ANL/ES/RP-67317

Model Year 2010 (Gen 3) Toyota Prius Level-1 Testing Report

Energy Systems Division

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9/8/2010

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1 Abstract

As a part of the US Department of Energy's Advanced Vehicle Testing Activity (AVTA), a model year 2010 Toyota Prius (Generation 3) was procured by eTec (Phoenix, AZ) and sent to ANL'S Advanced Powertrain Research Facility for the purposes of "Level 1" testing in support of the Advanced Vehicle Testing Activity (AVTA). Data was acquired during testing using non-intrusive sensors, vehicle network connection, and facilities equipment (emissions and dynamometer data). Standard drive cycles, performance cycles, steady-state cycles and A/C usage cycles were conducted. Much of this data is openly available for download in ANL's Downloadable Dynamometer Database (D^3). The major results are shown here in this report.

Given the preliminary nature of this assessment, the majority of the testing was done over standard regulatory cycles and seeks to obtain a general overview of how the vehicle performs. These cycles include the US FTP cycle (Urban) and Highway Fuel Economy Test cycle as well as the US06, a more aggressive supplemental regulatory cycle. Data collection for this testing was kept at a fairly high level and includes emissions and fuel measurements from the exhaust emissions bench, high-voltage and accessory current and voltage from a DC power analyzer, and minimal CAN bus data such as engine speed and pedal position. The following sections will seek to explain some of the basic operating characteristics of the MY2010 Prius over standard regulatory cycles.

2 Vehicle Description

The MY2010 Toyota Prius represents the most recent iteration of Toyota's hybrid system which began wide-scale production in 1997. As with the majority of Toyota hybrid systems, this version includes an Atkinson-cycle engine, two electric machines and a power-split device used to control the allocation of energy between the electric and mechanical (fuel) power paths. As with most hybrid systems, fuel economy and emission gains are enabled through regenerative braking, engine-off at idle, electric operation at low road loads, electric assist, and the general ability to operate the engine more optimally. In addition to the broad goal of generally improved fuel economy, the MY2010 Prius also specifically seeks to improve the vehicle's real-world fuel economy, namely, hot and cold weather operation as well as improving high-speed operation with minimal compromise to urban driving.

To accomplish these objectives, the majority of the Prius' hybrid components have been redesigned or updated. Engine displacement has increased to 1.8L versus the previous 1.4L in order to increase efficiency at higher vehicle speeds. In order to maintain low-speed vehicle efficiency, an Exhaust Gas Recirculation (EGR) system was included. Additional engine related improvements include an electric water pump and an exhaust heat recirculation system. The recirculation system allows for exhaust heat (loss) leaving the engine to be absorbed into the engine coolant when desired. The hybrid

transmission and electric machines were also redesigned to facilitate an overall transmission length and mass reduction. More specifically, gearing was included between the motor/planetary gear set and compound gearing was also included. The motor/planetary gearing is to allow for reduced motor torque while still providing high power through increased motor speed (~ 13000 rpm maximum versus previous ~9000 rpm maximum speed). The compound gearing integrates several functions such as a parking gear and counter drive into a more compact package. In addition to these mechanical components, the power electronics and battery packaging have also been redesigned to facilitate mass and volume reductions. Overall, much attention has been paid towards reducing the mass and volume of the newly developed system while continuing to improve fuel economy.

The following are Generation 3 Prius vehicle specifications according to Toyota Motor Corporation (http://www.toyota.com/prius-hybrid/specs.html).

Gasoline Engine
Type: Aluminum double overhead cam (DOHC) 16-valve VVT-i 4-cylinder
Displacement: 1.8 liters (1798 cc)
Bore x stroke: 3.17 in. x 3.48 in.
Compression ratio: 13.0:1
Valvetrain: Four valves per cylinder with Variable Valve Timing with intelligence (VVT-i)
Induction system: Sequential multi-point EFI with Electronic Throttle Control System with intelligence (ETCS-i)
Ignition system: Electronic, with Toyota Direct Ignition (TDI)
Power output: 98 hp @ 5200 rpm (73 kW @ 5200 rpm)
Torque: 105 lb.-ft. @ 4000 rpm (142 N•m @ 4000 rpm)
Emission rating: Advanced Technology Partial Zero Emission Vehicle (AT-PZEV)

Electric Motor
Motor type: Permanent magnet AC synchronous motor
Power output: 80 hp (60 kW)
Torque: 153 lb.-ft. (207 N•m)
Voltage: 650V maximum

Traction Battery
Type: Sealed Nickel-Metal Hydride (Ni-MH)
Power Output: 36 hp (27 kW)
Voltage: 201.6V

Hybrid System Net Power
134 hp (100 kW)

Mechanical/Performance
Transmission: Electronically controlled continuously variable transmission (ECVT)
- EV mode
- Eco and Power modes

Front Suspension: Independent MacPherson strut with stabilizer bar
Rear Suspension: Torsion beam
Steering: Electric Power Steering (EPS); rack-and-pinion with electric power-assist

Vehicle
Overall height/width/length (in): 58.7/68.7/175.6
Wheelbase(in): 106.3
Track (front/rear, in): 60.0/59.8
Curb weight (lb.): 3042
Seating capacity: 5
Passenger volume (cu. ft.): 93.7
Luggage capacity (cu. ft.): 21.6
Fuel tank (gal.): 11.9

Mileage estimates
MY 2010 Prius (Gen. 3)
MPG city: 51
MPG highway: 48
MPG combined: 50

Previous generation vehicle: MY 2004 Prius (Gen. 2)
MPG city: 48
MPG highway: 45
MPG combined: 46

3 Vehicle Instrumentation

3.1 Data Acquisition System

Argonne's chassis dynamometer facility was specifically designed to perform research-oriented testing. Because of this objective, a custom data acquisition and control system was built around the needs for hybrid vehicle testing. The custom design also allows integration with new measurement systems as different vehicles are tested in the lab. All data is collected from the various sources, time-aligned and merged by the Host Computer and saved along with other test information in a 10Hz data file.

3.2 Vehicle Signals

Facility Data		Comment
	Drive Schedule [MPH]	
	Bag Number [n]	
	Vehicle Speed [MPH]	
	Dyno_TractiveForce_Front [N]	
	Dyno Front Load Cell [N]	
	DilAir RH [%]	
	Tailpipe Pressure [in H2O]	
	Cell Temp [C]	
	Cell RH [%]	
	Cell Press [inHg]	
	Tire_Temp [C]	
Vehicle Network Data		
	Accel_Pedal_Position_CAN [%]	
	Veh_Spd_CAN [mph]	
	Powetrain_Torque_CAN	
	Eng_Spd_CAN [rpm]	
	Brake_Pedal_Force_CAN	
	Brake_Pedal_Switch_CAN	
	A/C_on_off_CAN	
	Eng_Temp_CAN	
	Batt_SOC_CAN	scaling found after testing
	Batt_Current_CAN [A]	
Installed Sensors		
	Eng_Temp_Oil_Dipstick[C]	
	Cabin_Vent_Temp[C]	
	Eng_Spd[rpm]	
	Dyno Spd Front copy [MPH]	
Hioki Analog		
	Batt_Curr_Hioki-I1 [A]	Ch1 = HV Battery
	Batt_V_Hioki-U1 [V]	Ch1 = HV Battery
	12VBatt_Curr_Hioki-I5 [A]	Ch2 = 12V Battery
	12VBatt_Volt_Hioki-U5 [V]	Ch2 = 12V Battery
Hioki Serial		
	U1	HV voltage
	I1	HV current
	P1	HV power
	IH1	HV Ah
	WP1	HV Wh
	U5	12V voltage
	I5	12V current
	P5	12V power
	IH5	12V Ah
	WP5	12V Wh
Emissions Bench		
	THC [mg/s]	
	CH4 [mg/s]	
	NOx [mg/s]	
	COlow [mg/s]	
	COmid [mg/s]	
	CO2 [mg/s]	
	HFID [mg/s]	
	NMHC [mg/s]	
	Fuel [g/s]	

4 Urban Cycle Operation

This section discusses vehicle performance over the Urban driving schedule. This schedule is meant to replicate typical stop-and-go city driving. Testing for this cycle is comprised of two repeated runs with a 10 minute soak period between repeats. The first run is referred to as “cold” due to the vehicle having no warm-up operation prior to running. The second repeat run is referred to as “warm” given the fact that the vehicle has run the cold cycle prior to running the next cycle. In addition to the overall performance over the Urban drive schedules, the difference between “hot” and “cold” operation is also of interest. Table 1 below shows the dynamometer tested fuel economy over both “warm” and “cold” cycles.

