ANL/ES/RP-71836

Hyundai Avante LPi Hybrid Level 1 Testing Report

Energy Systems Division

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1 Abstract

In collaboration with the Korea Automotive Technology Institute (KATECH), the Korean market only Hyundai Avante LPi Hybrid was purchased and imported to ANL'S Advanced Powertrain Research Facility for vehicle-level testing. Data was acquired during testing using non-intrusive sensors, vehicle network information, and facilities equipment (emissions and dynamometer). Standard drive cycles, performance cycles, steady-state cycles, and A/C usage cycles were conducted. The major results are shown in this report.

Given the benchmark nature of this assessment, the majority of the testing was done over standard regulatory cycles and sought 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. To assess the impacts of more aggressive driving, the LA92 cycle and a UDDS scaled by a factor 1.2x cycles were also included in the testing plan. Data collection for this testing was kept at a fairly high level and includes emissions and fuel measurements from an exhaust emissions bench, high-voltage and accessory current/voltage from a DC power analyzer, and CAN bus data such as engine speed. The following sections will seek to explain some of the basic operating characteristics of the Avante LPi Hybrid and provide insight into unique features of its operation and design. Figure 1 shows the test vehicle in Argonne's soak room.

Figure 1: Hyundai Avante LPi Test Vehicle

2 Vehicle Description

The Avante LPi hybrid uses a parallel-type architecture which locates the electric machine between the transmission and engine. The transmission for this vehicle is a continuously variable transmission (CVT) which allows for a wide range of engine operating speeds relative to vehicle speed. Generally speaking, the system is a "mild" type architecture which uses the hybrid system to provide electric launch assist, regenerative braking, fuel cut-off operation and idle stop, but the vehicle rarely runs on electric power alone. The most notable feature regarding the Avante Hybrid is that it runs on liquid petroleum gas (LPG), which is predominately butane in South Korea (as opposed to Propane in the United States). Another notable feature of this vehicle is its lithium polymer battery pack supplied by LG Chem.

The following are some approximate specifications for the Avante LPi Hybrid vehicle[1].

Combustion Engine
Drive Type: Front-Wheel Drive
Engine type: 1.6L Atkinson Cycle DOHC 4-valve engine
Transmission type: Continuously Variable Transmission (CVT)
Peak Horsepower (HP@rpm): 115 HP@ 6,000
Peak Torque (Nm@rpm): 201 @ 4,500
Compression ratio: 12:1

Electric Motor
Motor type: Permanent magnet AC synchronous motor
Power output: 15kW / 15.7 kW (Motoring / Generating)
Torque: 105 Nm / 125 Nm (Motoring / Generating)

Traction Battery
Type: Lithium Polymer
Power Output: 18 kW (14kW maximum observed)
Nominal Voltage: 180V
Nominal Capacity: 5.3 A-hr

3 Vehicle Instrumentation

3.1 Data Acquisition System

Argonne's chassis dynamometer facility was specifically designed to perform vehicle and component system oriented testing. With this objective in mind, a custom data acquisition and control system was built around the needs of 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.

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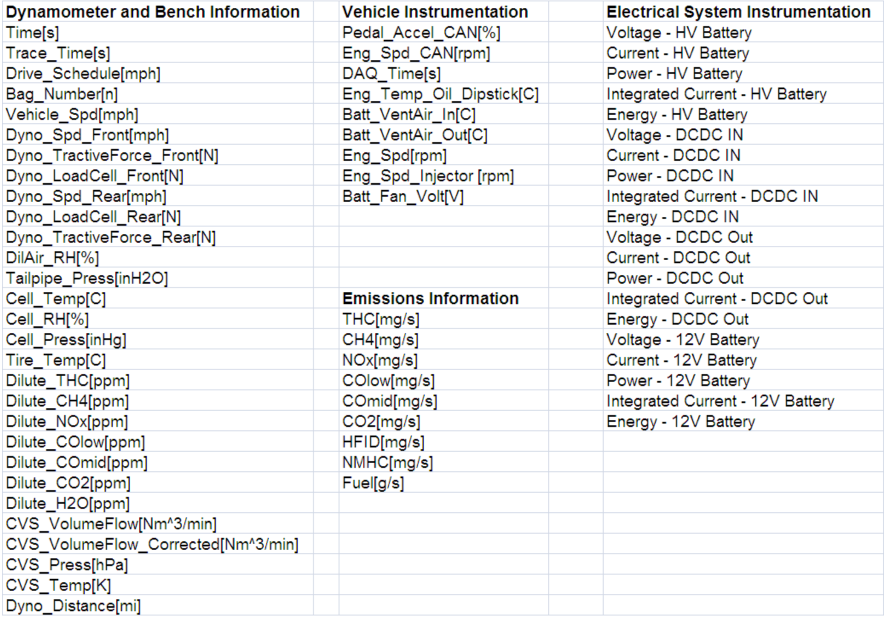
[1] Hyundai's LPG Hybrid, http://autospeed.com.au/cms/title_Hyundais-LPG-Hybrid/A_111460/article.html, 21 July, 2009

