution for the UDDS (Insight)

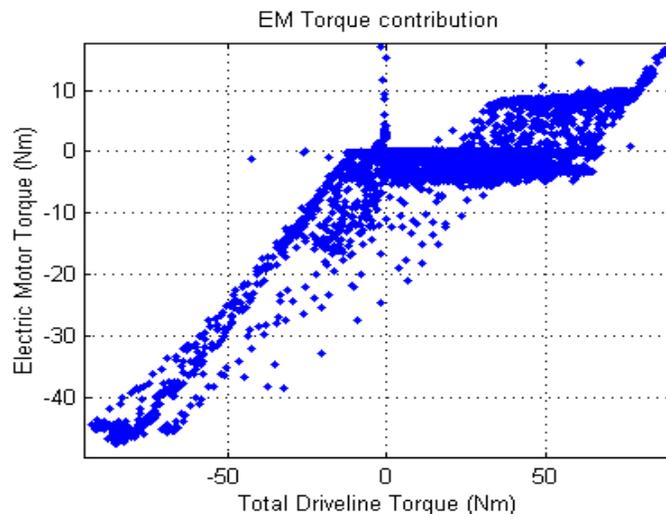


Figure 52: Electric motor contribution for the HWFET (Insight)

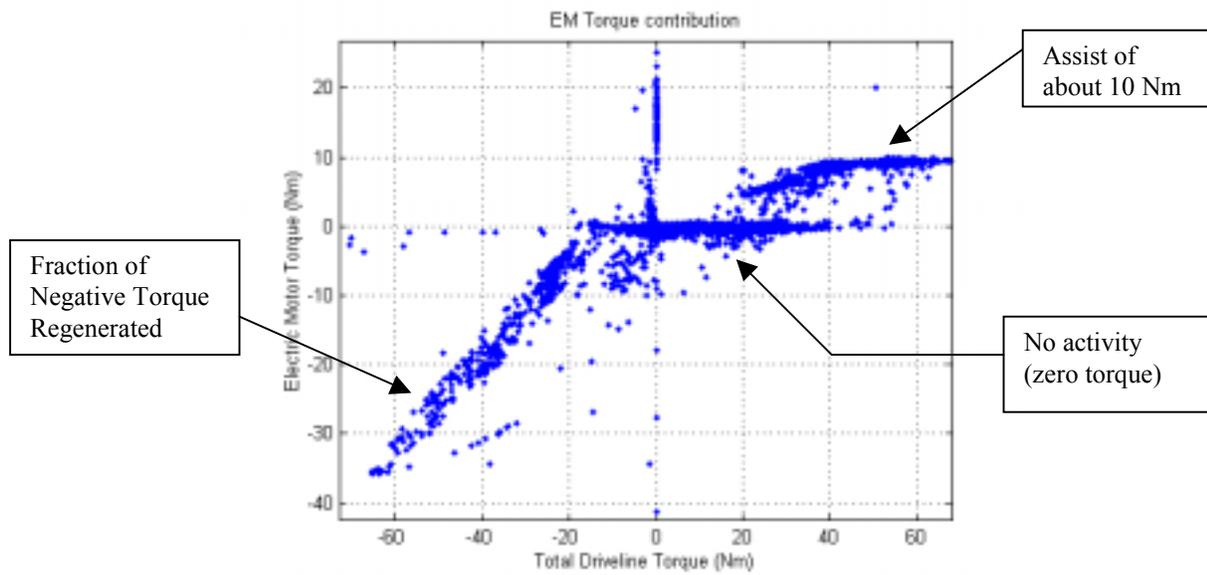


Figure 53: Electric motor contribution for the Jap 10-15 cycle

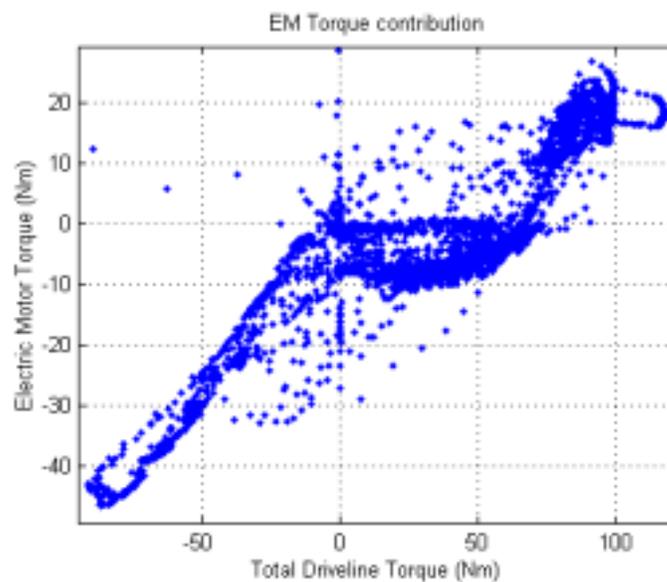


Figure 54: Electric motor contribution for the US06 cycle

The relationship for the electric motor (EM) torque contribution was derived using the following formulation:

$$Electric_Motor_Torque = \frac{Inverter_Power(kW) * efficiency}{Engine_speed(rad / s)}$$

Note that the electric motor is directly coupled to the output shaft of the engine, so that:

$$\text{engine speed} = \text{motor speed}$$

The above plots all indicate that, despite very different driving cycles, there exists a similar trend in the operation of the electric motor. The EM provides an assist of around 10 Nm at heavy accelerations. When negative torques are encountered, the electric motor functions as a generator and regenerates a portion of the negative torque as current to the battery. The percentage of negative torque regenerated seems to be a constant of around 50-60% of the total negative torque seen by the driveline. For the rest of the vehicle operation (such as light accelerations, cruising etc), the electric machine seems to have little activity. This is shown most clearly in Figure 53 for the Japanese 10-15 cycle, but is seen generally throughout except the US 06 (Figure 54).

Thus, the role of the electric machine does seem to be limited to heavy accelerations and picking up a portion of the negative regenerative torque available. This agrees well with the “*driving experience*”, in which the driver notices assist (from the dashboard display) only when certain power levels are demanded.

Alternator function

Since the Honda Insight does not have a separate alternator to power the accessories, the main electric motor acts as an alternator, generating a small current to supply the accessory loads. This feature is also incorporated into the model. (explained in the modeling chapter). Figure 55 shows this phenomenon, where the motor generates a small negative torque when not assisting the vehicle. This is also seen as a small negative charge torque at light loads in Figure 51 to Figure 54.

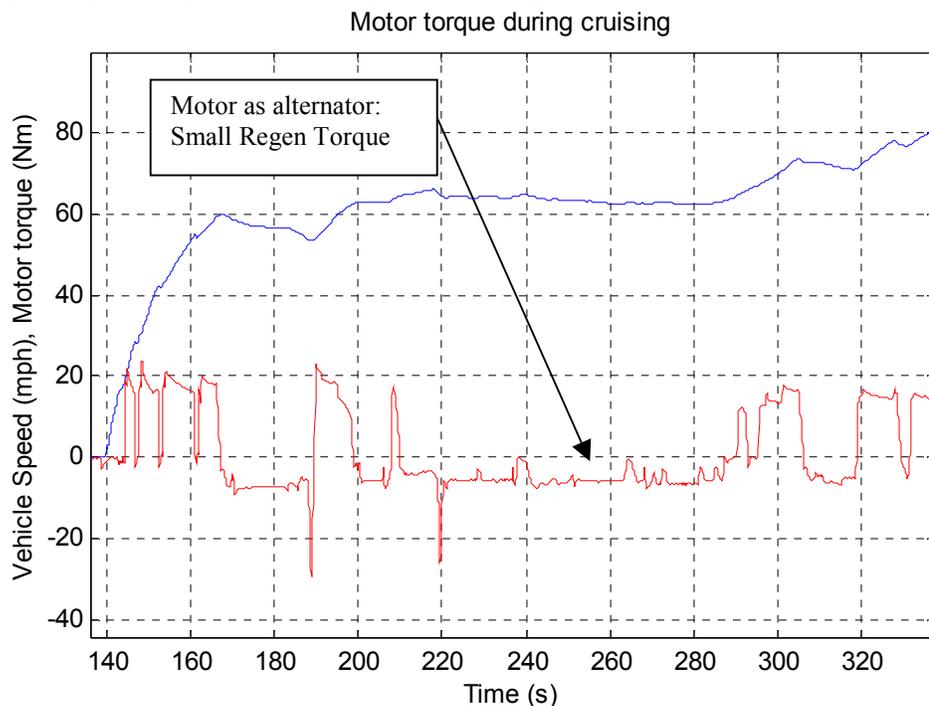


Figure 55: Alternator function (Insight)

Throttle position

The electric motor responds to throttle position as shown below (Figure 56).

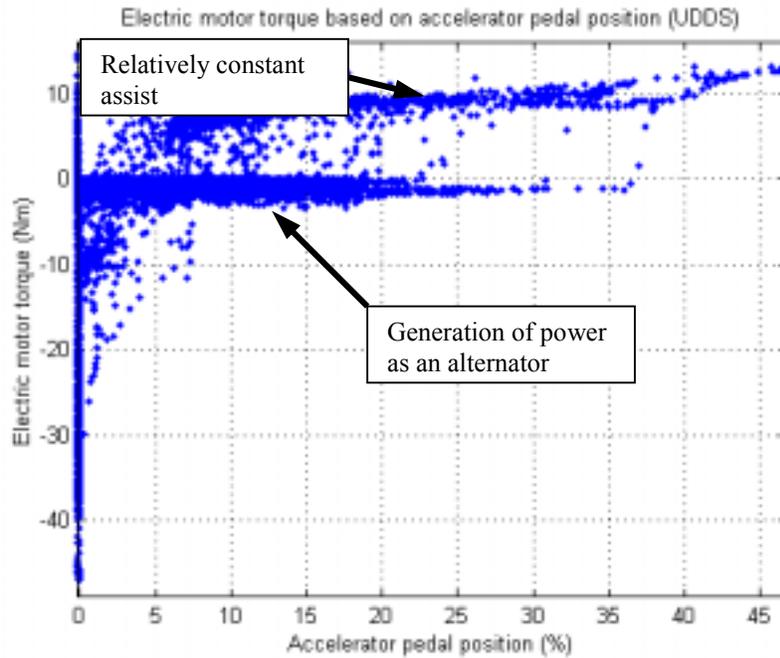


Figure 56: Effect of accelerator pedal position in the Insight (UDDS)

The assist seems to be relatively constant at around 10 Nm, except at very high accelerator pedal angles. (>40 %) The same characteristic is shown for the US 06 in Figure 57. It is seen that the accelerator pedal is floored (100%) in parts of this cycle, to meet the speed trace, and the level of assist is greater in this case. This explains the difference in the electric motor contribution as seen in Figure 54.

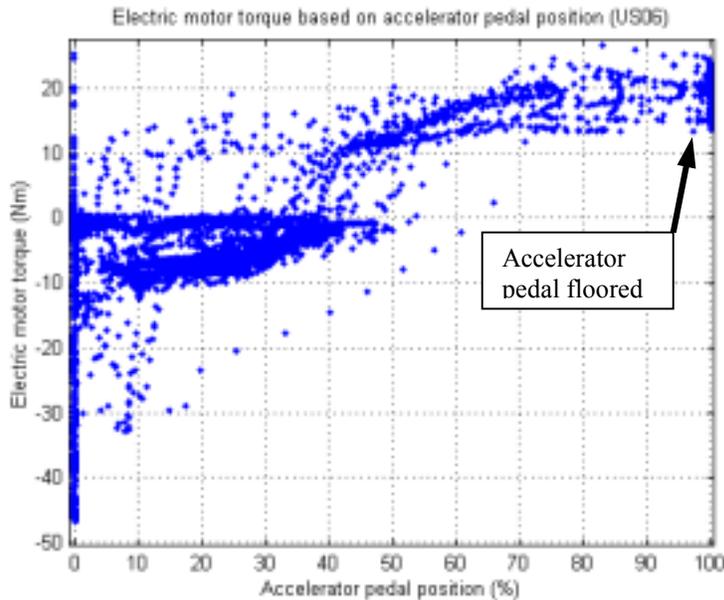


Figure 57: Effect of accelerator pedal position in the Insight (US06)

Effect of gear position in the electric motor's activity

Analysis of the test data also indicated that the electric motor is not active when the vehicle is in 1st gear. This phenomenon is shown in Figure 58. This plot shows engine rpm, COLOR CODED by gear ratio. (RED – 1st gear, GREEN – 2nd gear, BLUE, 3rd gear, MAGENTA – 4th gear, CYAN – 5th gear, BLACK – unknown gear ratio / slip). The electric motor torque is shown in RED.

It is clearly seen that the motor does not provide assist in first gear.

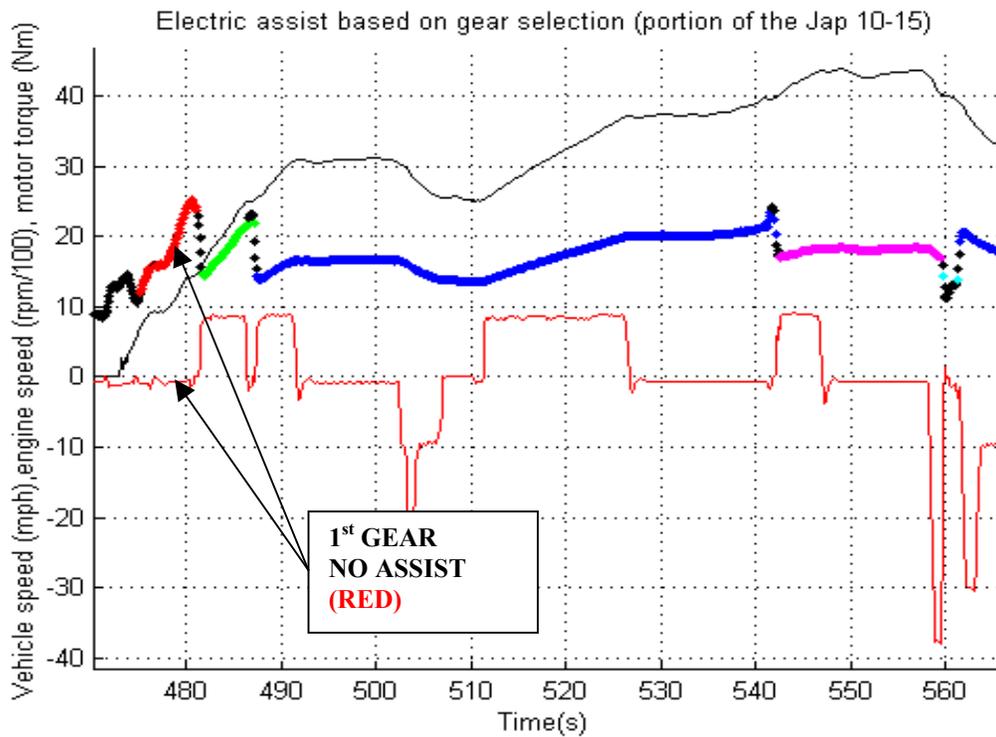


Figure 58: Effect of gear selection on the electric motor (Insight)

The following plots (Figure 59) further illustrate the motor torque contribution with total driveline torque, while the vehicle is in different gears. It is seen that while in 1st gear, the electric motor remains inactive. While in other gears, it follows the phenomenon discussed above.