Table 1: Urban Fuel Economy

	Urban Cold	Urban Warm
Unadjusted Fuel Economy (mpg)	63	70

In addition to the high fuel economy values, it is worth noting that the difference between the cold and warm urban is roughly 10%. This result is smaller than previous generation hybrid vehicles which typically have a difference of roughly 15%. While the urban cold and warm cycles are run with a fairly warm ambient temperature (~75F), the moderate differences between Urban cold and warm operation are illustrative towards understanding one of the main missions of this vehicle, namely, improved cold temperature (much colder than regulated) fuel economy.

4.1 Engine Operation

This reduced difference between warm and cold operation is mainly due to the Prius utilizing a similar amount of engine-off operation between the warm and cold cycles. While there is more engine-off operation for the warm cycle, the difference between the two is smaller compared to previous vehicles. Table 2 shows the fraction of engine off time for the warm and cold cycles.

Table 2: Urban Cycle Engine Off

	Urban Cold	Urban Warm
Engine-off Fraction of Total Time	0.63	0.66

The warm and cold cycles are also differentiated in terms of engine operating speed. The warm cycle appears to run the majority of engine-on operation at a slightly lower speed as compared to cold operation. Additionally, the warm operation appears to run at higher engine speeds slightly more frequently. The majority of the additional higher-speed engine operation observed during the warm Urban cycle occurs during the time of the cold cycle’s vehicle warm-up period. This higher speed is sensible given the need to reduce engine usage, especially at higher speeds, as the vehicle warms up. Figure 1 shows the engine speed histogram over the cold and warm cycles for all non-zero engine operation.

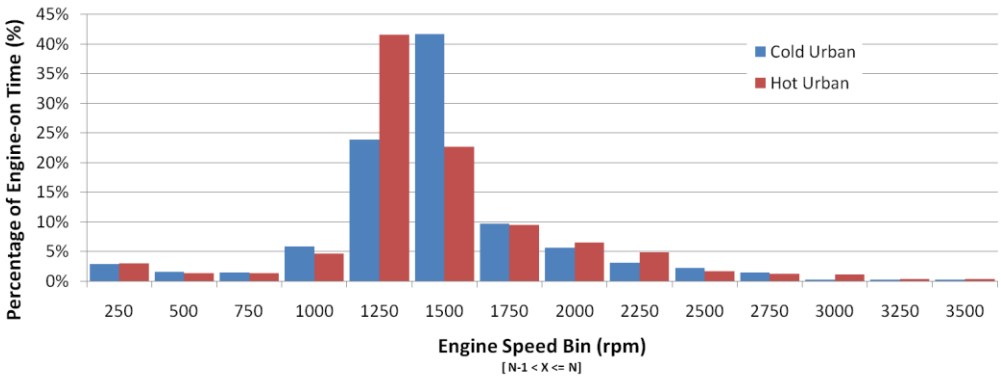

Figure 1: Urban Cycle Engine Speed Histogram

The following figures show more detailed information regarding the engine usage for the different cycles. As can be seen in Figures 2 and 3, following the first roughly 200 seconds, the vehicle operates the engine very similarly in terms of engine speed and fueling. During the first 200 seconds, or what may likely be considered vehicle warm-up operation, the cold operation is much different compared to the warm operation. Additionally, the first 50 seconds of engine operation appears to use a prescribed fueling rate which is most likely used for catalyst warm-up and cold engine start emissions abatement.

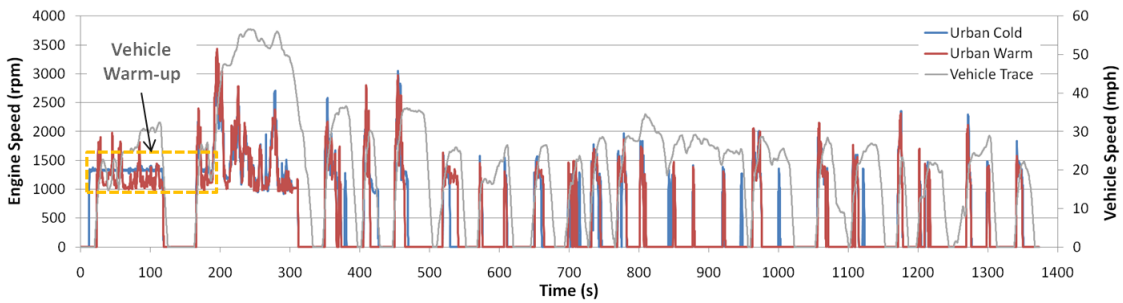

Figure 2: Urban Cycle Engine Speed

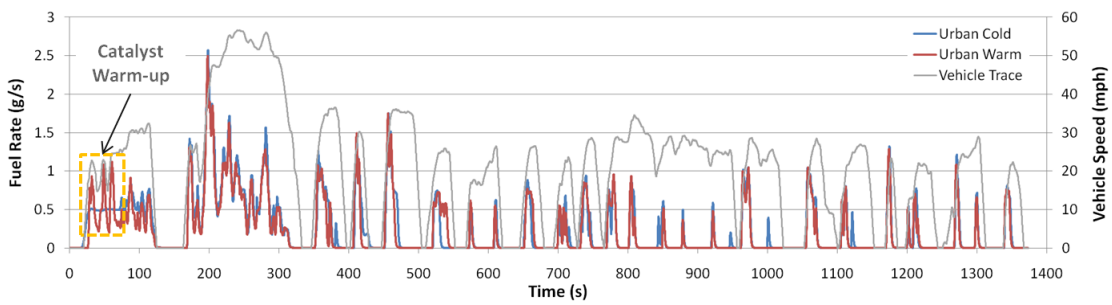

Figure 3: Urban Cycle Fuel Rate

Despite the initial operating differences to accommodate vehicle warm-up, the warm and cold operation following this initial 200 seconds is fairly similar which helps explain the reduced difference between warm and cold cycle fuel economy relative to the previous generation vehicle. This fuel economy difference is summarized in Figure 4.

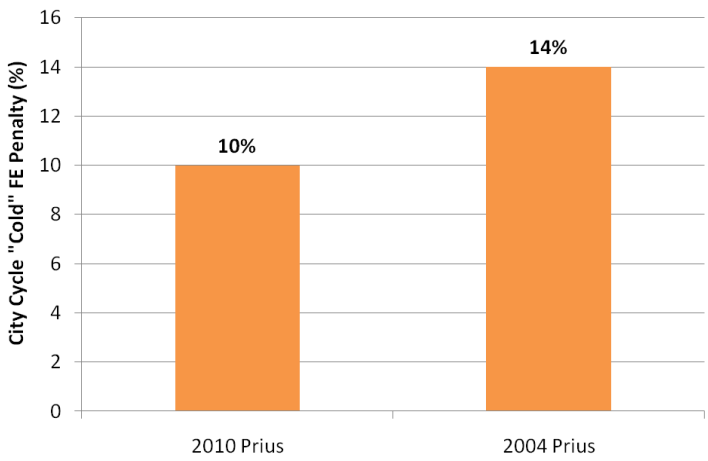

Figure 4: Urban Cold Penalty MY 2010 vs MY 2004 Prius

4.2 High Voltage Battery Usage

As with the engine usage, the battery usage is also fairly similar between the warm and cold cycles aside from the first 200 seconds. As can be seen below in Table 3, the peak positive battery power (from battery to powertrain) is slightly higher during the cold cycle, while peak regenerative power (from powertrain to battery) is very similar.

Table 3: Urban Cycle Battery Peak Power

	Urban Cold	Urban Warm
Peak Positive Battery Power (kW)	24.2	22.2
Peak Regen Battery Power (kW)	-24.7	-24.2

The detailed battery usage plot in Figure 5 shows the higher peak battery power during the cold cycle occurs during the prescribed catalyst warm-up period (first 50 seconds) and is used to supplement the lower engine power due to reduced engine fueling. Following this initial period, the battery usage between the two cycles is fairly similar.