3.2 Vehicle Signals



Dynamometer and Bench Information	**Vehicle Instrumentation**	**Electrical System Instrumentation**
Time[s]	Pedal_Accel_CAN[%]	Voltage - HV Battery
Trace_Time[s]	Eng_Spd_CAN[rpm]	Current - HV Battery
Drive_Schedule[mph]	DAQ_Time[s]	Power - HV Battery
Bag_Number[n]	Eng_Temp_Oil_Dipstick[C]	Integrated Current - HV Battery
Vehicle_Spd[mph]	Batt_VentAir_In[C]	Energy - HV Battery
Dyno_Spd_Front[mph]	Batt_VentAir_Out[C]	Voltage - DCDC IN
Dyno_TractiveForce_Front[N]	Eng_Spd[rpm]	Current - DCDC IN
Dyno_LoadCell_Front[N]	Eng_Spd_Injector [rpm]	Power - DCDC IN
Dyno_Spd_Rear[mph]	Batt_Fan_Volt[V]	Integrated Current - DCDC IN
Dyno_LoadCell_Rear[N]		Energy - DCDC IN
Dyno_TractiveForce_Rear[N]		Voltage - DCDC Out
DilAir_RH[%]		Current - DCDC Out
Tailpipe_Press[inH2O]		Power - DCDC Out
Cell_Temp[C]	**Emissions Information**	Integrated Current - DCDC Out
Cell_RH[%]	THC[mg/s]	Energy - DCDC Out
Cell_Press[inHg]	CH4[mg/s]	Voltage - 12V Battery
Tire_Temp[C]	NOx[mg/s]	Current - 12V Battery
Dilute_THC[ppm]	COlow[mg/s]	Power - 12V Battery
Dilute_CH4[ppm]	COmid[mg/s]	Integrated Current - 12V Battery
Dilute_NOx[ppm]	CO2[mg/s]	Energy - 12V Battery
Dilute_COlow[ppm]	HFID[mg/s]	
Dilute_COmid[ppm]	NMHC[mg/s]	
Dilute_CO2[ppm]	Fuel[g/s]	
Dilute_H2O[ppm]		
CVS_VolumeFlow[Nm^3/min]		
CVS_VolumeFlow_Corrected[Nm^3/min]		
CVS_Press[hPa]		
CVS_Temp[K]		
Dyno_Distance[mi]		

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 shows the dynamometer tested, unadjusted fuel economy over both “warm” and “cold” cycles. The difference between the cold and warm urban fuel economy is roughly 5%. This is a fairly typical result for a “mild” type system which does not see the significant reduction in initial engine-off operation experienced in a hybrid system with more electric-only operation. For vehicles with a significant amount of electric-only operation, the reduction in engine-off operation due to the initial “cold” start results in a larger 8-15% difference between warm and cold Urban fuel economy.

Table 1: Tested Urban Fuel Economy

	Urban Cold	Urban Warm
Unadjusted Fuel Economy (mpg)	40.0	42.1

** MPG shown is for liquid butane*

4.1 Engine Operation

Although the Avante does not have significant capability to drive with the engine at zero speed, it does have the ability to operate the engine in fuel cut-off mode during decelerations and limited low-power cruising events. While operating in fuel cut-off mode, the engine is rotating, but no fuel is being provided to the engine. The relatively small difference between warm and cold operation is likely due to the Avante's ability to operate in fuel cut-off mode for both the warm and cold cycles, thus the main difference between warm and cold cycle fuel economy is the fuel required for vehicle and catalyst warm-up. As would be expected for a more "mild" system, following a short vehicle warm-up period, the warm and cold Urban cycles operate very similarly.

As can be seen in the time-series plots of engine speed and fuel-rate in Figure 2 and Figure 3 respectively, following the first roughly 100 seconds of UDDS Cold cycle operation, the vehicle operates very similarly between the cold and warm cycles. This again speaks to the reduced "cold penalty" versus hybrid vehicles with more engine-off capability which, in turn, leads to longer warm-up times. During the 100 second warm-up period, the vehicle can be seen to operate the engine at a higher engine speed and fuel rate with a reduction in the amount of unfueled operation, whereas the warm cycle urban test shows reduced engine speed and some unfueled operation evidenced by near-zero fuel rates in Figure 3.