The plots given below are for the Japanese 10-15 cycle

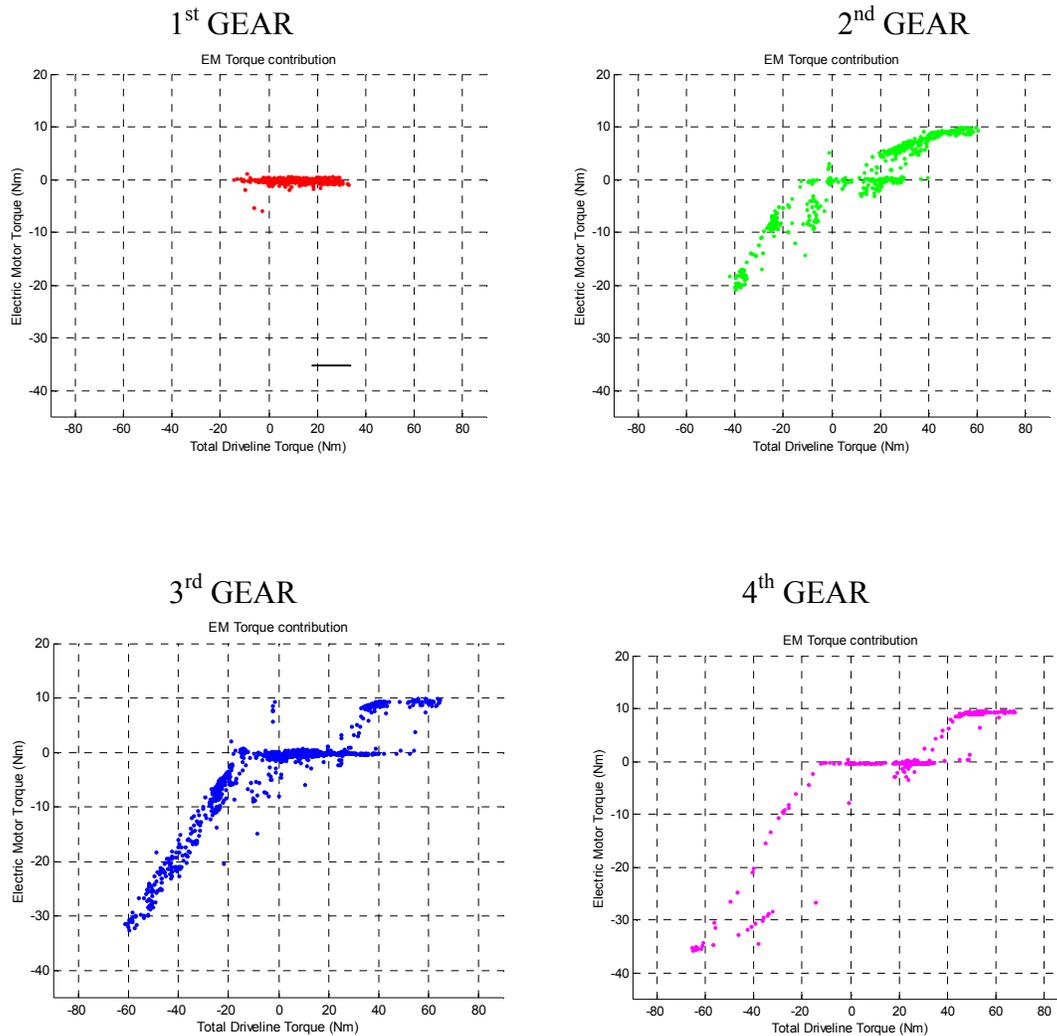


Figure 59: Electric motor behavior during the Japanese 10-15 cycle based on gear (Insight)

Effect of Brakes

The brake pedal has a very significant effect on the amount of regeneration supplied by the electric motor. When the brake pedal is depressed, the electric motor regenerates a greater percentage of the negative torque that the driveline receives. An exception to this rule arises when the vehicle slows down below around 10 mph. The friction brakes are solely used when the vehicle slows down below 10 mph.

The following plot indicates some of the characteristics of the braking in the vehicle, and it's effect on the motor regeneration. The brake signal (in black) is seen to trigger a large negative torque regeneration by the electric motor. Also, as the vehicle slows down considerably (below 10-15 mph), even though the brakes are depressed, regeneration reduces / stops.

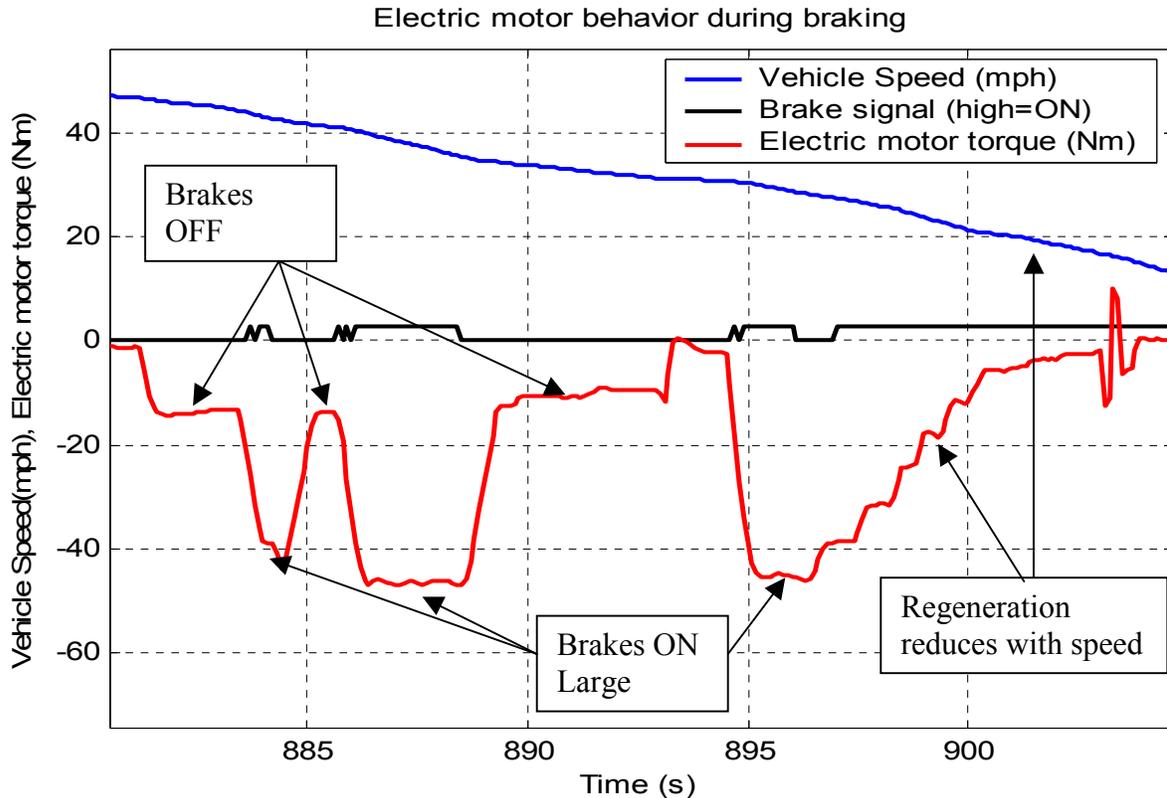


Figure 60: Electric motor behavior during braking (Insight)

Figure 60 shows that the system utilizes the regenerative energy very well when the brakes are depressed. About 50 % - 60% of the braking energy goes into the driveline and is captured by the electric motor.

Effect of Vehicle Speed

The behavior of the electric motor based on the vehicle speed was also analyzed with test data. It is found that the electric motor provides little or no assist or regeneration below vehicle speeds of approximately 10 mph. The plots in Figure 62 illustrate this phenomenon. These plots show the electric motor activity, during various vehicle speeds. It is seen that at lower speeds, the electric motor is not active.

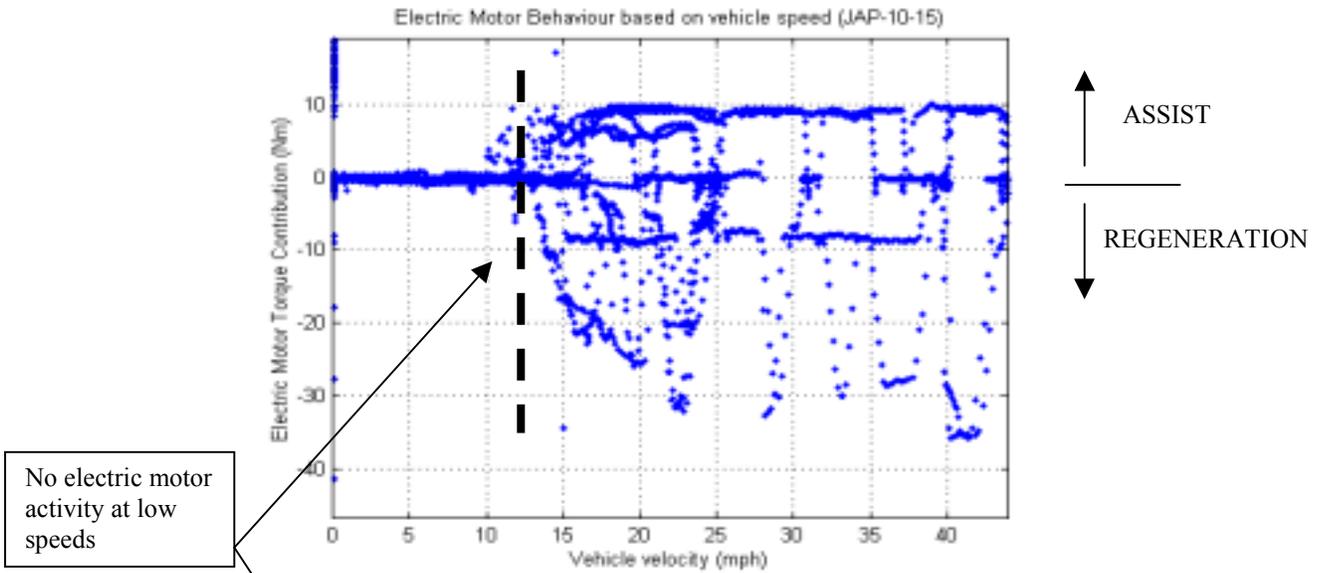


Figure 61: Electric motor behavior based on vehicle speed (Jap 10-15)

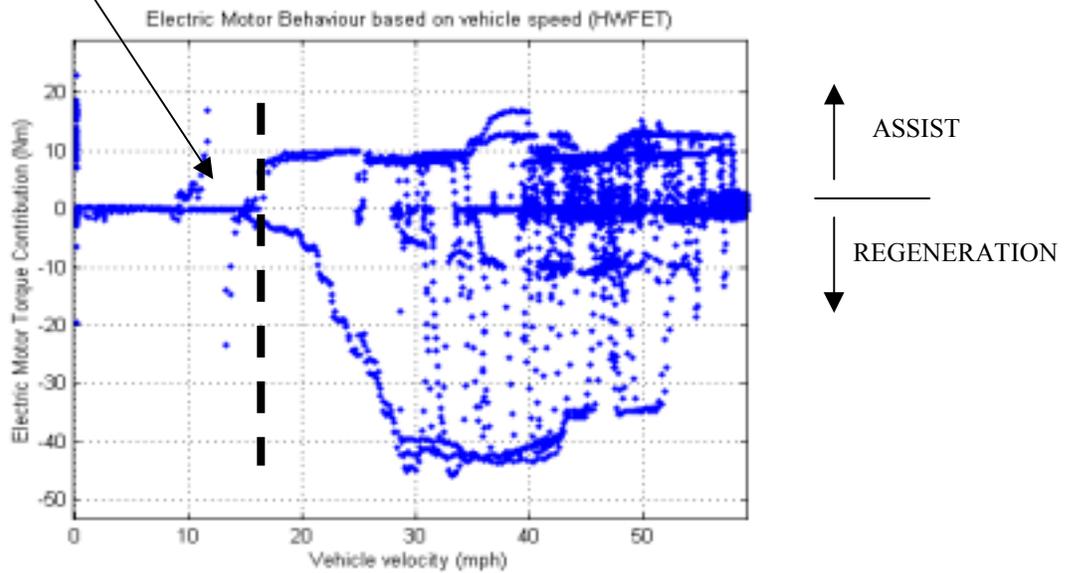


Figure 62: Electric motor behavior based on vehicle speed (HWFET)

This may be due to the fact that regenerative braking need not be used at very low speeds, which may provide lack of control and unwanted decelerations at very slow speeds. It may also be that the amount of regenerative energy available at low speeds is small. Figure 63 shows the amount of regenerative energy available to the driveline during a deceleration from 50 mph to 0 mph, during a portion of the UDDS. It is seen that when the vehicle slows below 10 mph, the amount of energy available is much lower than at higher speeds, due to the low speed of the motor.