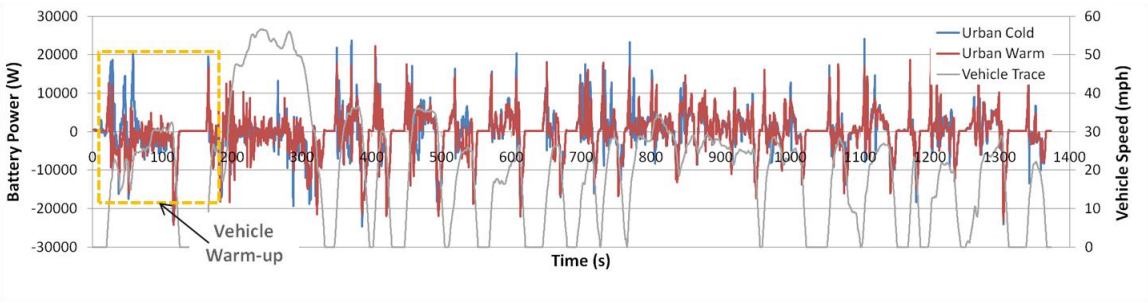

Figure 5: Urban Cycle Battery Power

In addition to measuring battery power, current measurements were also taken. Figure 6 shows the integrated current versus time for the warm and cold cycles. As would be expected, the additional battery usage during catalyst warm-up is the main point of deviation between the warm and cold cycles. Assuming a quoted pack capacity of 6.5

A-hr, the peak-to-peak state of charge swing during Urban operation may be estimated to be roughly 10% on an Amp-hr basis.

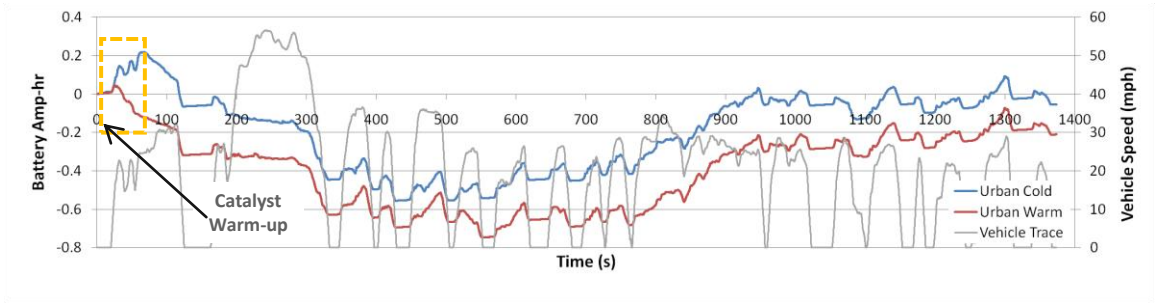

Figure 6: Urban Cycle Integrated Amp-Hours

4.3 Oil Temperature

Given the reduced cold penalty of the current generation vehicle over the Urban cycles, engine oil temperature is also of particular interest. Figure 7 shows the engine oil temperature measured at the dipstick for the cold and warm operation. Additionally, Figure 8 shows the oil temperature over an extended series of four back-to-back Urban cycles. As would be expected given the vehicle goal of improving cold performance, the oil temperature rises quickly and then remains fairly constant.

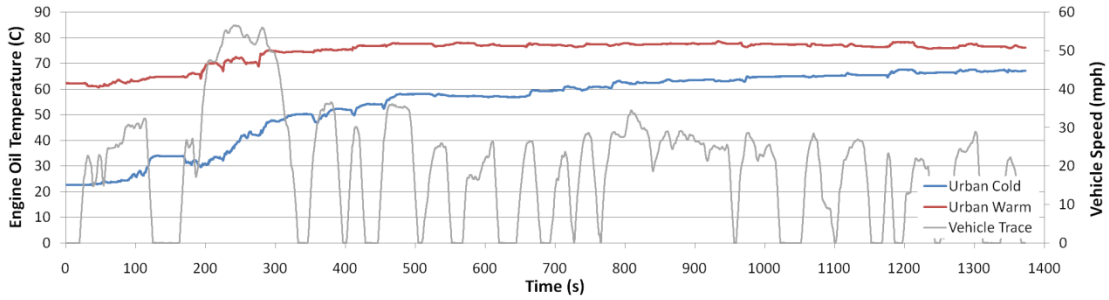

Figure 7: Urban Engine Oil Temperature (Cycles 1 and 2)

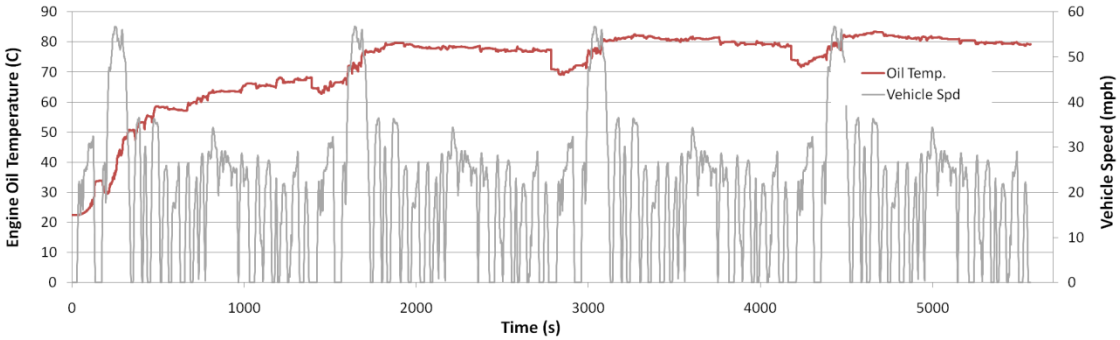

Figure 8: Engine Oil Temperature Over Repeated Cycles

4.4 Urban Operating Strategy Discussion

Although it can be inferred from the previous engine fueling and speed figures, Figure 9 shows a simplified version of the basic engine on/off strategy of the Prius over the warm urban cycle. Vehicle speed is plotted and coded relative to engine on/off operation: orange represents engine-on operation and grey represents engine-off operation.

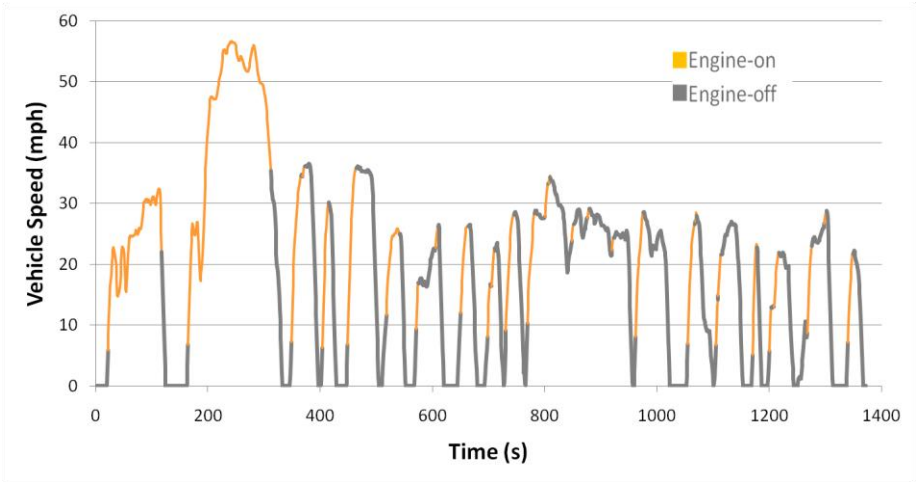

Figure 9: Warm Urban Engine On/Off Strategy Summary

To better illustrate the general electric-only operating envelop of the Prius, Figure 10 shows the vehicle's EV operation relative to the Urban cycle.