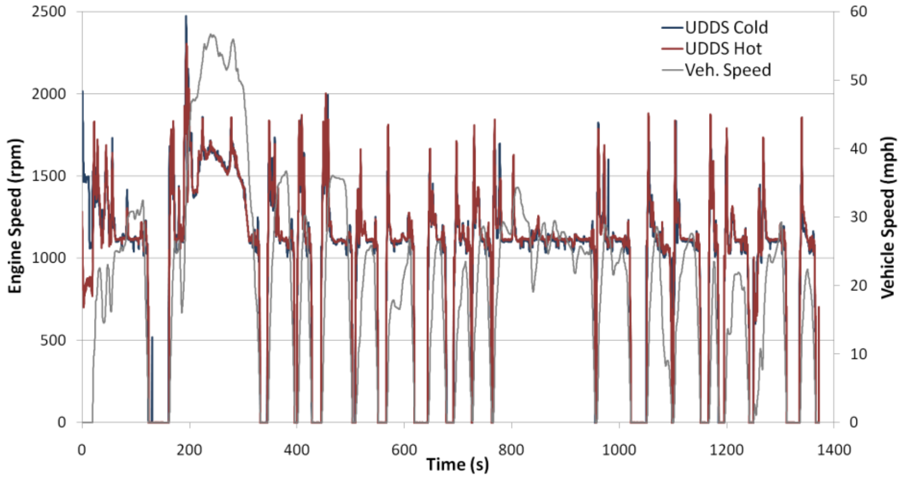


Figure 2: Urban Cycle Engine Speed

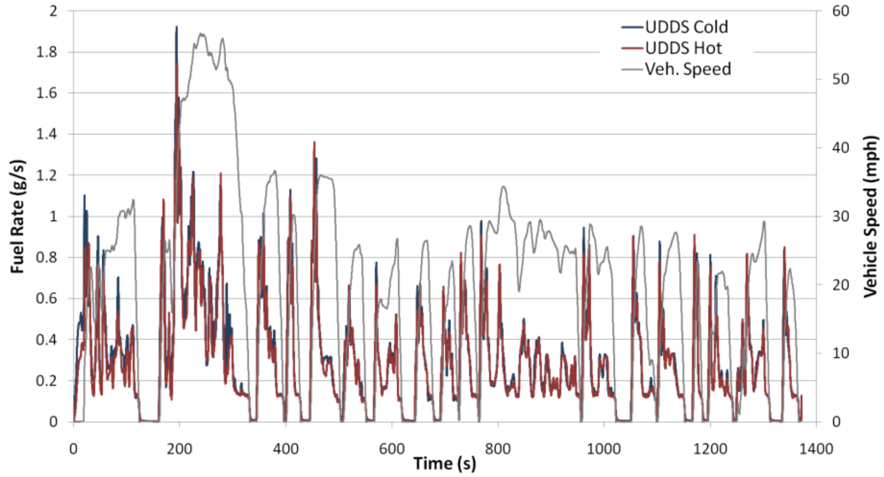


Figure 3: Urban Cycle Fuel Rate

4.2 High Voltage Battery Usage

As with the engine usage, battery use is also similar between the warm and cold UDDS cycles. As can be seen below in Table 2, both the peak positive battery power (from battery to powertrain) and the peak regenerative power (from powertrain to battery) are nearly identical between the hot and cold UDDS cycles.

Table 2: Urban Cycle Battery Peak Power

	Urban Cold	Urban Warm
Peak Positive Battery Power (kW)	8.7	8.6
Peak Regen Battery Power (kW)	-10.8	-10.3

From the detailed battery usage plot in Figure 4 it can also be seen that overall battery usage between the cold and warm cycles is fairly similar.

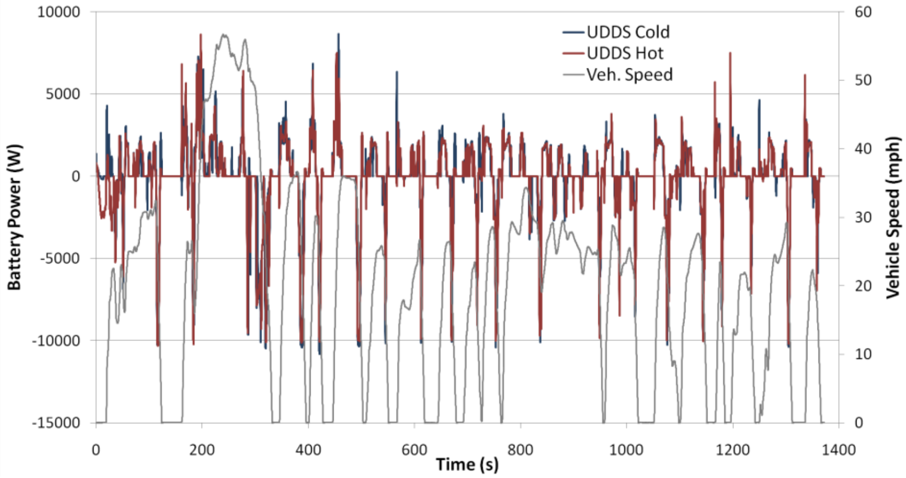


Figure 4: Urban Cycle Battery Usage

In addition to measuring battery power, integrated current was also measured. Figure 5 shows the integrated current versus time for the warm and cold cycles. The maximum A-hr swing observed over the cold and warm Urban cycle is 0.27 A-hr and 0.29 A-hr respectively. Assuming a 5.3 A-hr battery, these maximum swing amounts correspond to an approximate maximum SOC swing of roughly 5%.