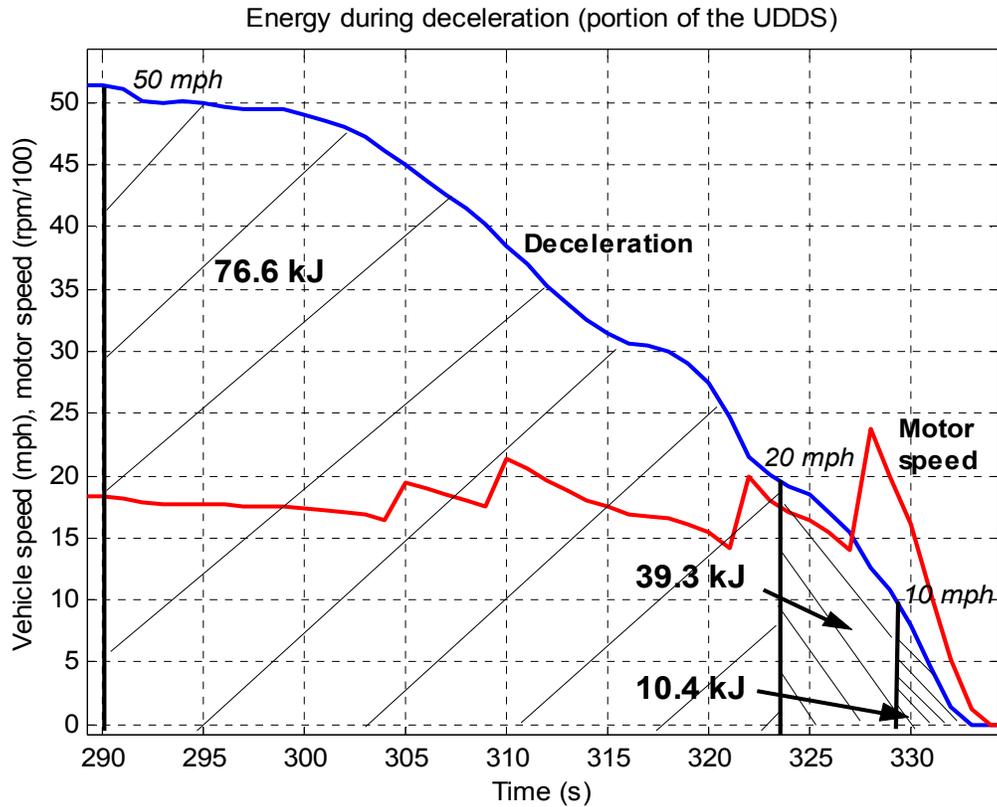


Figure 63: Regenerative energy during deceleration (Insight)

Engine on/off feature

The Insight has an interesting “engine-off” feature. The engine shuts off at certain times, when the vehicle is stopped, to prevent idle operations. This happens, if the vehicle comes to a stop at a traffic light etc. When the driver puts the vehicle in gear, the electric motor (Honda calls this IMA for Integrated Motor Assist) starts up the IC Engine in a very short time.

Generally, the conditions for engine shut-off are enlisted here:

The engine of the Insight will only shutdown under the following conditions:

- 1) Engine is warm and
- 2) Vehicle is decelerating at speeds below 20 mph or stopped and
- 3) Clutch is disengaged

This feature was seen clearly in the NREL test data, and was described in the FY00 milestone report.

MODEL UPDATES

Introduction

Based on analysis of test data from the Honda Insight, a model in NREL's ADVISOR (ADvanced VehIcle SimulatOR) was developed. Test data from the National Renewable Energy Laboratory (NREL) and Argonne National Laboratory (ANL) was used in the analysis. The aim of the model is to predict the control actions performed on the various components of the drivetrain (Engine, Electric motor, batteries etc.). The following major observed phenomena are modeled.

The electric motor of Honda's Integrated Motor Assist (IMA) provides approximately 10 Nm of assist in most cases when a large torque (approximately > 20 Nm) is commanded of the vehicle (This is physically interpreted as an indication for acceleration through depressing the accelerator pedal). An exception is when the vehicle is in first gear, wherein the motor does not assist the engine.

The electric motor of the Integrated Motor Assist (IMA) performs regeneration when the vehicle slows down, as there is torque from the inertia of the vehicle coming into the driveline. When the brakes are depressed, there is heavy deceleration, and a lot of negative regenerative torque is seen at the driveline. The controller senses the braking, and allows the motor to capture a part of that energy back into the battery. This ensures that the battery is charged and all energy is not lost in the form of heat. During braking, a small portion of the braking force is provided by the electric motor, and the remaining part from the friction brakes.

Using the above concepts, a *scalable controller* was developed and incorporated into ADVISOR, which allows for simulating the entire Insight drivetrain on the computer. The model was developed as Simulink blocks, which can be used by ADVISOR.

Vehicle Model

The base Insight Simulink model is shown below:

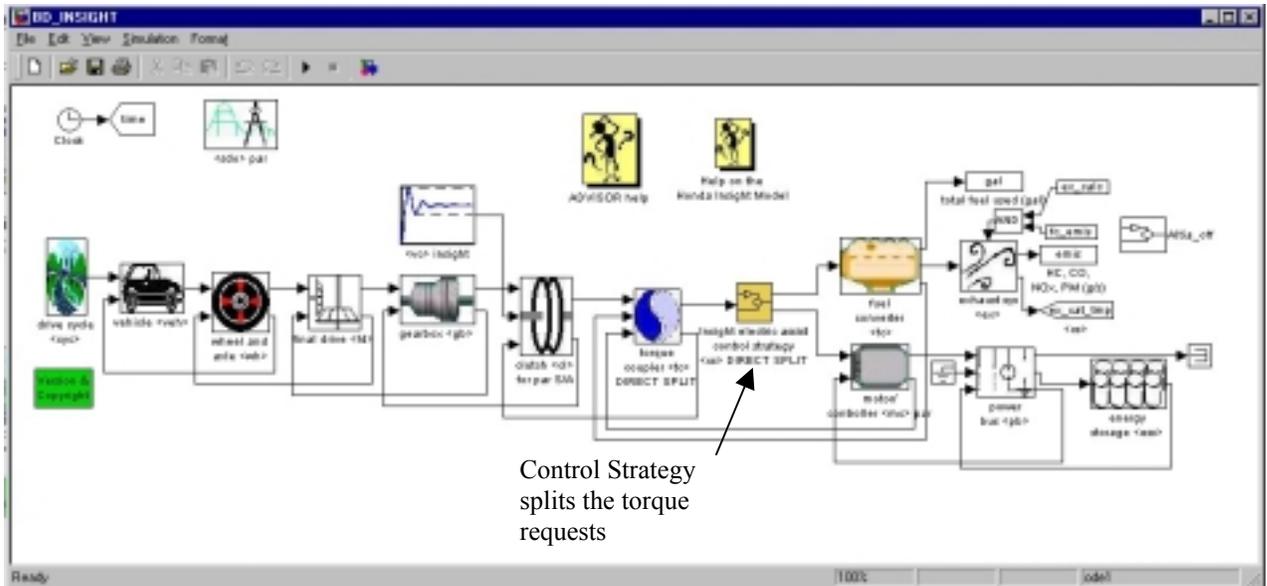


Figure 64: Base block diagram of the Insight in ADVISOR

The Insight base block uses a “direct split” of the torque signal, whereby the controller directly commands the torque from the 2 power sources, unlike the default parallel hybrid strategy. In the default strategy, the entire driving torque is requested from the IC engine, and the dearth of torque (unmet torque) is demanded from the electric motor (a feedback loop is constructed in the torque coupler). Here, there is a separate torque command sent to the electric motor, from the control strategy. This makes sure that the components provide the correct amount of torque commanded by the controller. The torque converter is used for summing the 2 torques and sending them back to the gear box. (No feedback is performed to the control strategy, based on the individual power sources).

Changes to the Insight model

The following changes were made to the existing Insight model in ADVISOR.

1. A new *scalable* Torque-Split Control Strategy based on test data analysis (block shown below in Figure 64)
2. Engine on-off control was added (previously included in ADVISOR 3.0)
3. Usage of engine fuel-use map data, based on vehicle component testing by Argonne National Laboratory (ANL).
4. State of Charge correction strategy
5. Documentation is added on the use of the scalable strategy.

The scalable control strategy

Based on the working of the Insight, a scalable control strategy was developed in ADVISOR. This strategy is very flexible in its parameters, and a user can use the new strategy for designing his own new controller. It also provides for conducting sensitivity analysis on existing parameters.

Figure 65 shows a schematic of the structure of the controller, and the variables used in defining such a system. The variables can be defined prior to simulation and can be changed independently, for altering the functionality of the electric motor.

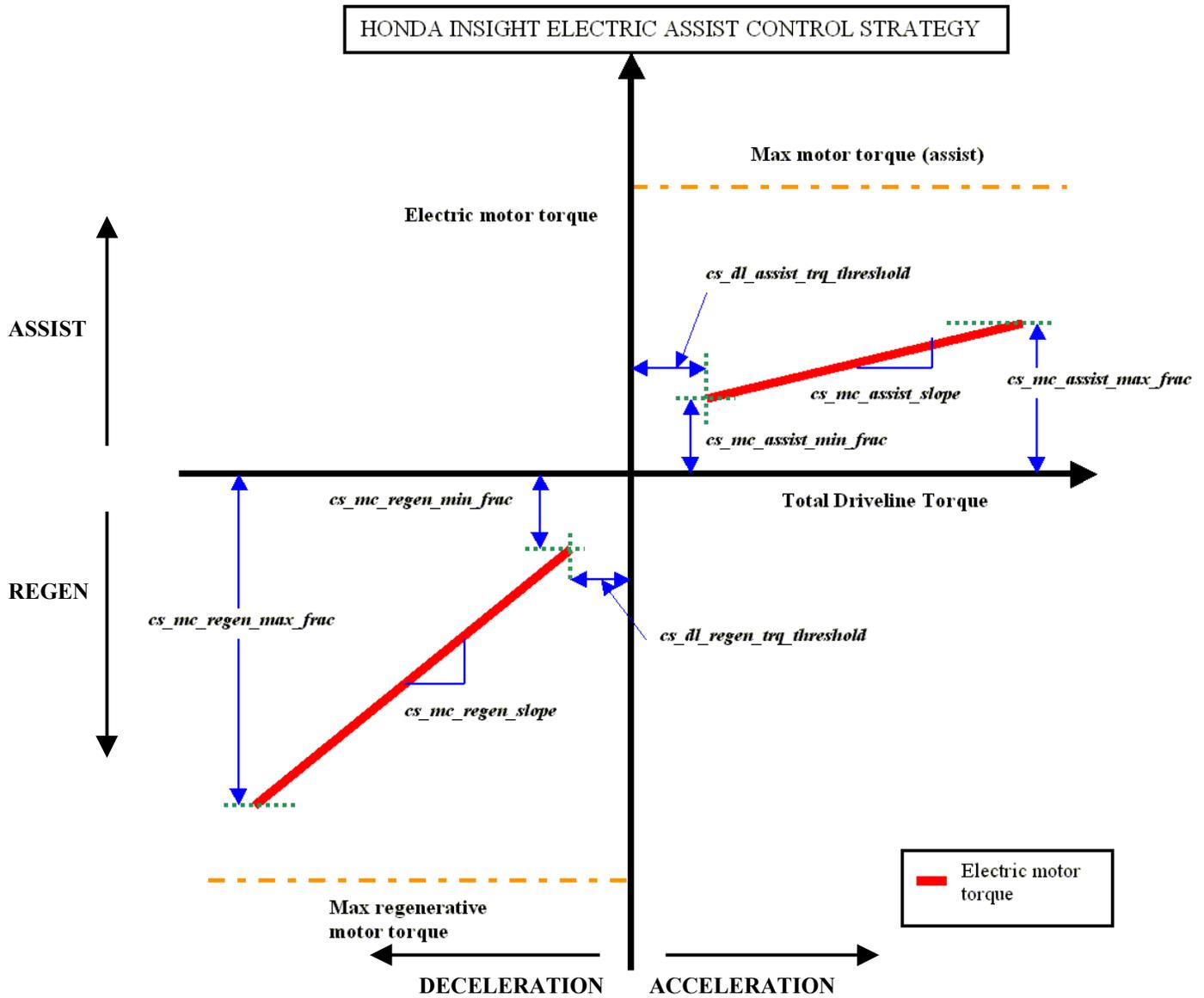


Figure 65: Scalable control strategy structure

In the above diagram, the parameters shown are used in determining the behavior of the electric motor, based on the vehicle torque demand. The solid red line in the upper right quadrant of the graph, defines the level of assist provided by the electric motor. When the driveline torque required exceeds the parameter " $cs_dl_assist_trq_threshold$," the motor provides assist, starting at a level indicated by " $cs_mc_assist_min_frac$," and increases according to the parameter " $cs_mc_assist_slope$," which indicates how much assist the

motor should provide, based on the driveline torque. The maximum assist of the motor can be limited by using the parameter “*cs_mc_assist_max_frac.*” The motor torque limits are represented as a fraction of the max torque capacity of the motor.

Similarly, the solid red line in the lower left quadrant defines the level of regeneration provided by the electric motor. When regenerative torques seen by the driveline exceed the parameter “*cs_dl_min_trq_threshold,*” the motor starts regenerating with a minimum value equal to “*cs_mc_regen_min_frac,*” and increases according to “*cs_mc_regen_slope.*” This parameter defines the amount of regen the motor provides, based on what is seen at the driveline. As in the case of assist, motor regen torque can be limited using the parameter “*cs_mc_regen_max_frac.*” These limits are a function of the maximum regenerative capacity of the motor.

Table 13 provides a summary of the parameters used in this scalable control strategy. For the Insight, the parameters were chosen based on actual test data from various driving cycles.