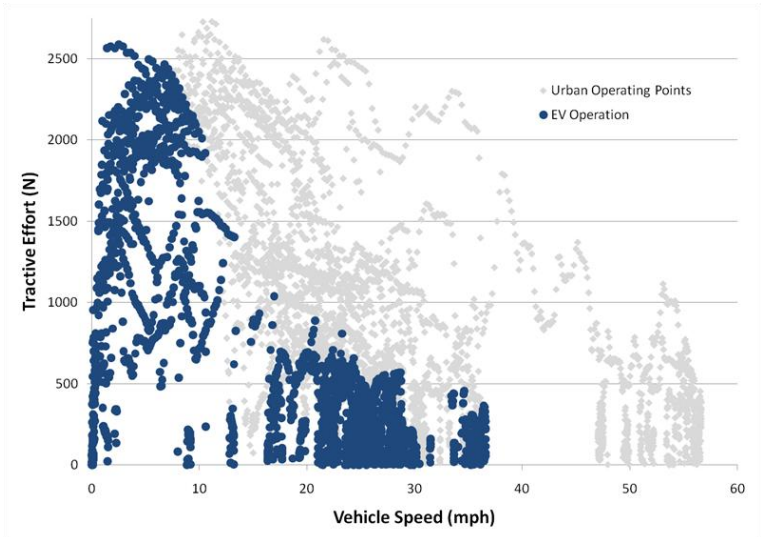

Figure 10: Urban Cycle EV Usage

An additional point of interest resulting from the back-to-back urban cycles is that the engine on/off behavior continues to change most likely due to continued vehicle warm-up. More specifically, the fourth repeated cycle turns the engine off during the light deceleration that occurs between 175 and 190 seconds of the Urban cycle. Given nearly identical pedal inputs during this segment, it is hypothesized that this behavior is

due to continued vehicle warm-up beyond a certain threshold. Figure 11 shows a magnified view of this section of the Urban cycle and Figure 12 shows the engine oil temperature, which can be seen to be warmer for the 4th cycle during the period of interest. While this effect may not be entirely related to oil temperature, it serves as a fairly representative number for the thermal state of the entire system.

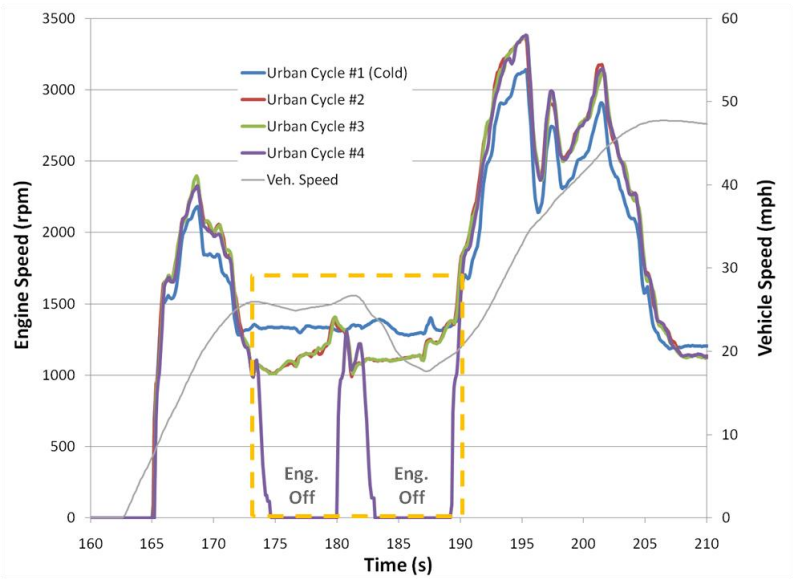

Figure 11: Urban Engine Off Variability with Repeated Cycles

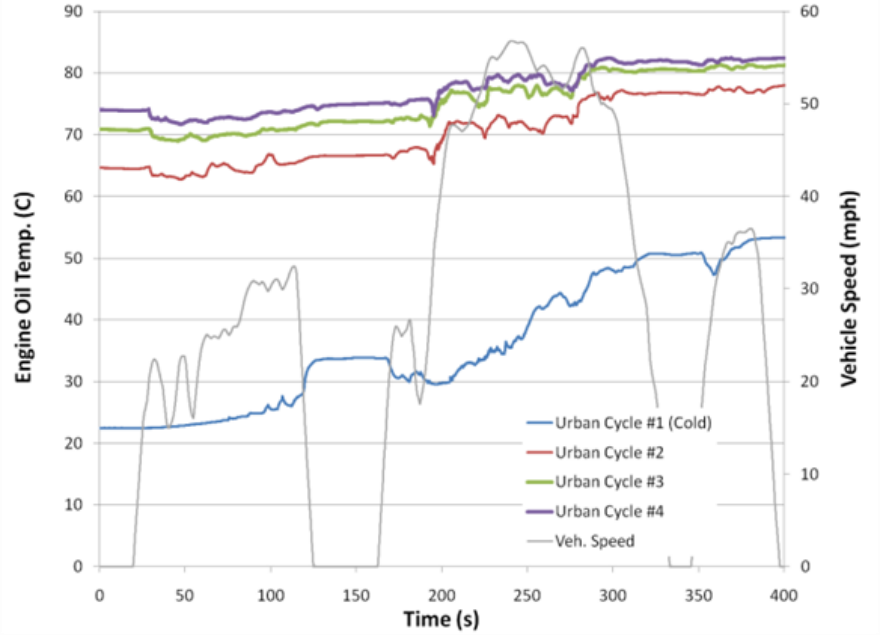

Figure 12: Continued Engine Oil Warm-up

5 Highway Cycle Operation

This section discusses operation over the Highway cycle. As its name implies, this cycle is used to evaluate higher-speed, fairly steady driving. In contrast to the Urban cycle, only the warm results for this cycle are currently evaluated for regulatory purposes. Recalling the initial section on powertrain system updates versus previous generations, the engine displacement for this vehicle has been increased to 1.8L to improve efficiency for this type of driving. Table 4 shows the tested fuel economy for this cycle.

Table 4: Highway Cycle Fuel Economy

	Hwy Cycle
Unadjusted Fuel Economy (mpg)	67

5.1 Engine Operation

As mentioned previously, the larger engine displacement in this version of the Prius system is to facilitate lower engine speeds during high speed operation. Figure 13 demonstrates this behavior and shows the current and previous generation engine speed histograms over the Highway cycle. As would be expected at elevated vehicle speeds, engine-off operation is fairly limited and represents roughly 7% of the total operating time.

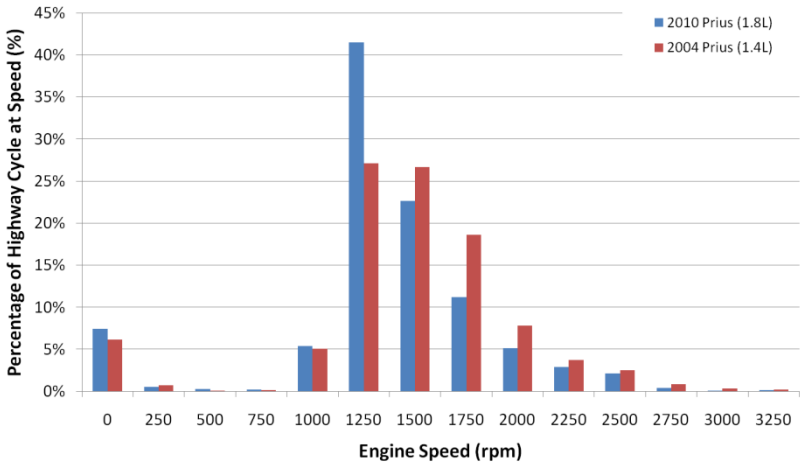

Figure 13: Highway Engine Speed 2010 vs 2004 Prius

More detailed information is available in the engine speed and fueling plots of Figures 14 and 15 respectively. It is notable that even during the higher speed Highway cycle, the vehicle displays some engine-off (RPM=0) operation. This higher speed engine-off operation is primarily limited to deceleration and is used to improve regenerative braking energy capture.