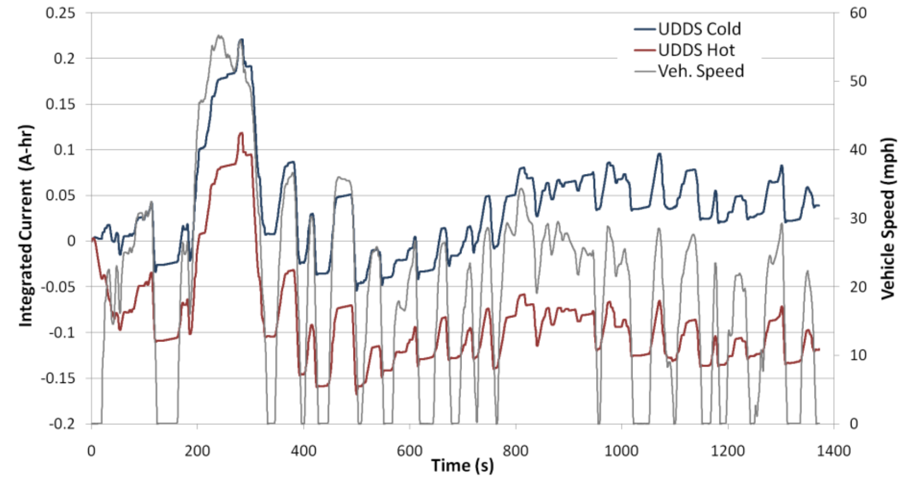


Figure 5: Urban Cycle Integrated Current

5 Highway Cycle Operation

This section discusses vehicle 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. Table 3 shows the tested fuel economy for this cycle.

Table 3: Highway Cycle Fuel Economy

	Hwy Cycle
Unadjusted Fuel Economy (mpg)	55.9

** MPG shown is for liquid butane*

5.1 Engine Operation

As would be expected given higher vehicle speed of the Highway cycle, the observed engine speed for the LPI Avante is higher compared to that of the Urban cycle. Furthermore, at elevated and more stable vehicle speeds, unfueled engine operation is limited and represents roughly 7% of the total operating time. More detailed information regarding engine operation is available in the engine speed and fueling plots of Figure 6 and Figure 7. Again, it is notable that even during the higher speed Highway cycle, the vehicle displays the ability to cut-off fueling during decelerations (as indicated by near-zero downward fuel rate spikes).

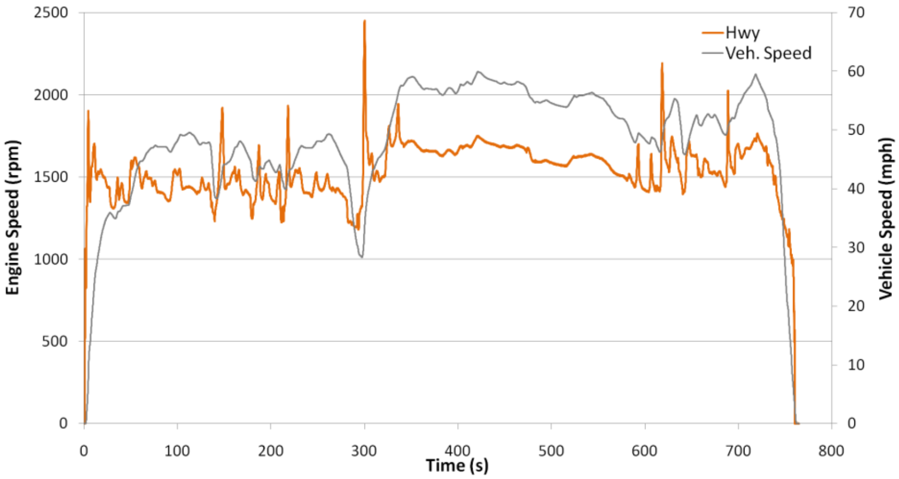


Figure 6: Highway Cycle Engine Speed

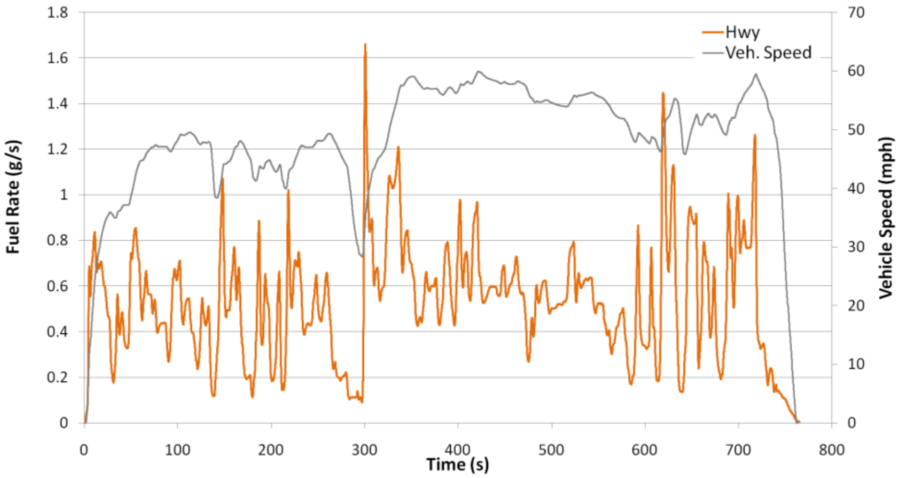


Figure 7: Highway Cycle Fuel Rate

5.2 High Voltage Battery Usage

During Highway operation, battery usage is fairly minimal with the engine providing the majority of vehicle tractive power. Observed regenerative braking peak power is very similar compared to the Urban cycle. Table 4 shows the peak positive and negative power observed during Highway operation.