Table 13: Summary of parameters used in the scalable control strategy

Variable	Description
<i>cs_dl_assist_trq_threshold</i>	Driveline torque threshold below which the electric machine does not assist
<i>cs_mc_assist_min_frac</i>	Minimum torque normally provided by the electric motor when driveline torque exceeds threshold (as a fraction of max torque)
<i>cs_mc_assist_slope</i>	Fraction (slope of the line) of the driveline torque provided by the electric motor when the driveline torque exceeds threshold
<i>cs_mc_assist_max_frac</i>	Maximum motor torque requested from the motor during assist (as a fraction of max torque)
<i>cs_dl_regen_trq_threshold</i>	Driveline regenerative torque threshold above which the electric machine does not regen at low speeds
<i>cs_mc_regen_min_frac</i>	Minimum regen torque normally provided by the electric motor when driveline torque exceeds regen threshold (as a fraction of max regen torque)
<i>cs_mc_regen_slope</i>	Fraction (slope of the line) of the negative driveline torque regenerated by the electric motor when the driveline torque exceeds threshold
<i>cs_mc_regen_max_frac</i>	Maximum regen motor torque requested from the motor during regeneration/braking (as a fraction of max regen torque)
<i>cs_decel_regen_threshold</i>	Speed during deceleration below which the electric motor does not regenerate (all emphasis on friction braking)

The controller block

The Insight parallel hybrid controller block, used to implement the above structure is shown below:

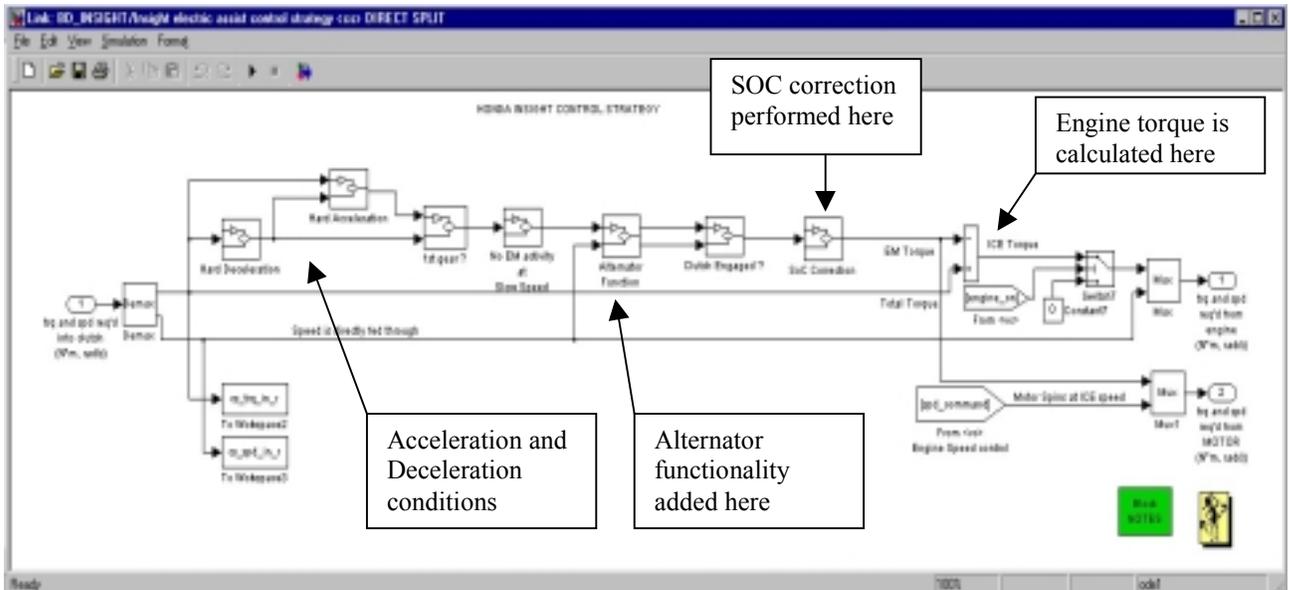


Figure 66: Insight control block in ADVISOR

The controller block is used to decide the torque contribution of the IC engine and the electric motor. Based on the total torque request, and the characteristics of the motor as described in the previous chapter, the controller decides the contribution of the electric motor. The remaining unmet torque request is supplied by the IC engine upto its maximum torque limit. In case the 2 sources acting synergistically are unable to meet the torque demand, then the vehicle falls short on speed, as is observed during demanding driving conditions.

SOC Balancing

The State of Charge (SOC) of the battery pack is an important factor in the operation of a hybrid electric vehicle. In the Honda Insight, the battery pack SOC limits are set to 20% (lower) and 80% (upper) respectively. When the battery pack reaches the lower limits of SOC (near 35 %), the controller reduces the amount of assist (current flow out of the battery) by the electric motor. The reduction of “allowable assist” continues until the SOC reaches 20%, when no assist is allowed thereafter. This prevents the battery pack from damage.

Similarly, when the battery pack SOC reaches the upper limits of 80%, all regeneration by the electric motor (current flow into the battery) is stopped. This prevents the battery pack from overcharging, and damaging the system. These phenomena were observed during dyno and on-road testing of the Insight at NREL. Refer to Figure 40 for an indication of this phenomenon. Shown below, in Figure 67, is the result of this feature in the ADVISOR Insight model. It is seen that as the battery pack SOC drops, the assist

capability of the motor is curtailed, and the assist current drops. Also shown in Figure 68 is the stopping of all regeneration when the SOC reaches 80%.

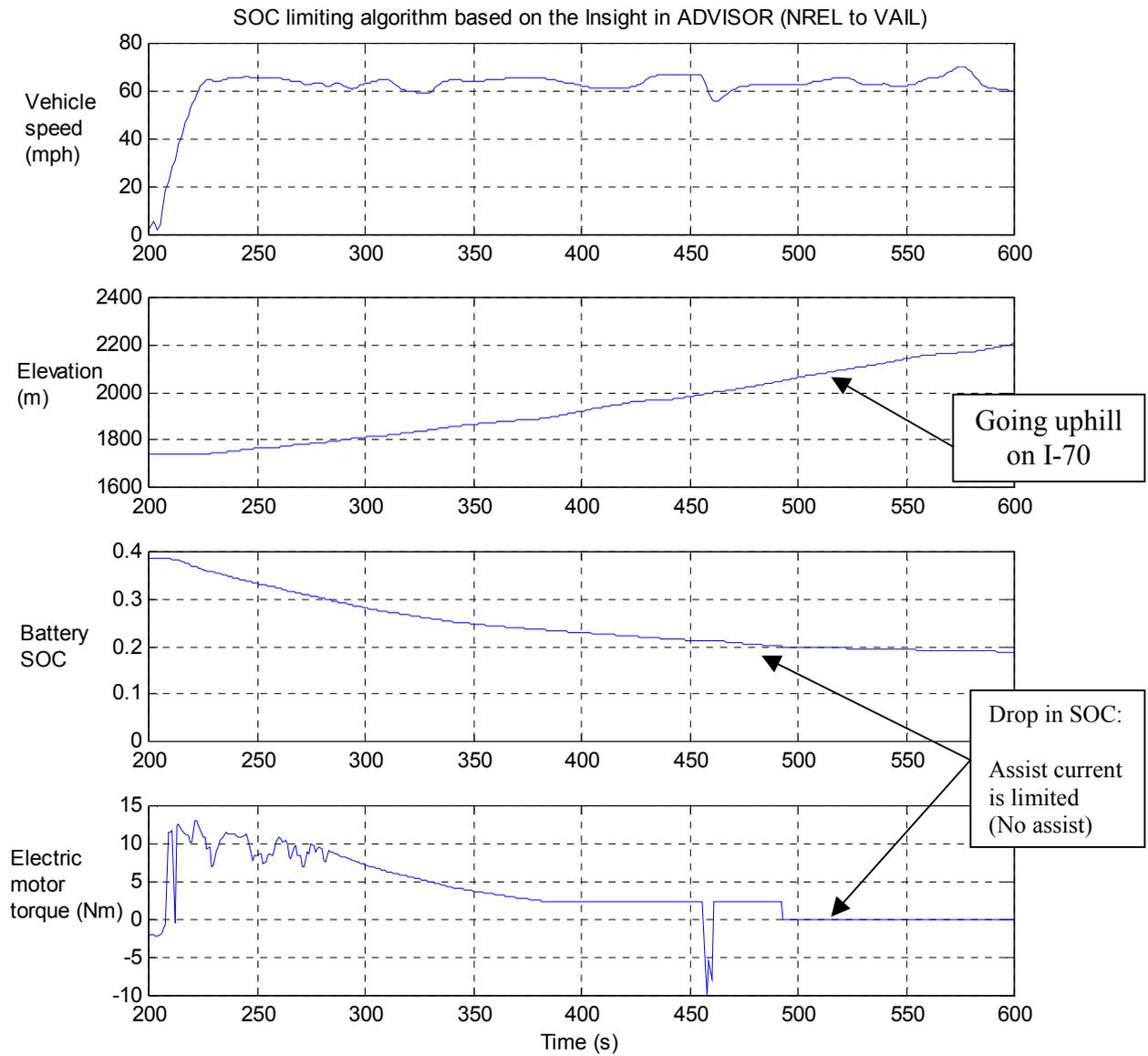


Figure 67: Effect of assist-control during low battery SOC in the Insight model

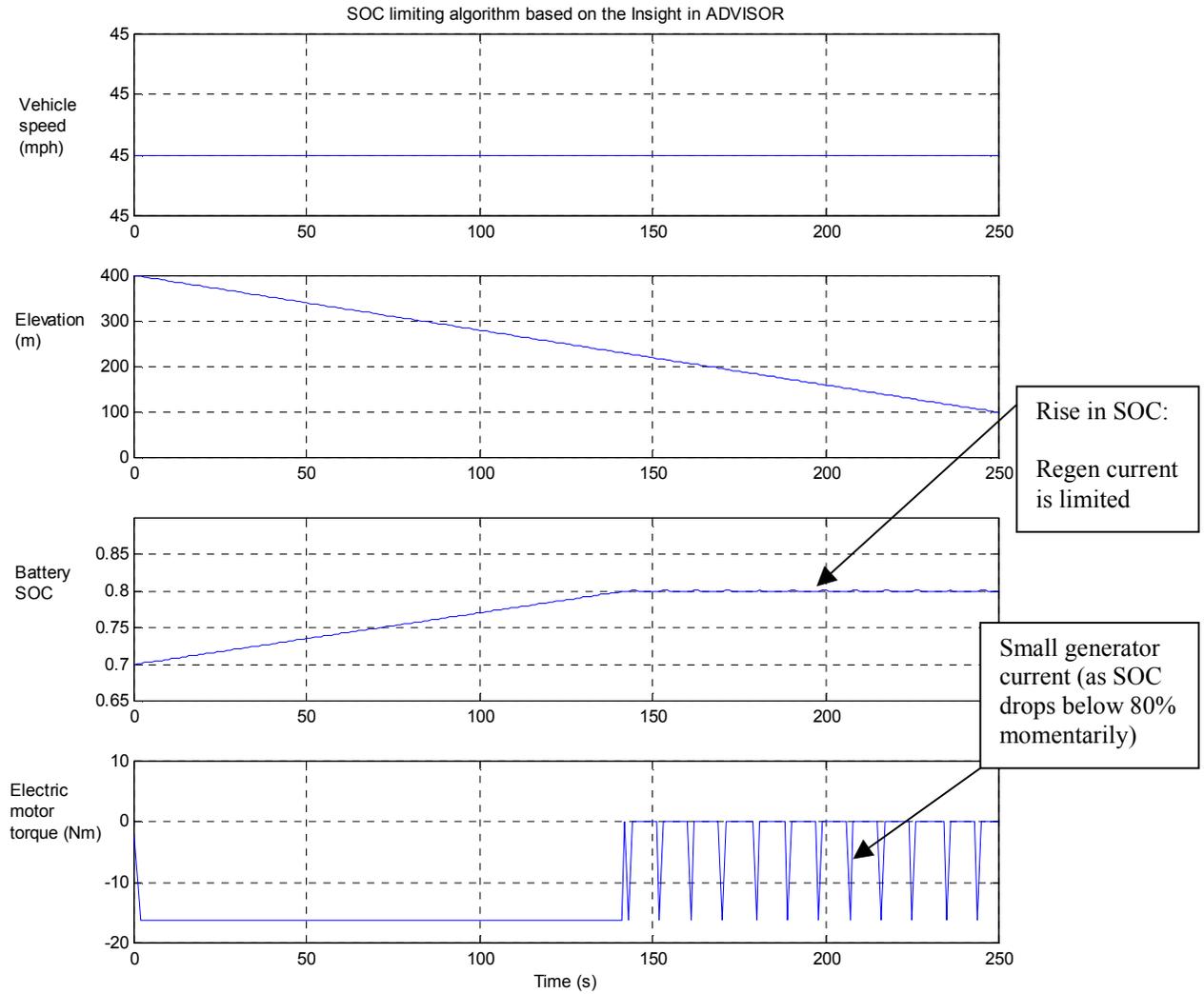
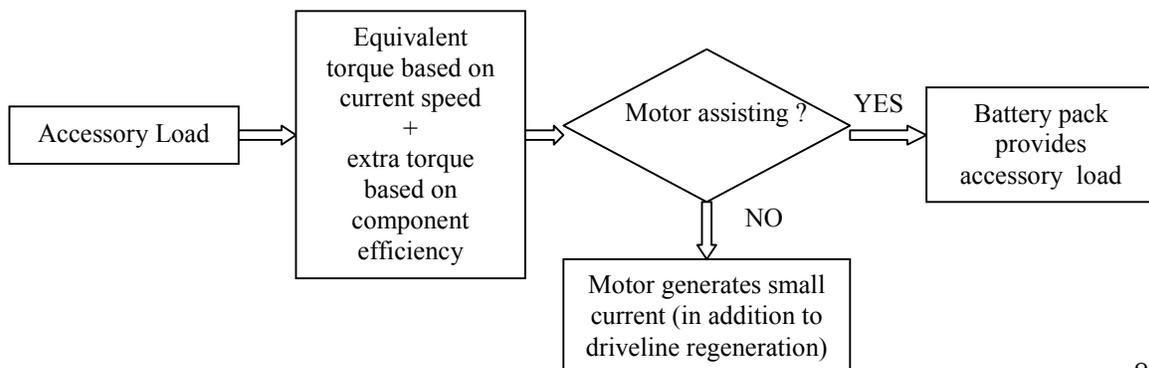


Figure 68: Effect of regen control during high battery SOC

Alternator function

As mentioned before, in the Insight the electric motor performs the function of the alternator. This is modeled in ADVISOR based on the accessory loads. The accessory load is converted to an equivalent torque request based on the instantaneous speed, and the electric motor is commanded to generate this value of torque when not assisting, or in addition to driveline regeneration.



Comparison of Data from SIMULATION and TESTING

The following parameters are considered in comparing the performance of the simulator, with the test data used for analysis.

Electric Motor behavior

The following graphs depict the behavior of the electric motor (IMA), either performing assist, regeneration or remaining inactive. In the following plots, the electric motor torque is plotted against time along with the speed trace, and experimental motor torque. Figure 69 through Figure 71 show that there is very good agreement between the motor torque predicted by ADVISOR and the test data for the HWFET, UDDS and Japanese 10-15 driving cycles. Some differences that exist are attributed to particular driver behavior or calculation difficulties (such as divide by zero).