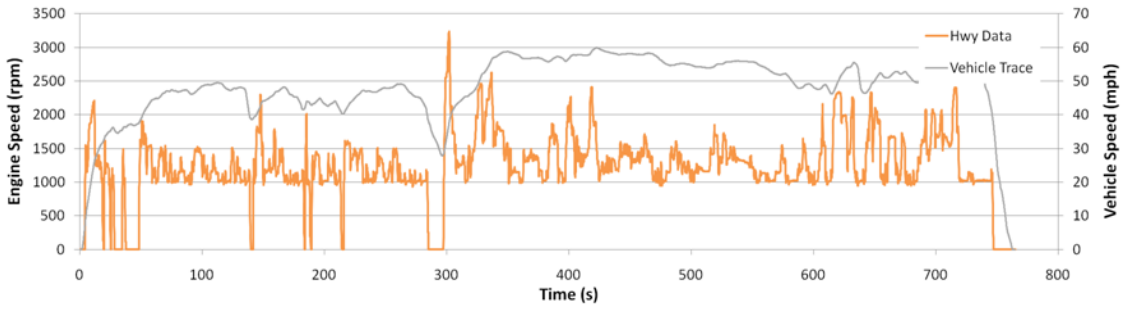

Figure 14: Highway Cycle Engine Speed

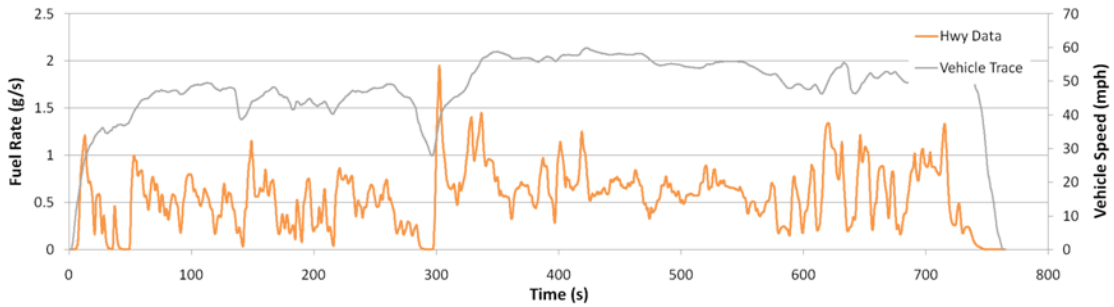

Figure 15: Highway Cycle Fuel Rate

To summarize the basic engine operation strategy, Figure 16 provides engine on/off state coded on to the vehicle speed trace. Note: some of the engine-off operation during temporary decelerations is very short in duration and thus are fairly hard to see in Figure 16.

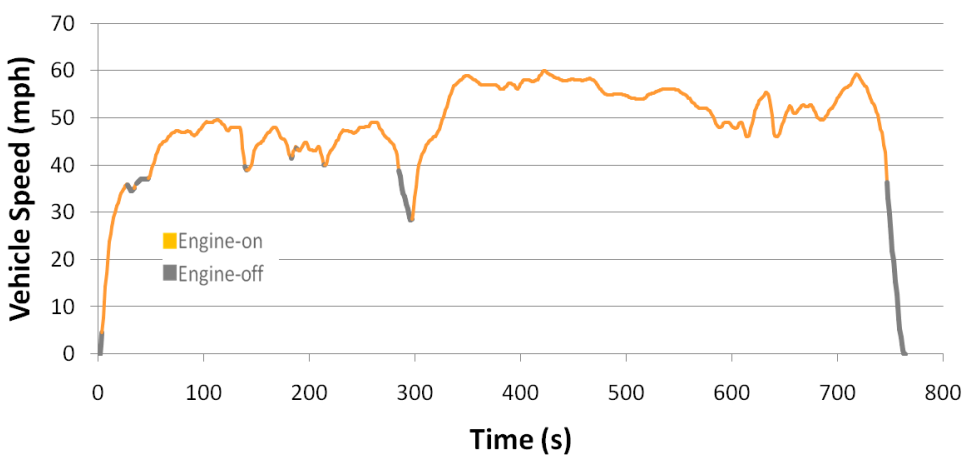

Figure 16: Highway Engine On/Off Strategy Summary

5.2 High Voltage Battery Usage

During Highway operation, battery usage is fairly minimal with the engine providing the majority of the vehicle tractive power aside from a few occasions for engine restarting and torque assistance. In fact, observed peak battery power is slightly higher compared to the Urban cycle due to a high-power engine start. Regenerative braking peak power is very similar to the Urban cycle. Table 5 shows the peak positive and negative power

observed during Highway operation and Figure 17 provides a histogram of battery usage during positive tractive effort events.

Table 5: Highway Cycle Peak Battery Power

	Hwy Cycle
Peak Positive Battery Power (kW)	26.8
Peak Regen Battery Power (kW)	-24.8

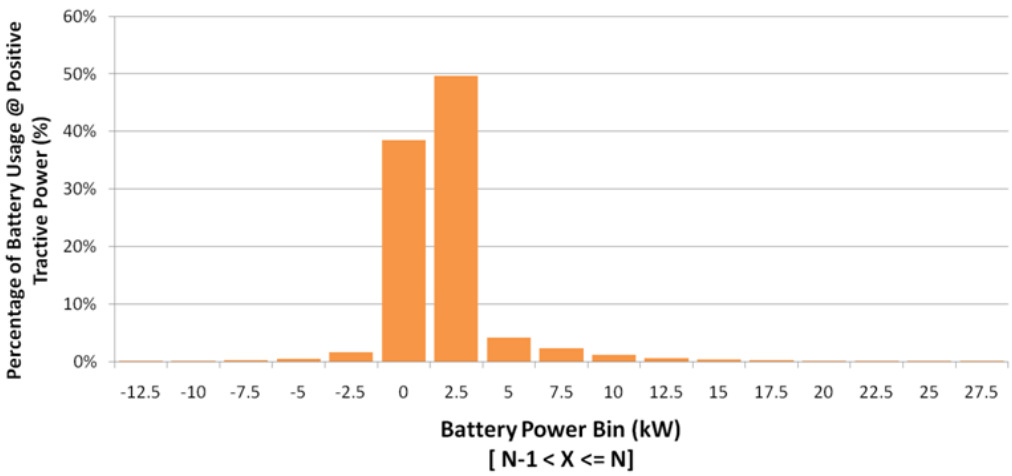

Figure 17: Highway Cycle Battery Usage Histogram

As with the engine data, more detailed, time-series data is provided as well. Figures 18 and 19 show the battery power and integrated current plots relative to the entire cycle.

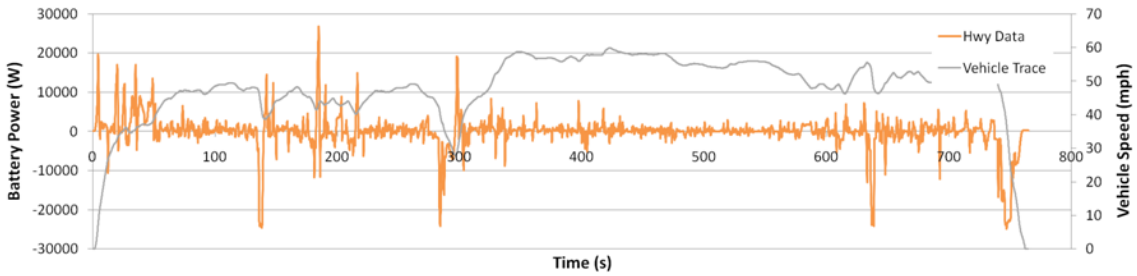

Figure 18: Highway Cycle Battery Power

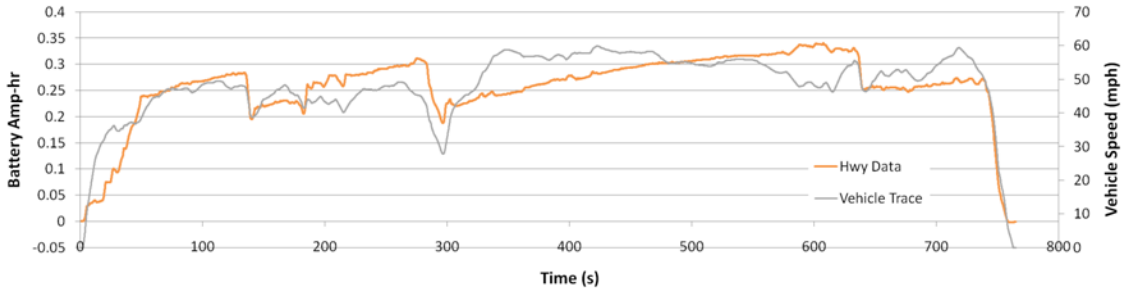

Figure 19: Highway Cycle Integrated Current

5.3 Engine Oil Temperature

Engine oil temperature was also collected during highway operation. Figure 20 shows the engine oil temperature over the second Highway cycle. In contrast to Urban operation, the observed engine oil temperature during the Highway cycle was higher, in the range of 90-98C.