Table 4: Highway Cycle Peak Battery Power

	Hwy Cycle
Peak Positive Battery Power (kW)	7.6
Peak Regen Battery Power (kW)	-10.7

As with the engine data, more detailed, time-series battery data is provided as well. Figure 8 and Figure 9 respectively show the Highway cycle battery power and battery integrated current. The maximum A-hr swing observed over the Highway cycle is roughly 0.21 A-hr versus 0.27-0.29 A-hr for the Urban cycle.

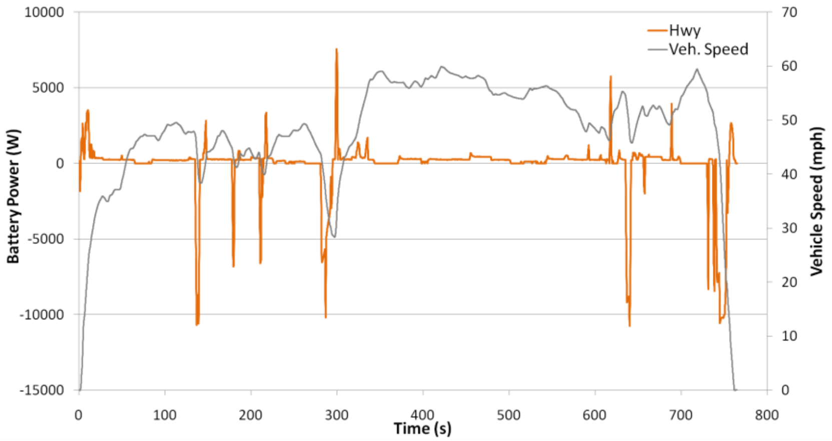


Figure 8: Highway Cycle Battery Power

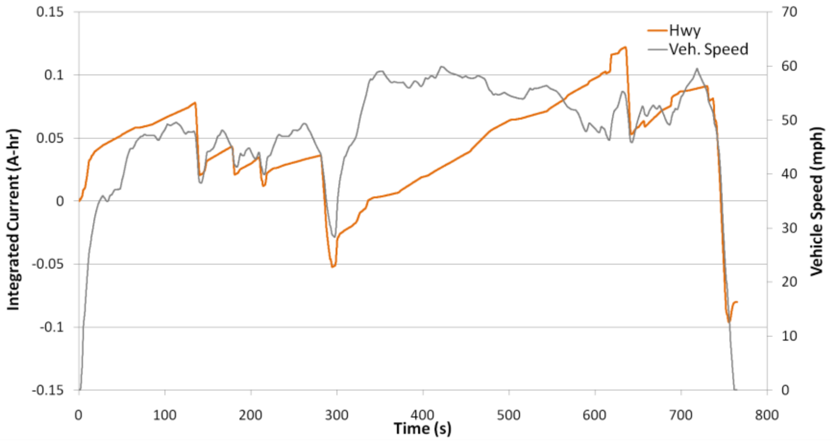


Figure 9: Highway Cycle Integrated Current

6 US06 Cycle Operation

This cycle represents a mix of more aggressive stop-and-go driving and higher speed freeway type driving, at speeds generally higher than the Highway cycle. As with the Highway cycle, only the warm cycle is used for regulatory purposes. Table 5 shows the tested fuel economy over the US06 Cycle.

Table 5: US06 Cycle Fuel Economy

	US06 Cycle
Unadjusted Fuel Economy (mpg)	35.3

** MPG shown is for liquid butane*

6.1 US06 Engine Operation

In a similar manner to the higher-speed Highway engine usage, the Avanti LPI shows an increase in engine speed related to the higher vehicle speed of the US06 cycle. Even relative to the Highway cycle, the more aggressive driving of the US06 cycle shows more operation at higher engine speeds due to the need for additional engine power. Due to the stop-and-go nature of certain sections of the cycle, the vehicle still operates the engine unfueled about 26% of the total cycle time.

Figure 10 and Figure 11 show more detailed information regarding engine speed and fueling over the US06 cycle. Given the mix of more aggressive, stop-and-go driving and high speed operation, the engine speed and fueling during the US06 cycle show a much greater range of operation as compared to the Highway and Urban cycles.