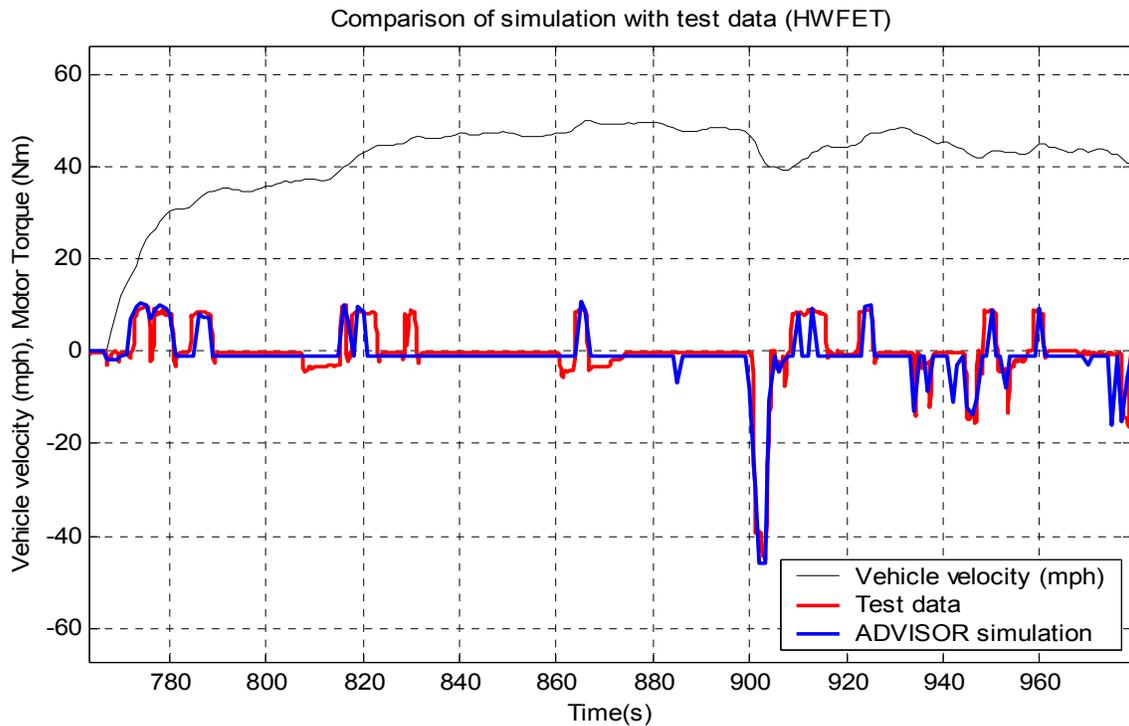


Figure 69: Comparison of motor torque with test data (HWFET)

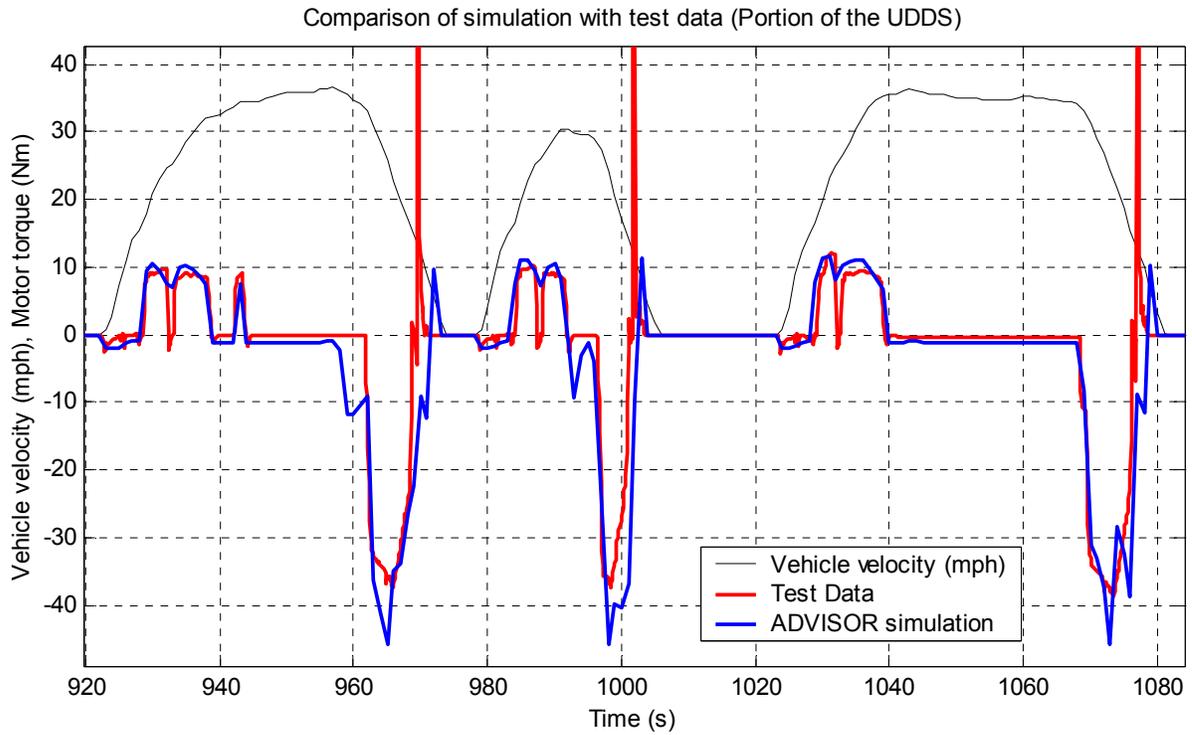


Figure 70: Comparison of Insight motor torque with test data (UDDS)

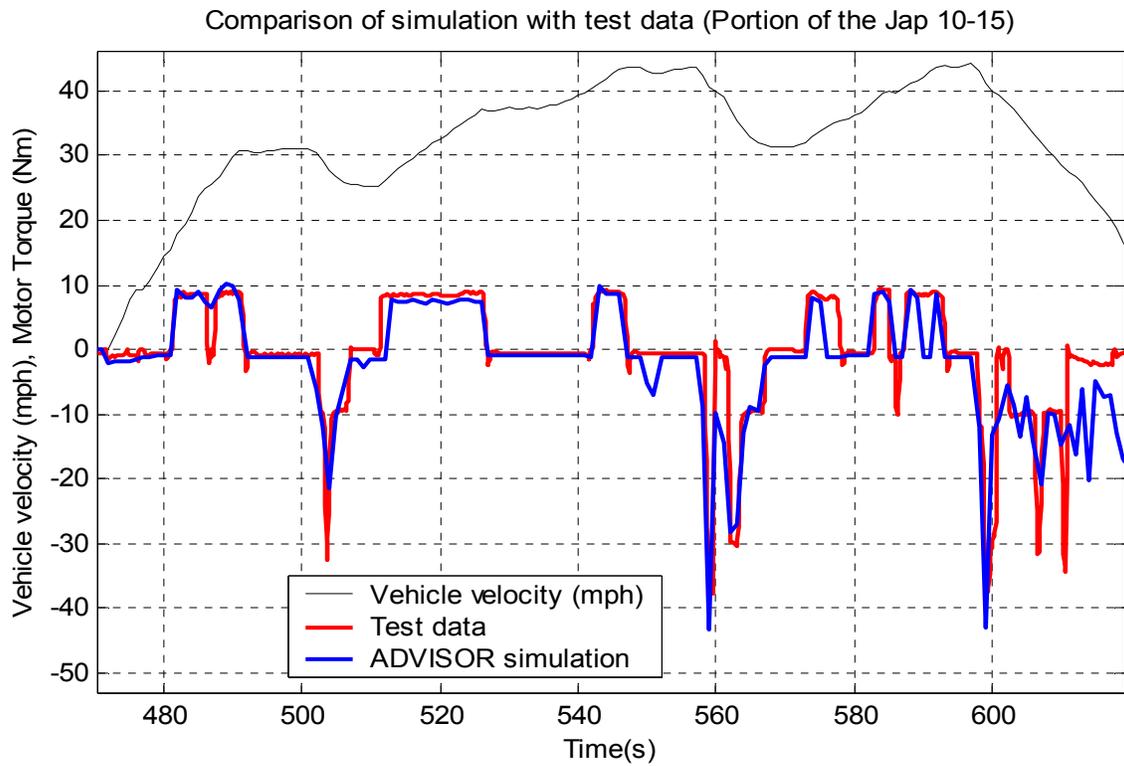


Figure 71: Comparison of Insight motor torque with test data (Jap 10-15)

Figure 72 shows a comparison of the electric motor torque contribution along with the total torque demanded from the driveline for the UDDS cycle. The figure shows the control strategy (in RED) overlaid on the test data (in BLUE). The upper right hand corner region depicts assist and the lower left corner depicts braking / regeneration.

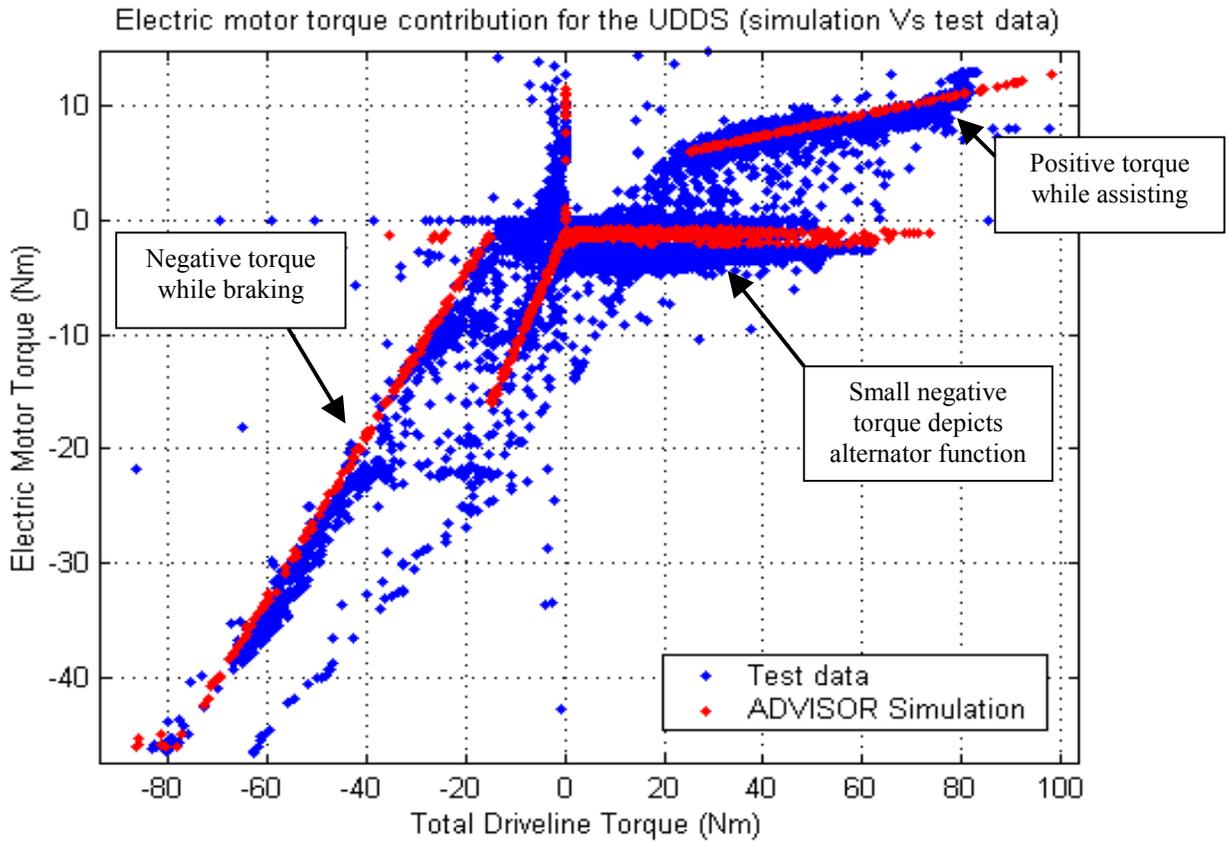


Figure 72: Comparison of the Insight motor torque with test data (UDDS)

Battery pack State of Charge (SOC)

The battery pack State of Charge (SOC) as computed by simulation is compared with the SOC from test data. Figure 73 shows a plot of the SOC from simulation and test data for the UDDS. As explained earlier, this SOC profile is very characteristic of the Insight's battery usage. Similarly, good agreement was observed for other test cycles.

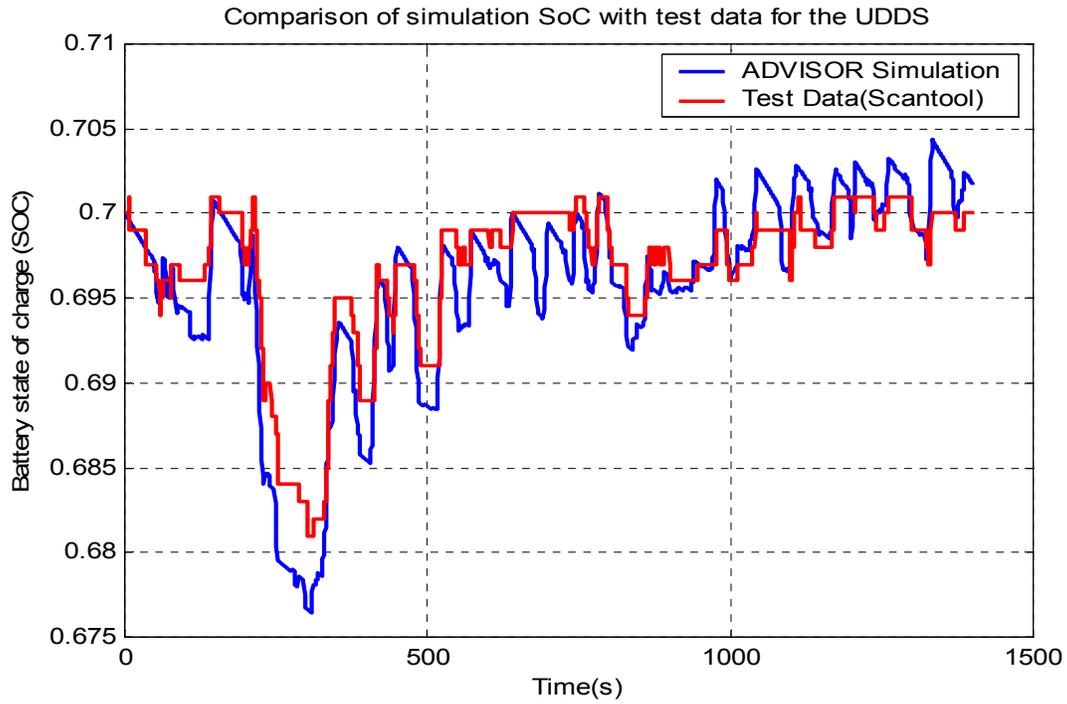


Figure 73: Comparison of Insight battery SOC with test data (UDDS)

Fuel Economy

The fuel economy obtained by ADVISOR simulation is compared with those from test data, for different driving cycles. The results are shown in Figure 74. It is seen that the simulation results closely match the fuel economy numbers from test data.