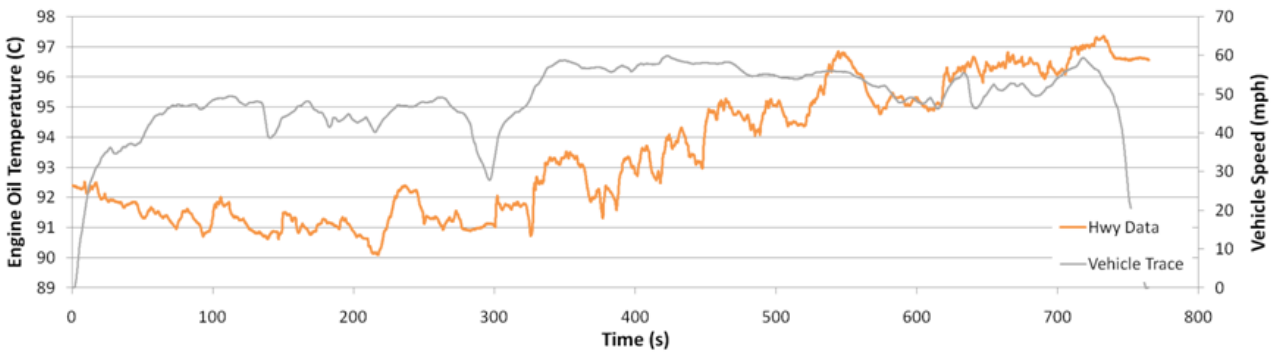

Figure 20: Highway Cycle Engine Oil Temperature

6 US06 Cycle Operation

The final regulatory cycle used for this AVTA baseline testing is the US06 cycle. This cycle represents a mix of more aggressive stop-and-go driving and higher speed freeway type driving, but at generally higher speeds than the Highway cycle. As with the Highway cycle, only the warm cycle is used for regulatory purposes. Table 6 shows the tested fuel economy over the US06 Cycle.

Table 6: US06 Fuel Economy

	US06 Cycle
Unadjusted Fuel Economy (mpg)	44

6.1 US06 Engine Operation

In a similar manner to the higher-speed Highway engine usage, the Prius shows a relatively large fraction of operation in the 1250-1500 RPM operating range. However, the more aggressive driving of the US06 cycle also shows much more usage at higher engine speeds and thus power levels. Figure 21 shows the histogram of engine usage over the US06 cycle. Due to the stop-and-go nature of certain sections of the cycle, the vehicle also operates in engine-off mode about 20% of the total cycle time.

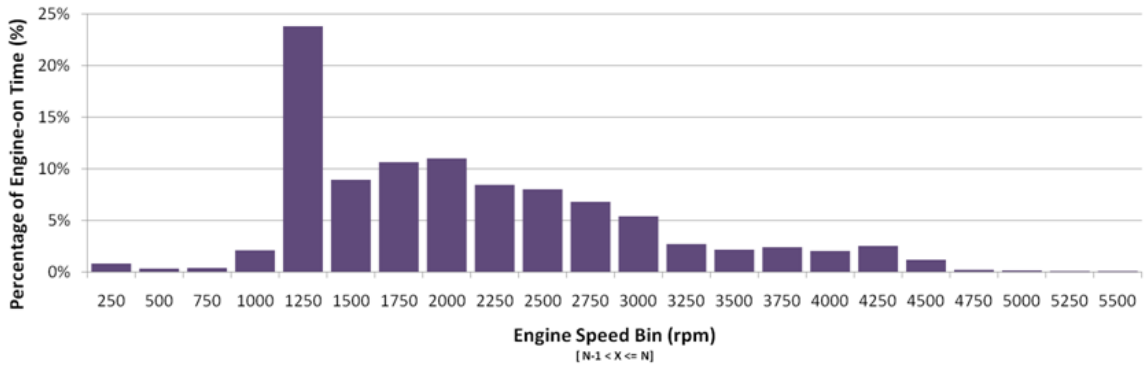

Figure 21: US06 Cycle Engine Speed Histogram

Figures 22 and 23 show more detailed information regarding engine speed and fueling over the US06 cycle. As can be expected with the more aggressive operation, engine speed and fueling show a much greater range of operation.

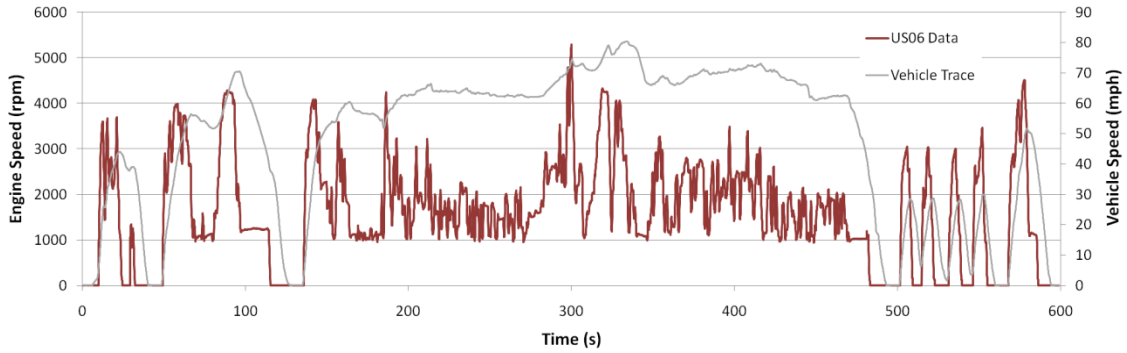

Figure 22: US06 Cycle Engine Speed

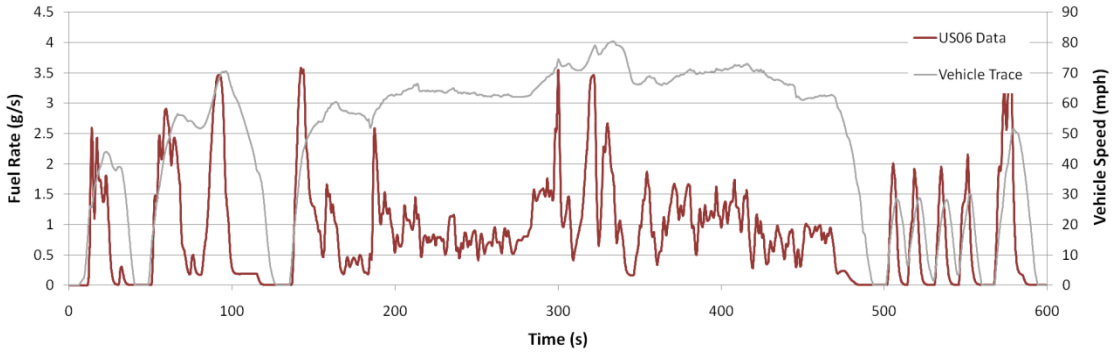

Figure 23: US06 Cycle Fuel Rate

Figure 24 shows a summary plot of the basic engine on/off strategy relative to vehicle speed over the US06 cycle. As would be expected for this more aggressive cycle engine-off operation is limited primarily to during vehicle decelerations.

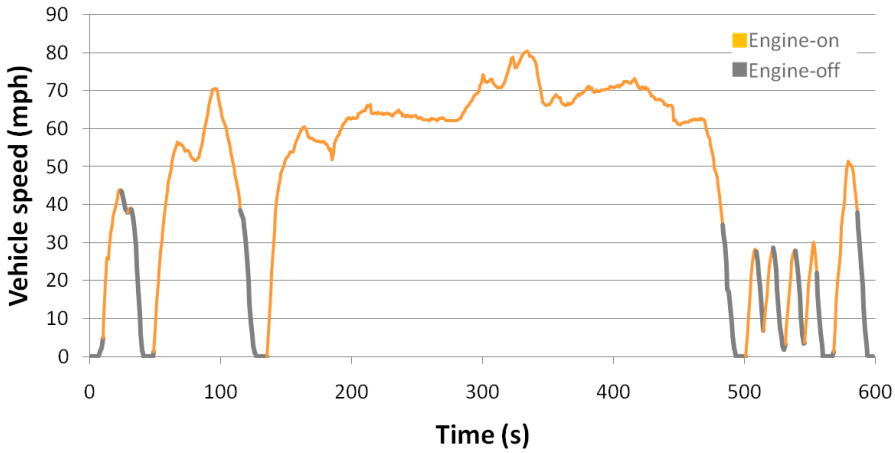

Figure 23: US06 Engine On/Off Strategy Summary

6.2 High Voltage Battery Usage

Battery usage over the US06 cycle displays quite a bit of battery assistance and overall shows a higher peak positive power as compared to the other cycles. Interestingly, the regenerative braking power observed is lower than that seen during Highway and Urban operation. It would be expected that at least a similar level of regenerative braking based battery power would be observed due to the US06 cycle's more aggressive braking. More discussion regarding this issue will be included later in this section. Table 7 summarizes the observed peak battery power.