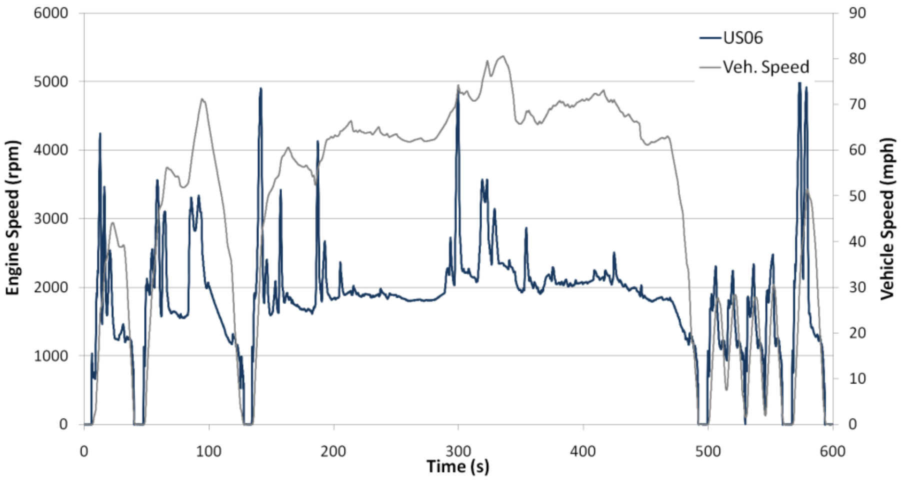


Figure 10: US06 Cycle Engine Speed

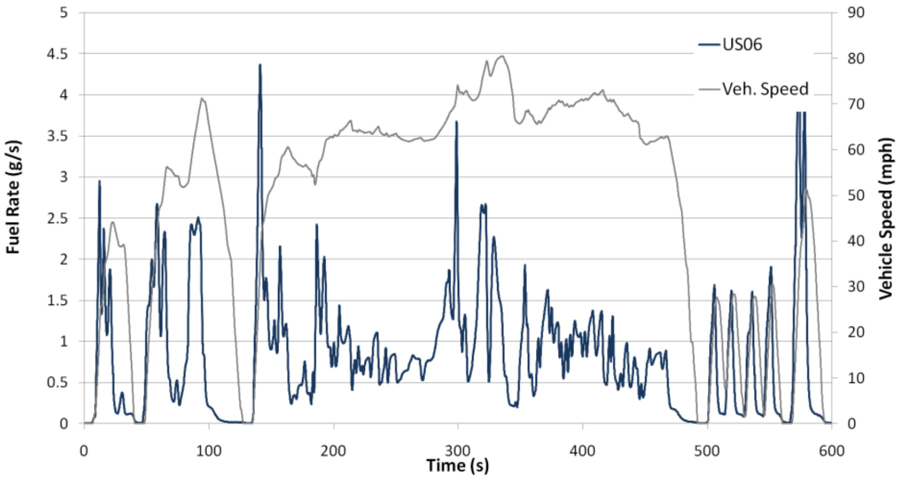


Figure 11: US06 Cycle Fuel Rate

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 and comparable peak regenerative braking power as compared to the other cycles. Table 6 summarizes the observed peak battery power. The higher peak positive power is due to the US06's aggressive accelerations, which necessitate fast engine ramp-up and higher-power engine starts.

Table 6: US06 Peak Battery Power

	US06 Cycle
Peak Positive Battery Power (kW)	13.8
Peak Regen Battery Power (kW)	-11.2

More detailed information regarding the battery power and integrated current is shown in Figure 12 and Figure 13. As mentioned previously, battery power varies much more under these more aggressive conditions. Given this higher range of power use, maximum integrated current swing during the US06 cycle is 0.34 A-hr, much larger than the swing observed during Urban and Highway operation. This represents an approximate SOC swing of roughly 7% assuming a 5.3 A-hr battery.