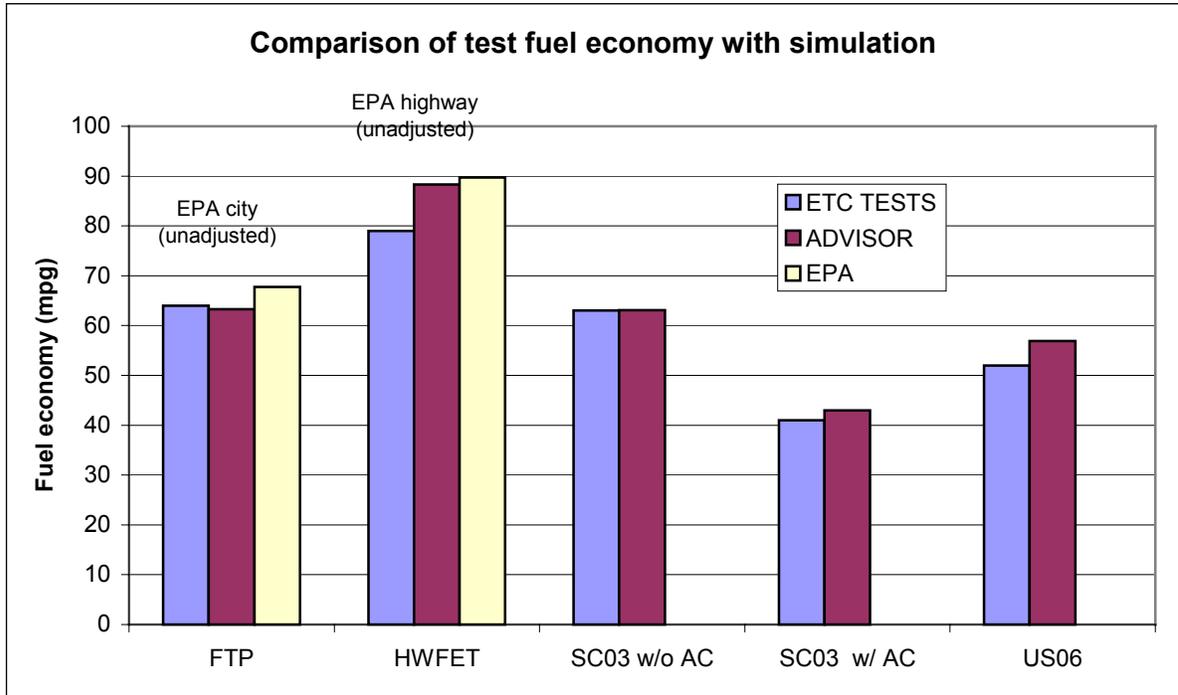


Figure 74: Comparison of Insight fuel economy with ADVISOR simulation

A summary of the Insight's fuel economy numbers from NREL's test data and ADVISOR simulation is shown in Table 14. Also enlisted, is the fuel economy for the FTP and HWFET as published by EPA.

Table 14: Summary of Insight fuel economy from test data and simulation

	ETC TESTS	EPA		ADVISOR Simulation	
	mpg	mpg	Difference from ETC tests	mpg	Difference from ETC tests
FTP	64	67.7	5.9 %	63.3	-1.0 %
HWFET	79	89.7	13.5 %	88.3	11.7 %
SC03 w/o AC	63	n/a	n/a	63.1	0.1 %
SC03 w/ AC	41	n/a	n/a	43	4.8 %
US06	52	n/a	n/a	56.9	9.4 %

Application of the model in ADVISOR

Scalability

Based on the Honda Insight model, a scalable new control strategy is now included in ADVISOR. This allows the user to develop his own strategy and apply it to different vehicles, based on the structure provided. The design flexibility of this strategy allows the user to vary the electric motor torque contribution for assist and regeneration, based on the torque requested from the driveline (source).

Sensitivity analysis based on the Insight model

A limited sensitivity analysis was performed on the Insight model, to illustrate the potential for studying the effects of changes to the vehicle control strategy parameters and behavior of the components. The following are the results of some sensitivity analysis.

Variation of level of assist

By varying the level of assist provided by the electric motor, we can determine an optimal assist level, that does not deplete the battery pack, and increases the fuel economy of the vehicle.

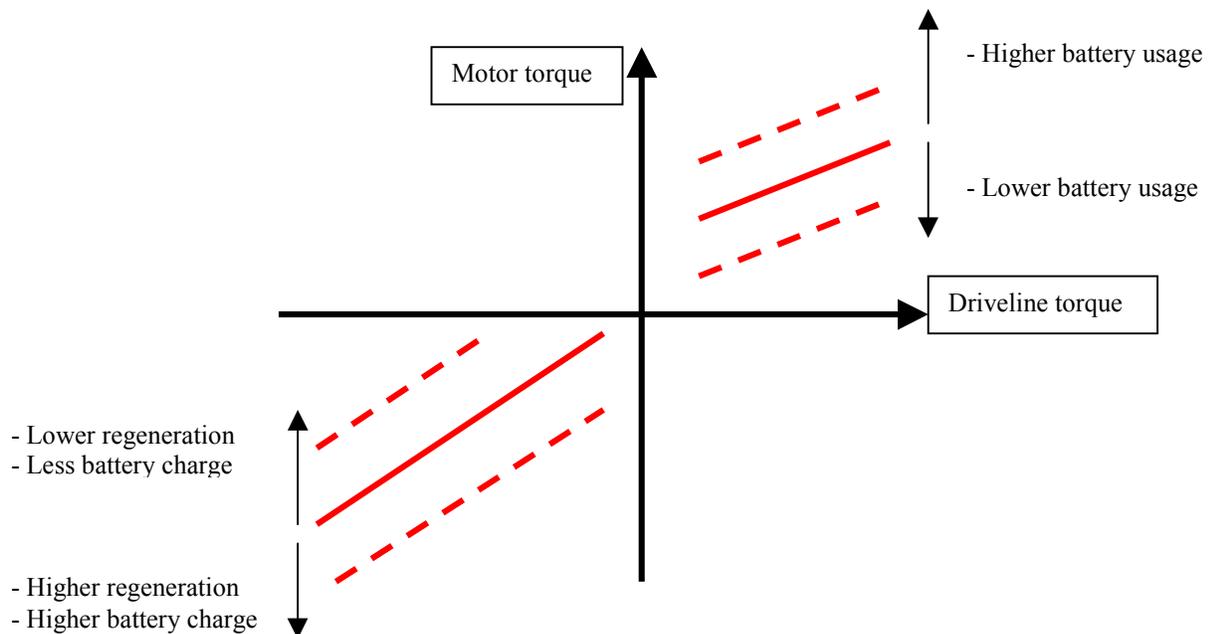


Figure 75: Variation of assist/regen using the Insight scalable control strategy

A couple of examples are illustrated below, to show the effect of varying the control strategy parameters. Table 15 shows the effect of varying the minimum electric assist of motor, as denoted by the parameter “*cs_mc_assist_min_frac.*” This corresponds to using more electric motor assist during accelerations. As expected, as the electric motor is used more vigorously, the fuel economy numbers go up, and battery SOC decreases, because these are not SOC balanced runs. The result of varying the minimum electric assist on the battery SOC and fuel economy are shown in Figure 77. In the schematic below, the solid RED line in the upper right quadrant indicates the electric motor assist level.

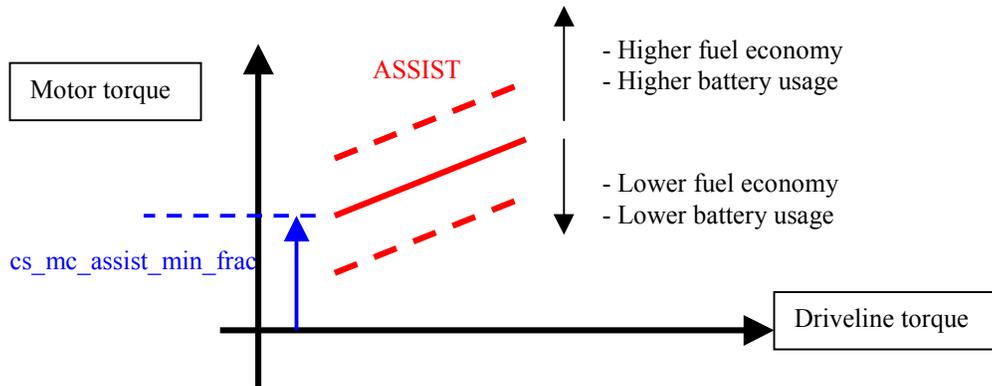


Figure 76: Variation of level of electric motor assist (Insight model)

Table 15: Effect of varying minimum electric assist (Insight model)

<i>cs_mc_assist_min_frac</i>	mpg	DeltaSOC
0.05	64.1	0.039
0.17	65.8	-0.019
0.29	67.7	-0.082
0.41	69.6	-0.151
0.53	71.4	-0.229
0.65	72.4	-0.306

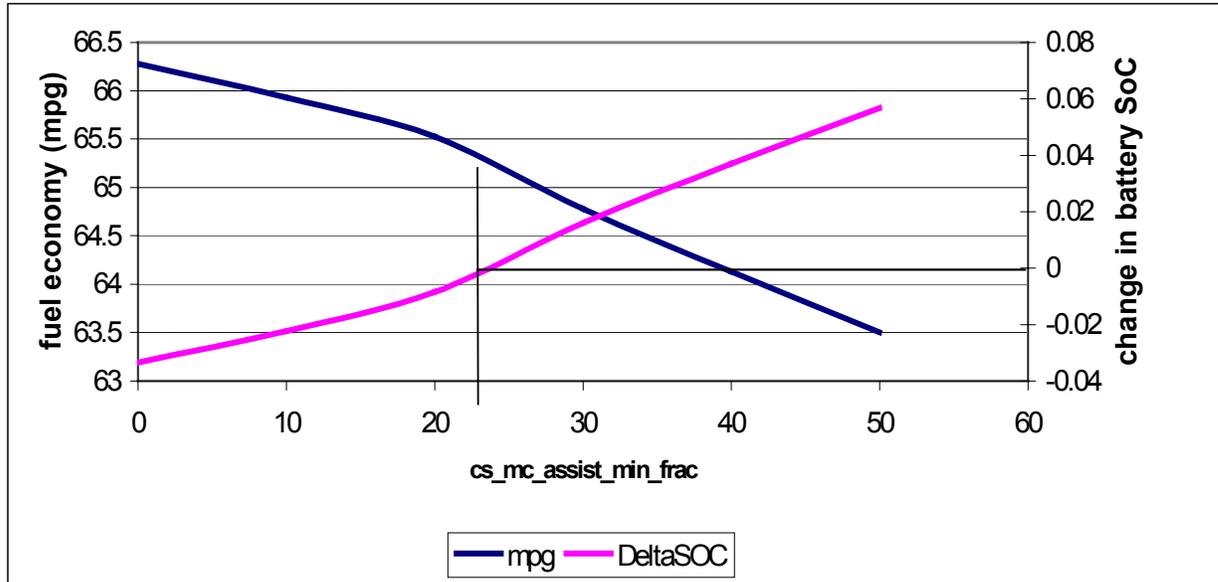


Figure 77: Effect of varying minimum electric assist (Insight model)

Another parameter that can be varied is the minimum driveline torque threshold value, above which the motor must assist the engine. The higher this value is, the greater the acceleration needs to be, before the motor provides assist. This value is denoted by the parameter “*cs_dl_assist_trq_threshold*.” The effect of varying this parameter is shown in Table 16 and graphically in Figure 79.

Table 16: Effect of varying assist threshold (Insight model)

cs dl assist trq threshold	mpg	DeltaSOC
0	66.3	-0.033
10	65.9	-0.022
20	65.5	-0.009
30	64.8	0.016
40	64.1	0.037
50	63.5	0.057

In the schematic below (Figure 78), the solid RED line in the upper right quadrant indicates the electric motor assist level. As this threshold is increased, the electric motor activity is curtailed, thus using less battery charge.

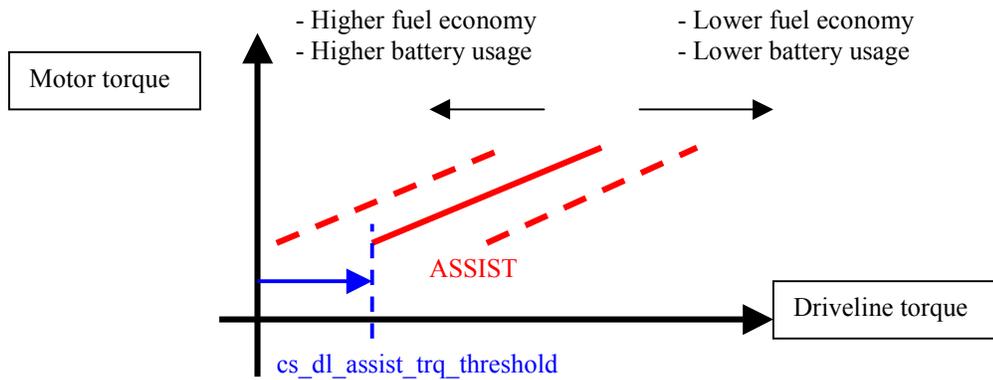


Figure 78: Variation of level of electric motor assist (Insight model)

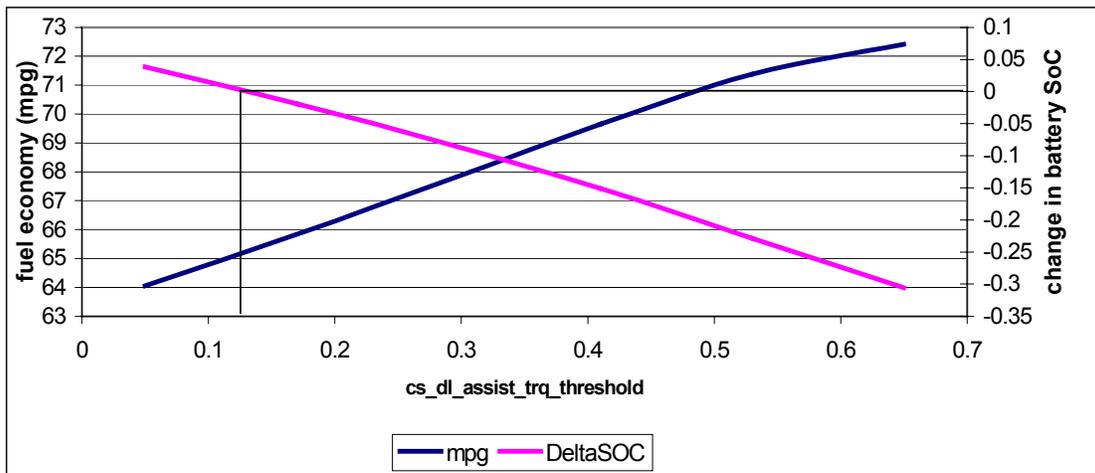


Figure 79: Effect of varying assist threshold (Insight model)

The scalable control also allows for varying the level of regeneration captured by the electric motor. This value is decided by the parameter “*cs_mc_regen_slope*.” This value can be set between 0 and 1. When set to 0, the electric motor does not regenerate any negative torque seen at the driveline. When set to 1, the motor regenerates all available negative torque at the driveline. The higher this value is set, the more charge is fed into the battery pack. Table 17 shows the effect of varying this parameter. It was seen that this parameter does not affect the fuel economy much, but affects the battery State of Charge (SOC) considerably. The higher the fraction, the higher the charge put into the battery pack. In actual design of a vehicle, the higher this parameter is, the better the capability of the drivetrain to perform regenerative braking, and prevent energy being lost solely as heat in the friction brakes. The effect of the parameter is shown graphically in Figure 81.