Table 7: US06 Peak Battery Power

	US06 Cycle
Peak Positive Battery Power (kW)	28.0
Peak Regen Battery Power (kW)	-20.0

Figure 25 shows the battery usage histogram over the US06 cycle for all positive tractive effort events. While there is still a significant amount of time spent at minimal battery usage, the US06 shows a much wider range of both positive and negative battery operation.

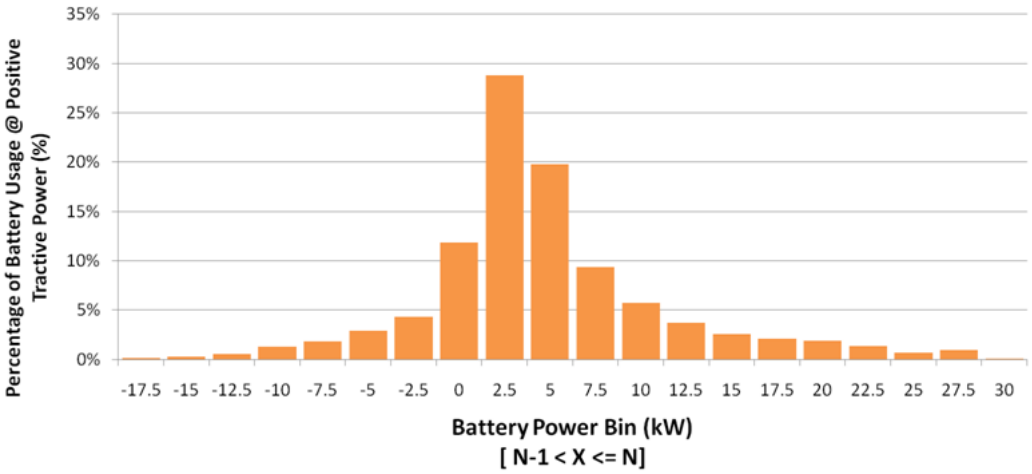

Figure 25: US06 Cycle Battery Power Histogram

As mentioned previously, it is counterintuitive that the peak observed regenerative braking power for the US06 cycle would be lower compared to the Urban and Highway cycles. This behavior appears to be due to a de-rating of regenerative braking capability (battery power) between the first (warm-up) and second (regulated) repeats of the US06 cycle. As can be seen clearly in Figure 26 the first US06 cycle shows increased regenerative capability much more in line with the roughly 25 kW observed from the other cycles. It is hypothesized that this de-rating may be related to the more frequent use of the battery during the US06 cycle and thus the need to reduce power availability to maintain a stable battery temperature.

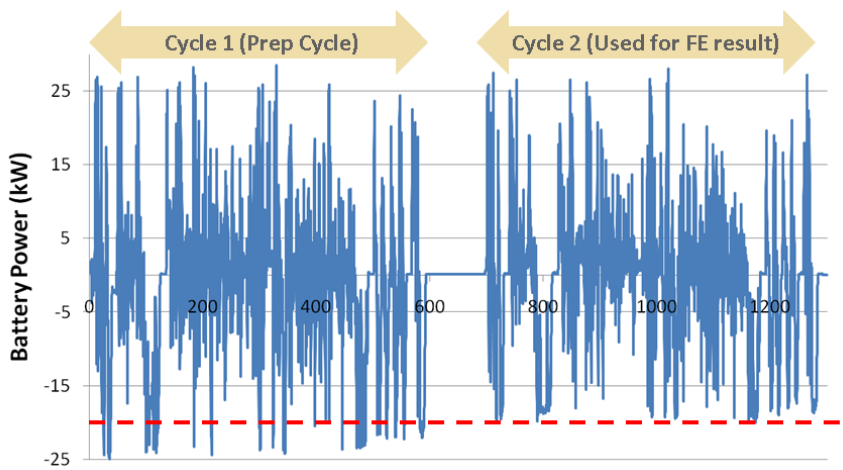

Figure 26: US06 Cycle Battery Power Prep. vs FE Cycle

More detailed information regarding the battery power and integrated current is shown in Figures 27 and 28. As mentioned previously, battery power varies much more under these more aggressive conditions. Assuming a 6.5 A-hr total battery capacity results in roughly a 10% SOC swing on an Amp-hr basis, similar to what was observed on the Urban cycle.

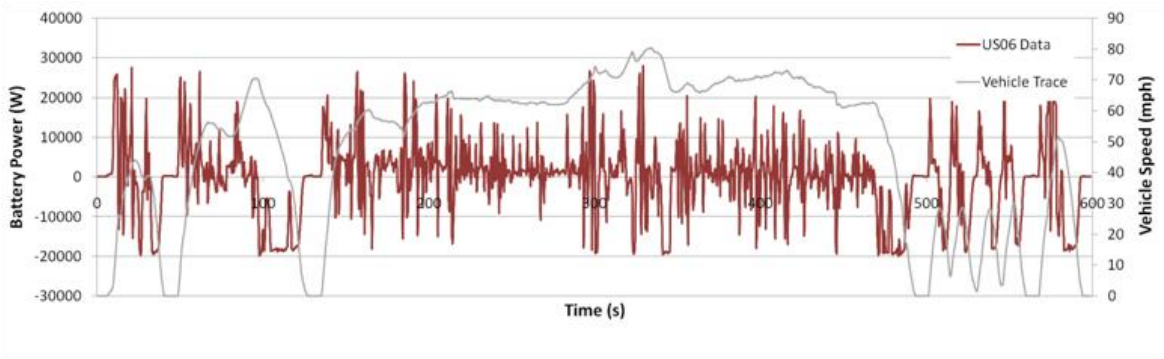

Figure 27: US06 Cycle Battery Power

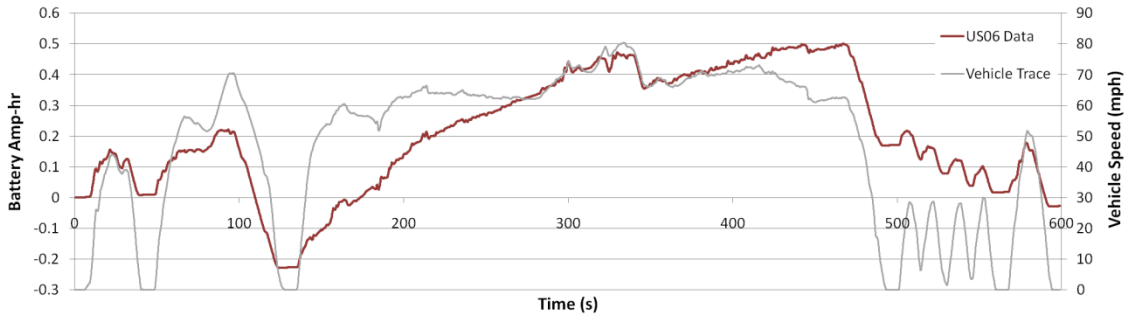

Figure 28: US06 Cycle Integrated Amp-Hours

6.3 Engine Oil Temperature

Engine oil temperature during the US06 cycle behaves as a mix between the Urban and Highway cycles. During the more Urban sections, oil temperature is fairly steady. During higher speed driving, oil temperature increases. Figure 29 shows the engine oil temperature over the US06 cycle.