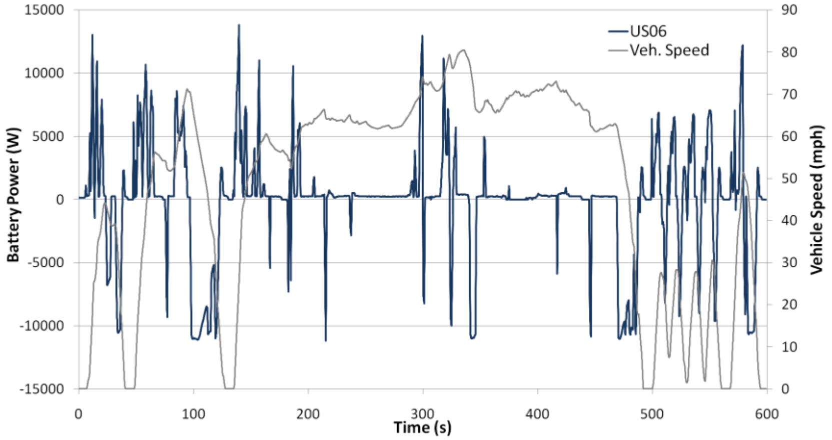


Figure 12: US06 Battery Power

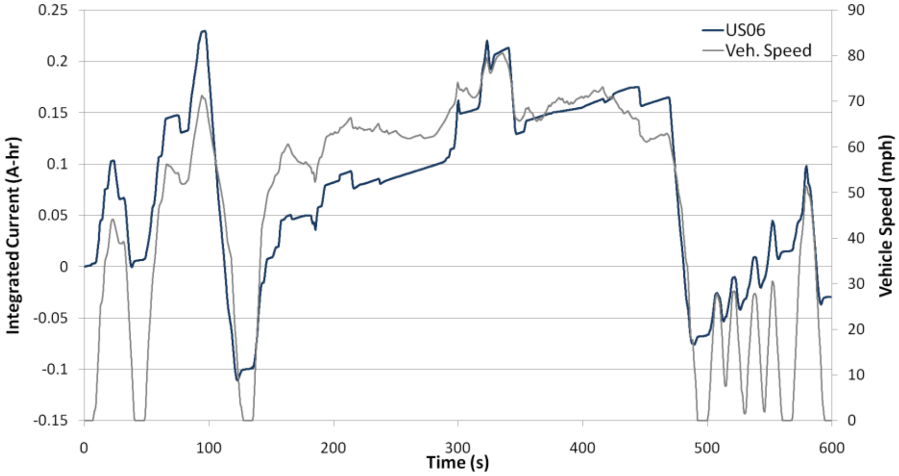


Figure 13: US06 Battery Integrated Current

7 Other Operation

In addition to operation over regulatory cycles, this report also provides analysis regarding the Avante's operation for several additional scenarios and supplemental drive cycles. More specifically, this section seeks to discuss the Avante's behavior over repeated accelerations, while operating with the air-conditioning system activated, and over some supplemental real-world, aggressive type drive cycles.

7.1 Repeated Accelerations

For this testing, eleven back-to-back aggressive accelerations were run to assess performance fade, the degradation of performance over repeated aggressive accelerations. Hybrid vehicles typically scale back acceleration performance after a certain number of runs due to battery management issues relating to state-of-charge management or thermal management. Figure 14 shows the battery power and vehicle speed over repeated performance cycles for the Avante. From this plot, it can be see that performance stays fairly constant for the first 7 cycles, this consistent performance is due to minimal de-rating of positive battery power. Following the 7th acceleration, the battery assist (positive power) is reduced. Following 3 accelerations with reduced assist, but full regen, the battery actually recharges enough that the full power can be used on the 11th acceleration. This is a clear case of reducing acceleration performance in order to maintain proper battery state-of-charge.

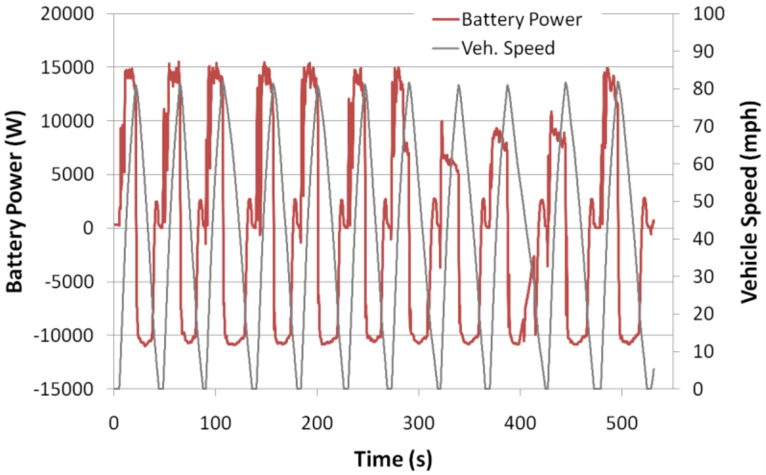


Figure 14: Battery Usage for Repeated Accelerations

As mentioned previously, the observed performance fade during these repeated accelerations is typically due to battery management issues. Figure 15 shows the integrated battery current during the repeated accelerations. As mentioned earlier, the integrated current can be seen to increase until the 7th acceleration and then begins to reduce until the 11th, where the current level is similar to the initial cycles.

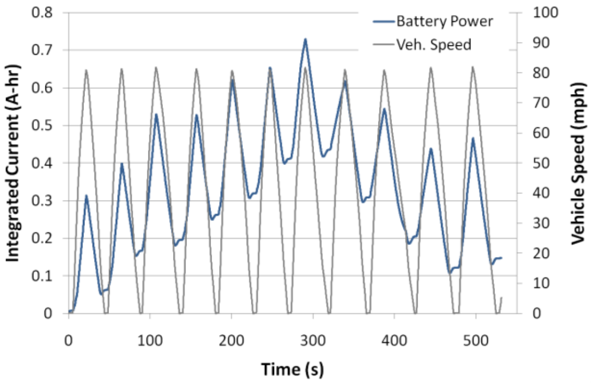


Figure 15: Battery Integrated Current over Repeated Accelerations

7.2 Impact of Air Conditioning

In order to assess the impact of air-conditioning, tests were run with the test cell at an elevated temperature while operating the air-conditioning. For this testing, the test-cell temperature was raised to 95^{o} F and the Urban and Highway tests were run for a comparative basis to the previously discussed runs without air-conditioning. While air conditioning tests frequently include an additional solar load, this additional load was not included due to test-cell capability limitations. Figure 16 below shows the sizeable impact air-conditioning operation has on vehicle fuel economy. It is worth noting that this number will vary significantly depending on outside temperature and humidity as well as vehicle temperature settings, but these results do help illustrate the large impact air conditioning has on fuel economy.