Table 17: Effect of varying motor regeneration fraction (Insight model)

cs_mc_regen_slope	mpg	DeltaSOC
0.4	60.94	-0.040
0.5	60.94	-0.025
0.6	60.93	-0.011
0.7	60.93	0.003
0.8	60.93	0.016
0.9	60.92	0.026

In the schematic below (Figure 81), the solid **RED** line in the lower left quadrant indicates the electric motor regeneration level. The higher the slope, the more negative torque is regenerated by the motor.

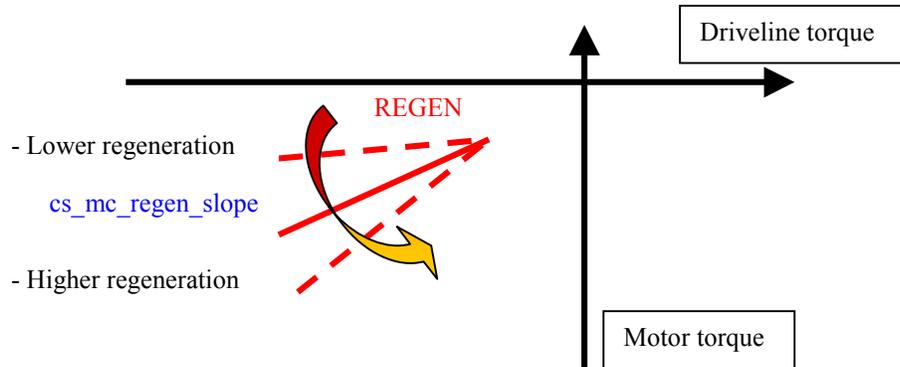


Figure 80: Variation of level of electric motor regeneration (Insight model)

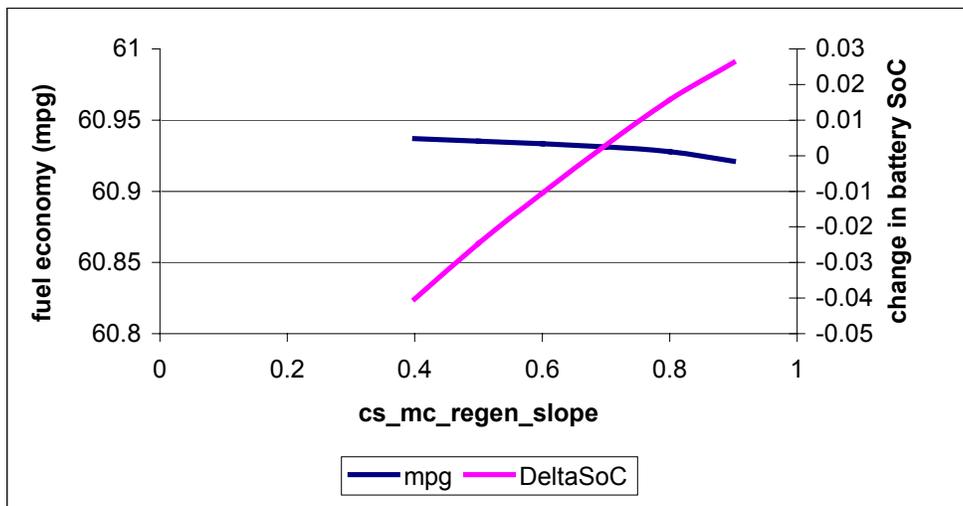


Figure 81: Effect of varying motor regeneration fraction (Insight model)

Idle stop feature

The idle stop feature (which allows the engine to shut off during a vehicle stop) can be disabled in simulation by the variable “*vc_idle_bool.*” The following table describes the benefits of the feature (in the Insight), and its effects on fuel economy and battery State of Charge (SOC). Here, we see in Table 18 that by using ADVISOR to eliminate the idle-stop feature results in a 6.5% decrease in fuel economy with only a limited change in battery SOC. The Battery SOC decreases, since there is no regeneration during the idling process.

Table 18: Sensitivity of the scalable model

Parameter	Idle stop OFF	Idle stop ON	Effect of adding idle stop (ON)
Fuel economy (on the UDDS)	56.9 mpg	60.9 mpg	Increase of approx. 6.5 %
Battery SOC (on the UDDS)	Small net positive charge into battery during idle	No net charge into the battery during stops	Moderate drop in SOC OFF – SOC gain = 1.88 % ON – SOC gain = 0.3 %

The following plot (Figure 82) shows the effect of the engine idle-stop feature on the engine operation.

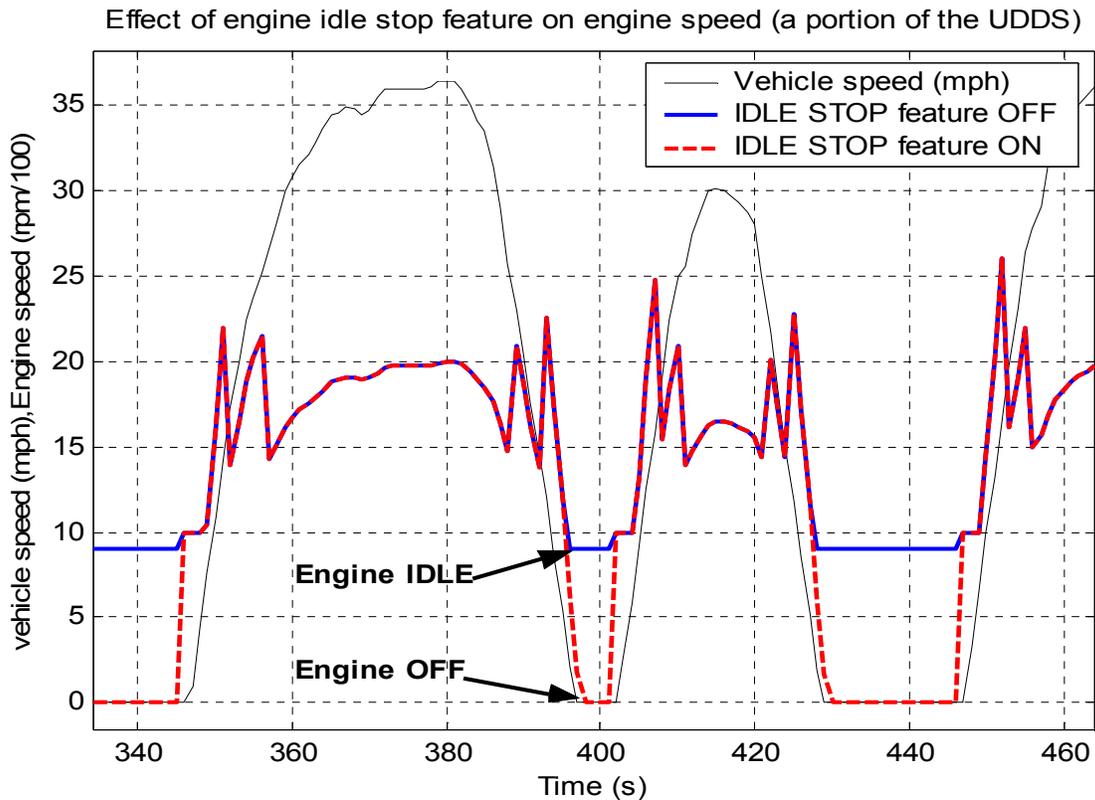


Figure 82: Engine idle-stop feature in simulation

Summary of Conclusions

In developing the test plan for these two vehicles NREL set out to answer several questions that it deemed important to the understanding of the vehicle behavior. These questions are listed below with answers based on the work that has been completed so far.

How much does the fuel economy and emissions of high efficiency vehicles like the Insight and Prius suffer when the air-conditioning is used under hot conditions?

The impact of air conditioning on vehicle fuel economy is one of the clearest and most dramatic results from the testing. ETC tested both vehicles using the EPA's procedure for evaluating emissions while using air conditioning (SC03). Two tests were performed: one with the AC on and one with the AC off. The Insight showed a 34% reduction in fuel economy with the air conditioning on. The Prius showed a 30% reduction in fuel economy with the air conditioning on.

In terms of emissions, the Insight showed significant increases in CO₂ and CO emissions with the air conditioning on. Emissions of NO_x and HC were not statistically different between the two tests. The Prius showed substantial increases in CO₂, HC, and CO with the air conditioning on. Emissions of NO_x were actually higher with the AC off than with the AC on. Results for the Insight were verified through repeat testing. Repeat testing of the Prius will be conducted before the end of the fiscal year 2001.

Other effects of air conditioning include:

- the Insight was not able to fully follow the SC03 driving trace with AC on and required significantly more use of the motor assist and therefore battery power
- the Prius was able to follow the SC03 driving trace, but required greater use of the gasoline engine
- for the Insight, electrical energy from the high voltage battery pack used to power auxiliary systems increased from 170 W to 900 W with the AC on
- for the Prius, electrical energy from the high voltage battery pack used to power auxiliary systems increased from 300 W to 800 W with the AC on

When and to what degree do the Insight and Prius use their electric traction motors and batteries to assist the engine and capture regenerative braking?

Utilization of the traction motor and battery pack is a key feature of any hybrid vehicle model. NREL's instrumentation of the Insight and Prius focuses on collection of the appropriate electrical signals to answer this question. Axle torque data was provided by Argonne National Laboratory from their testing of the Honda Insight at Automotive Testing Laboratories in Ohio.

For the Insight, the gasoline engine is the primary motive source and the electrical motor is used to assist in conditions of high load. NREL's analysis indicates that the electric motor kicks in when the driveline torque required exceeds 20 Nm and that it provides a

relatively constant torque of approximately 10 Nm (data shows that actual motor torque levels vary from 8 Nm to 12 Nm while assisting). Input power levels to the electric motor during the FTP (city) driving cycle were between 2.5 kW and 4.5 kW. On the more aggressive driving cycles such as the US06, input power levels peaked at a high of 6.5 kW. The Insight's permanent magnet DC motor has a maximum torque of 50 Nm and a peak power of 10 kW.

The Insight's regenerative braking has two modes of operation. One when the vehicle is "coasting down" with the vehicle in gear, and the other with the driver's foot on the brake. The amount of regenerative braking varies linearly with the amount of torque available through the driveline. The test data indicates that approximately 50% of the braking energy goes into the driveline to be captured by the electric motor. Power levels from the motor/generator on standard driving cycles were often as high as 6 kW on the FTP cycle and 7 kW to 9 kW on the more aggressive US06 driving cycle.

Less analysis has been performed on the data from the Prius, since the testing has not yet concluded. However, the following observations can be made from the existing data. The Prius uses the electric motor in a wider range of modes. The Prius gasoline engine is shut off during a significant portion (46%) of the UDDS (the first two phases of the FTP) driving cycle. Twenty percent of this is while the vehicle has come to a stop. This means that the Prius is running all-electric during 26% of the UDDS cycle. The Prius also uses the electric motor and the planetary gear to reduce the transient operation of the gasoline engine and thereby reduce emissions and fuel use. Test data shows that during certain portions of the driving cycle, when both the electric motor and the gasoline engine are operating, the gasoline engine does not directly follow the speed of the vehicle and therefore experiences fewer transients.

Both vehicles have nickel-metal hydride battery packs with a 6.5 Ah rating. The Insight battery pack has 120, 1.2 V cells for a nominal voltage of 144 V. The Prius battery pack is nearly twice as large with 228, 1.2 V cells for a nominal pack voltage of 273.6. Testing on the dynamometer determined that the Insight maintains control limits on the battery pack that only allow 3.7-3.9 Ah, or between 57% and 60% of the rated capacity. This agrees well with published information that indicates that the Insight maintains its battery state-of-charge (SOC) between 20% and 80% SOC. Testing also revealed that the Prius has control limits of 40% to 80% SOC, so that the Prius battery pack useful capacity is 40% of the rated 6.5 Ah, or 2.6 Ah.

Additionally, the NREL tests showed that while the Insight seems to continually add a small amount of charge to the vehicle over standard drive cycles like the FTP and HWFET, the Prius tends force its battery to within a narrow band around 56% SOC. In testing the Insight over back-to-back cycles it tended to exhibit the same SOC profile no matter independent of the initial SOC. The exception to this is when the Insight pack reaches 80% SOC and no longer accepts regenerative power, or when it reaches about 36% SOC and begins tapering off the amount of available power provide for motor assist. The latter situation was seen both on the dynamometer and during on-road mountain driving conditions in which the vehicle began limiting motor assist long before the top of

the grade was reached. By comparison, testing of the Prius showed that it drastically adjusts its use of the battery pack depending on the initial SOC until it reaches the target 56% SOC. For example, when running a city driving cycle with an initial SOC of 40% and the engine already warm, the Prius did not shut off the engine for the first time until it reached the target SOC.

Engine-off operation for the two vehicles is also very different. For the case of the Insight this basically refers to elimination of idling when the engine is warm and has come to a stop or is decelerating at speeds less than 20 mph. For the Prius “engine-off” occurs during low speed, low load conditions during which the vehicle can run in all-electric mode. When conducting a cold-start FTP test the Prius engine is off 46% of the time, while the Insight engine shuts off only 18%. An ADVISOR simulation of the effect of eliminating engine-off operation indicated that this has about a 6% impact on fuel economy. On the HWFET test, which does not have any stops during the cycle, the Prius engine was off during 4% of the cycle while the Insight engine did not shut off. Engine-off operation during the hot US06 cycle occurred 16% of the time for the Prius and only 7% of the time for the Insight.

How do the Insight and Prius battery thermal management systems behave under various ambient temperature conditions?

Although the Insight and Prius both have nickel-metal hydride battery packs with a rated 6.5 Ah capacity, their configurations and thermal management systems have some significant differences that are apparent in the test results. Both vehicles force cabin air through the pack to cool the batteries, but the pack geometries are very different. The Insight pack consists of a set of 20 cylindrical models stacked in rows of 3. The Prius pack consists of a set of 38 prismatic modules stacked side-by-side.