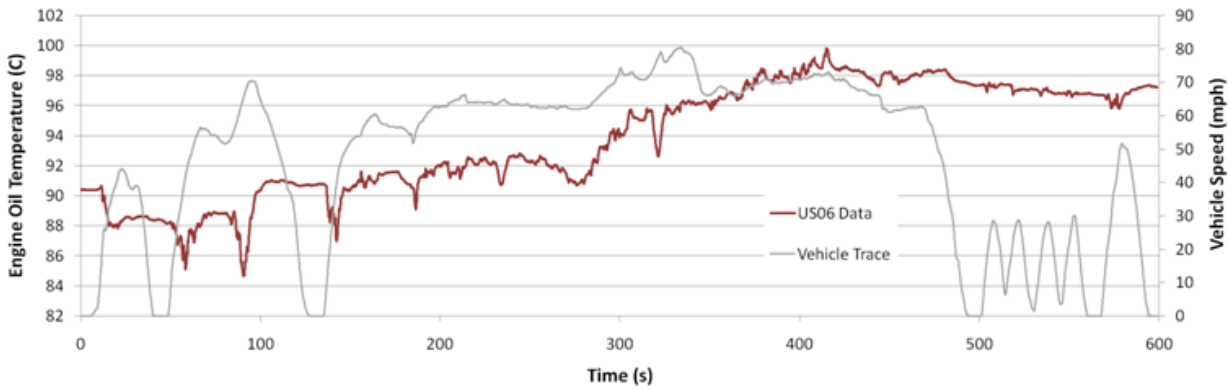

Figure 29: US06 Cycle Engine Oil Temperature

7 Other Operation

In addition to the regulatory cycles, this AVTA baseline analysis also provides insight regarding the current generation Prius relative to its driver selectable Eco and Power modes and behavior over repeated accelerations.

7.1 Eco and Power Modes

The Prius provides the driver with selectable Eco and Power modes which change the accelerator pedal mapping for the vehicle. Using the various modes on the Urban cycle, minimal fuel economy change was observed. Figure 30 shows the tested Urban fuel economy for the Prius operating in Standard, Power, and Eco mode. The observed variation in fuel economy is well within expected test-to-test variation and should be considered minimal.

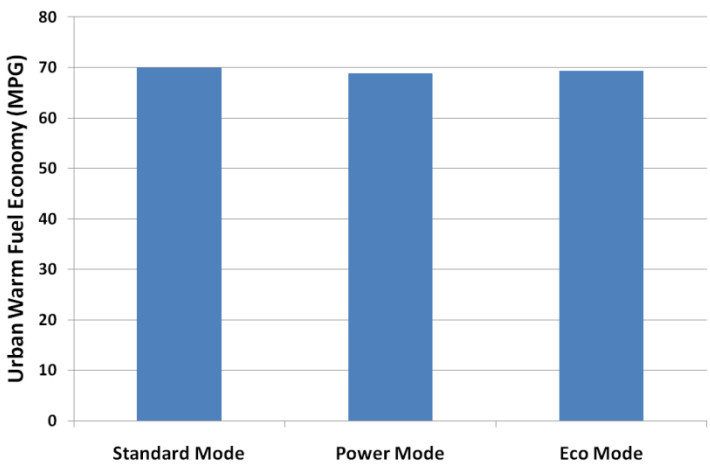

Figure 30: Standard, Power, and Eco Mode Urban Warm Fuel Economy

Given the nature of pedal signal remapping, these results are reasonably expected over a prescribed drive trace. Despite this fact, real-world fuel economy is likely to improve when running in Eco mode due to the smoothed accelerator demand and additional effort required to drive the vehicle aggressively. For comparison, Figure 31 shows the pedal position over the same portion of the Urban cycle for the Standard, Eco, and Power modes.

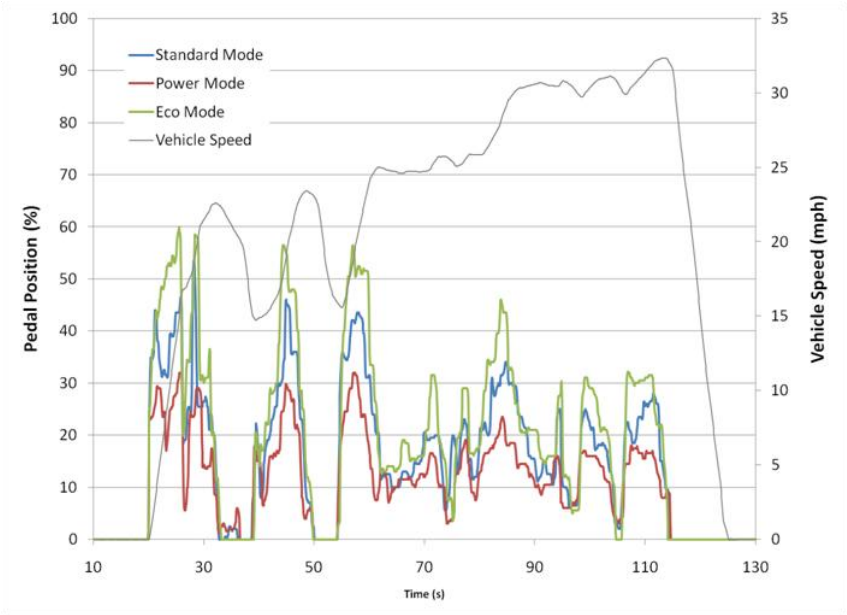

Figure 31: Standard, Eco, and Power Mode Pedal Position During Urban Cycle

7.2 Repeated Accelerations

For this testing, 10 back-to-back maximum accelerations were run to assess performance fade, the degradation of performance over repeated runs. Hybrid vehicles typically scale back performance after a certain number of runs due to battery management issues relating to state-of-charge management or thermal management. Figure 32 shows the repeated performance cycles for the current generation Prius. It is quite interesting to see that performance stays nearly constant across all of the 10 runs. This consistent performance is due to minimal de-rating of positive battery power even after 10 performance runs. Also of interest, is that regenerative power during the deceleration back to zero mph begins to reduce after about the fourth cycle. This is similar to what was observed during the US06 cycle and suggests that the regenerative power is reduced before reducing the tractive power, minimizing the effect on acceleration performance.

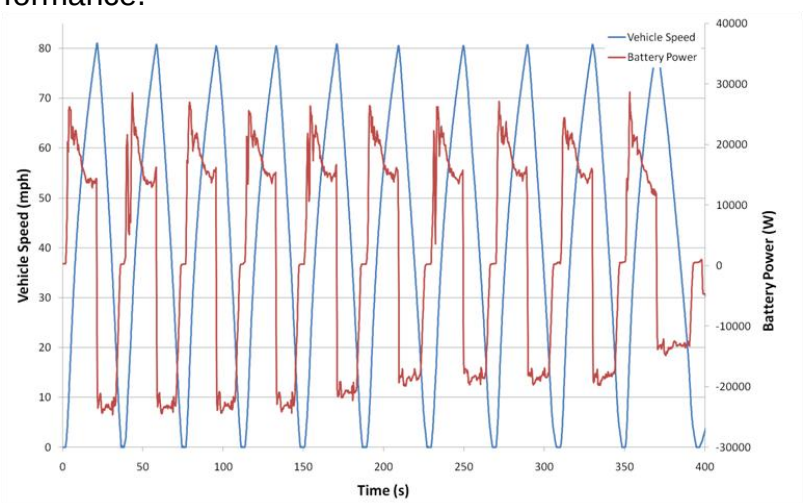

Figure 32: Battery Usage for Repeated Accelerations

8 Conclusions and Future Work

Preliminary testing has provided significant insight into the operating strategies and behavior of this new and state-of-the-art vehicle. The MY2010 Prius achieves high fuel economy and clearly works to improve operating regimes that are often problematic for hybrid vehicles. Relevant findings include:

- Significant engine-off operation during Urban operation as well as some engine-off operation at higher speeds.
- A reduced fuel economy penalty between warm and cold Urban operation.
- Use of a specific fueling/operating strategy for initial catalyst warm-up during the cold Urban cycle.
- Lower speed engine operation at higher vehicle speeds due to larger engine displacement.
- De-rating of battery regeneration capability during US06 testing and repeated acceleration.

For the next phase of testing, the MY2010 Prius will be extensively instrumented and tested over a much wider variety of cycles. This instrumentation will be used to gain more insight into the operating strategies of this vehicle as well as delve more deeply into the performance characteristics of the various components. Additionally, the vehicle will be tested over many cycles in addition to the standard regulatory cycles as well as different ambient temperatures to investigate specific design choices and evaluate the real-world fuel economy of the vehicle in greater detail. This deeper research will strongly leverage the preliminary testing and analysis contained in this report and seek to understand the research findings in greater detail. Once complete, the in-depth testing and analysis combined with this preliminary analysis will proved a much deeper understanding of the MY2010 Prius as well as its applicability to additional advanced vehicle research.

Detailed data regarding this vehicle as well as additional AVTA vehicles may be found in ANL's Downloadable Dynamometer Database (D^3) at https://webapps.anl.gov/vehicle_data/.

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