From the tests conducted it appears that the Prius thermal management system is more effective at transferring heat away from the pack than the Insight’s is. However, under relatively mild conditions such as those encountered during standard FTP and HWFET tests, the thermal management systems on both vehicles appear to be adequate. On the FTP cycle the change in average battery pack temperature from the beginning of the test to the end of the test was 2.5°C, and the temperature distribution across the pack was 1.3°C. Compared to the Insight, the Prius used five times more battery energy over the FTP cycle, yet the increase in temperature from beginning to end was only 5°C and the temperature distribution across the pack at the end of the test was 4°C.

Under the more aggressive driving conditions of the US06 cycle where the Prius pack transferred 3x more energy, the change in battery temperature from the beginning to the end of the test cycle was 7.5°C for the Insight and 8°C for the Prius. Temperature distributions across the pack at the end of the US06 cycle were 2°C for the Insight and 4°C for the Prius.

Hard charging of the Insight revealed an apparent control strategy that limits the amount of power available from the battery pack when battery temperatures reach 45°C to 50°C.

This power limiting had a significant effect on the Insight's ability to meet the US06 driving trace when the test procedure was initiated at 40°C. Cold temperature testing of the Insight also showed reduced power available from the battery and a reduced ability to meet the driving trace for the initial 0°C US06 driving cycle. The Prius did not have a problem following the driving trace for any of the US06 tests (0°C, 20°C, 40°C), but analysis of the power availability from the battery pack under these conditions has not yet been completed.

Are the ADVISOR battery models of the Insight and Prius accurate when compared with in-vehicle usage of the pack?

For the Insight, ADVISOR simulations of battery current and voltage over the various test cycles were in very good agreement with the test data. Battery state of charge predictions also agreed well with the test data. At the time this report was written the ADVISOR model of the US Prius had not yet been developed.

Do the ADVISOR Insight and Prius models accurately predict the emissions & fuel consumption of the Insight and Prius vehicle on standard driving cycles?

Using NREL's newly developed Honda Insight control strategy model, the best available vehicle and component information available including an engine fuel use map provided by Argonne National Laboratory, ADVISOR's predictions of fuel economy were fairly consistent with the EPA's fuel economy numbers and with the ETC test results. Comparisons of emissions were not possible since an accurate emissions map from the Insight has not yet been incorporated into the model.

ADVISOR predicted fuel economy of 63.3 mpg on FTP test and 88.3 mpg on the HWFET test within 7% of the unadjusted EPA city fuel economy and within 2% of the unadjusted EPA highway fuel economy values. The fuel economy test results from ETC were 7% lower than the EPA city result and 12% lower than the EPA highway cycle results. When comparing the ADVISOR predictions to the ETC test data, the ADVISOR results were within 1% on the FTP, 12% on the HWFET, 9% on the US06, 0.2% on the SC03 without air conditioning, and 5% on the SC03 with air conditioning. For the cycle with air conditioning the simulation was run with an electrical auxiliary load of 800 W and an additional mechanical load of 3 kW to account for air conditioning.

A comparison of the Prius test results to ADVISOR simulations was not possible at this time, since the US Prius model has not yet been developed in ADVISOR.

Other Findings and Accomplishments

A number of other findings and accomplishments from this testing are described in the report. The report provides a contrast and comparison of many of the features of the first two production HEVs available in the US. A key accomplishment is the inclusion of the new Honda Insight control strategy in the August 2001 public release of ADVISOR 3.2. This is a new parallel vehicle control that, while it is a relatively simple motor assist strategy, it is a popular approach for mild hybrids. The parametric design allows the user

to perform “what if” investigations on parameters such as the level of torque contribution from the electric motor, at what point should the motor provide assist, and the level of regen energy available.

Future Work

For the Insight, only a limited amount of additional modeling work is planned. Most notably, NREL plans on incorporating an engine emissions map in ADVISOR based on test data from ANL. This activity may also include incorporation of catalyst efficiency information and the incorporation of a NO_x trap if this information becomes available.

For the Prius, NREL will complete testing of the Prius at ETC during the end of FY2001. This will include repeat tests on most of the procedures discussed here along with some extended tests such as multiple back-to-back FTP, HWFET, and US06 cycles to determine the thermal behavior of the battery pack over an extended period. Once the testing has been completed additional analysis will be performed and a US Prius model will be developed in ADVISOR. The US Prius model will most likely use the Japanese Prius as the starting point and incorporate new information based on testing at NREL and ANL.

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 - c) <http://www.honda2000.com/models/insight>
18. Prius Web Pages:
 - a) <http://prius.toyota.com>

APPENDIX

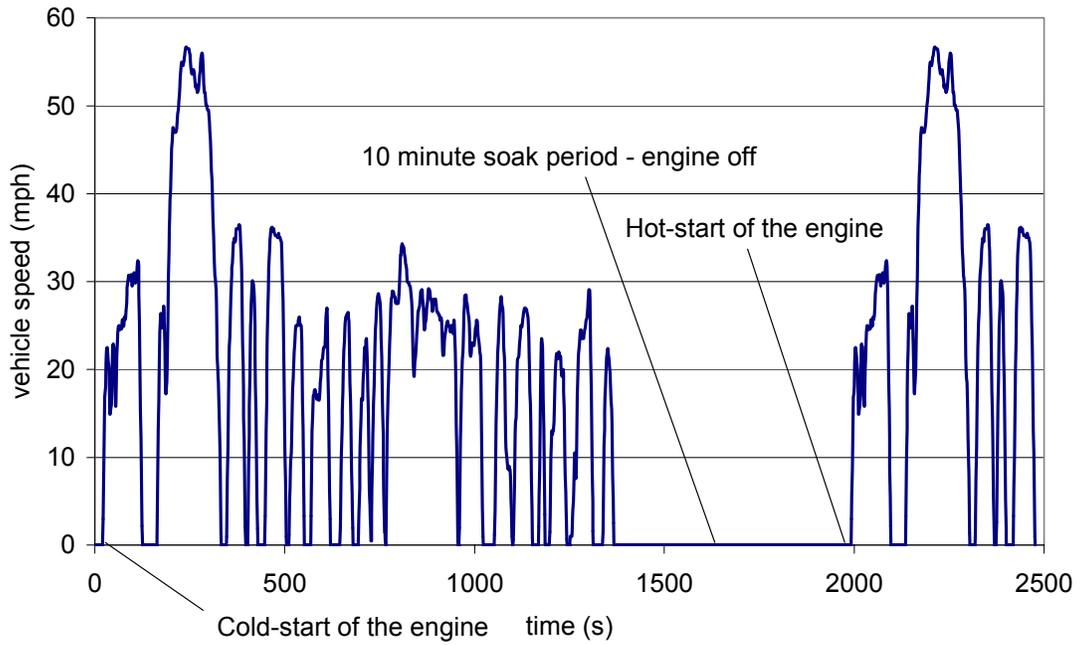


Figure 83: Federal Test Procedure (FTP-75)

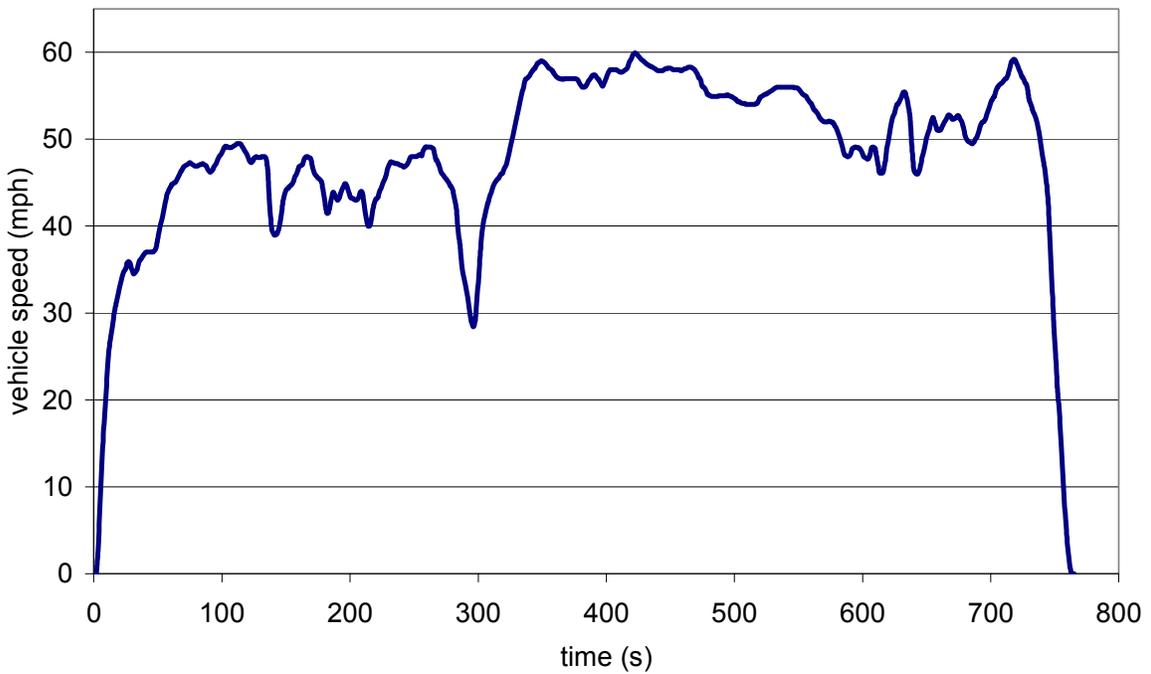


Figure 84: Highway Fuel Economy Test (HWFET)

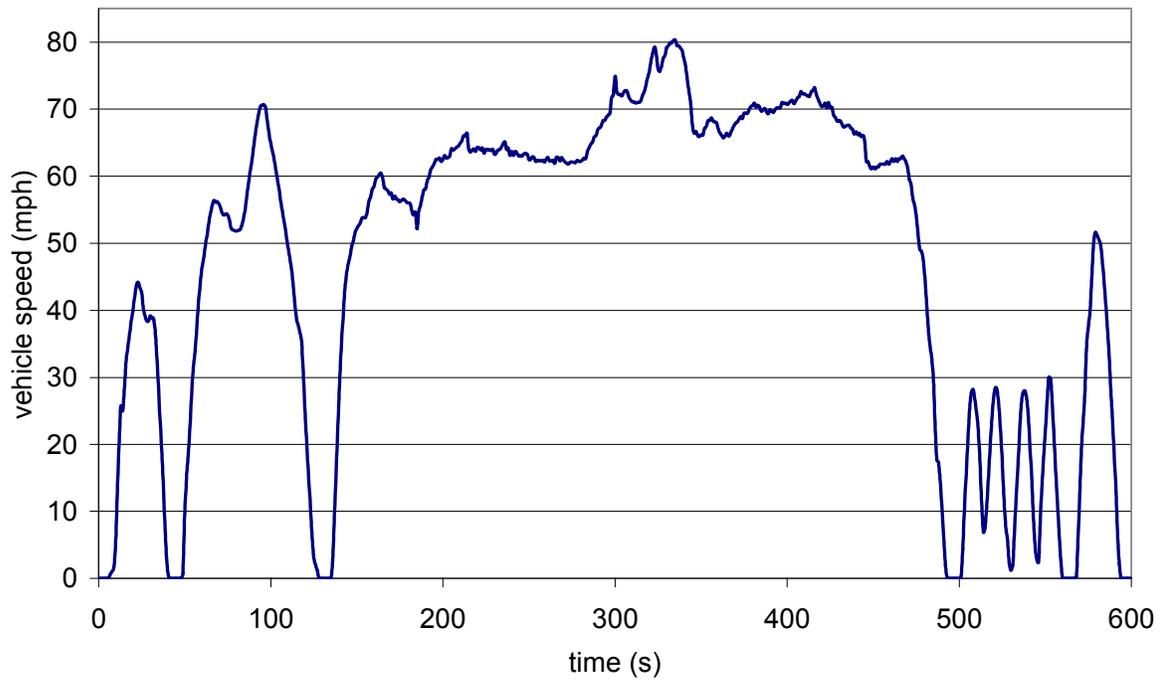


Figure 85: Aggressive driving cycle (US06)

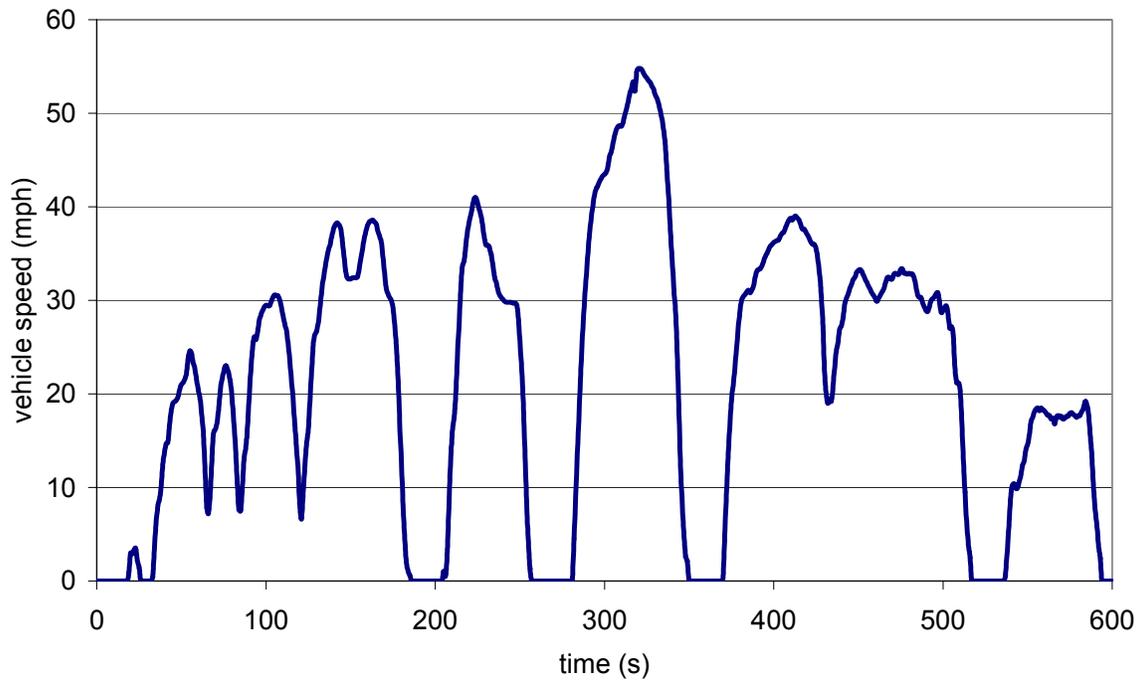


Figure 86: Air-Conditioning test driving cycle (SC03)