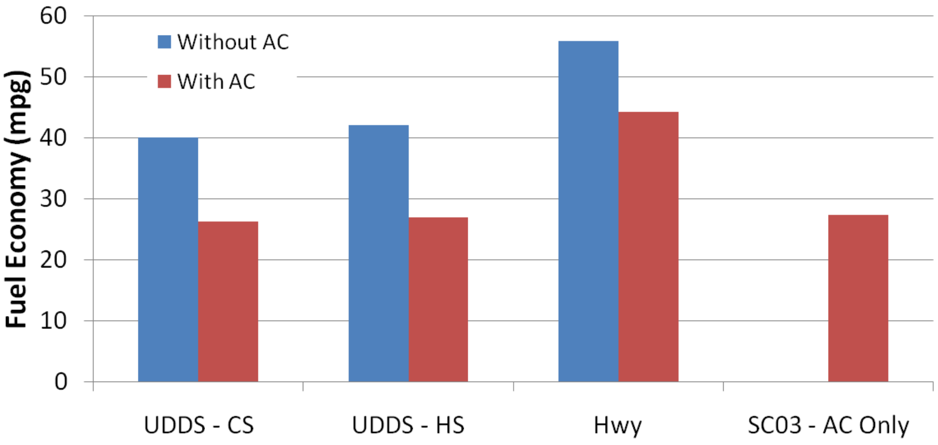


Figure 16: Fuel Economy Impact of Air-Conditioning
* MPG shown is for liquid butane

7.3 Assessment of Real-World Aggressive Driving

In addition to the aggressive driving of the US06 cycles, additional tests were done using cycles representative of more aggressive driving. These cycles are the LA92 cycle and the UDDS cycle where the amplitude of the accels is multiplied by a factor of 1.2x. The LA92 cycle is more aggressive than the UDDS cycle; having higher speed, higher acceleration, fewer stops per mile, and reduced idle time. The 1.2x multiplied UDDS cycle has been shown to be fairly representative of in-field observed acceleration and deceleration levels and has shown to correlate well with real-world fuel economy for several vehicle types. As can be seen in Figure 17, for this vehicle, the more aggressive cycles show similar fuel economy to the US06 cycle.

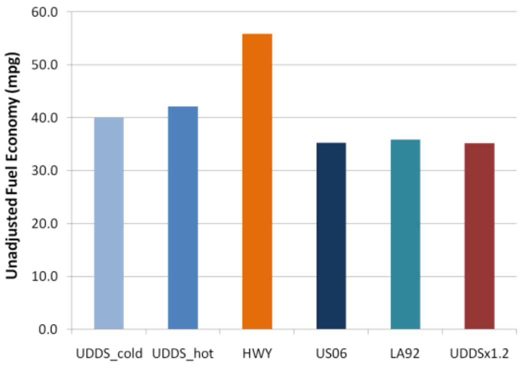


Figure 17: Vehicle Fuel Economy over FE Certification and Supplemental Cycles
** MPG shown is for liquid butane*

Figure 17 shows the peak positive and negative (regenerative) battery power observed for all of the cycles evaluated for this testing. For the majority of the cycles tested, both positive and negative battery power is fairly consistent. Peak positive power is increased for the US06 and UDDSx1.2x cycles due to the additional electric assist during the more aggressive accelerations contained in these cycles.

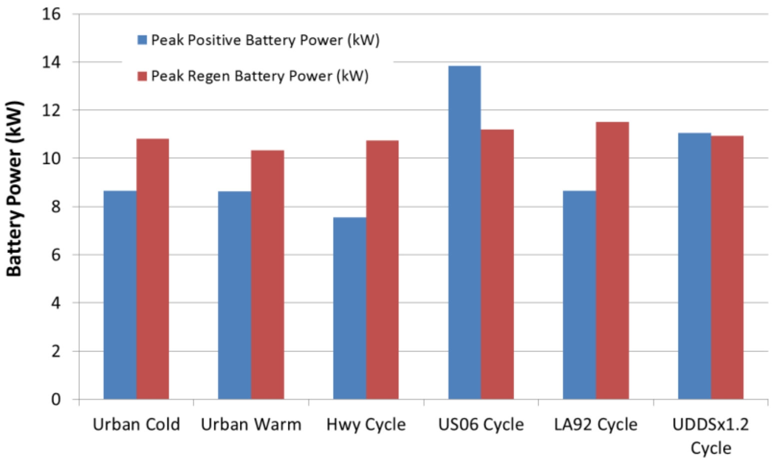


Figure 18: Peak Positive and Negative Battery Power Observed over Tested Cycles

8 Simplified Battery Pack Characterization

Given the high fidelity voltage and current measurements taken during vehicle testing, a basic characterization of the Avante’s lithium polymer battery pack can be made. By plotting the measured battery voltage versus the measured current and creating a voltage versus current best-fit line several basic parameter estimates can be made. Observing the slope (resistance estimate) and offset (rough nominal voltage estimate at operating SOC) of the best-fit line shown in Figure 19, the Avante's battery pack has an observed resistance of roughly 0.13 Ohms and an observed nominal pack voltage of 181 Volts at normal operating SOC levels. It should be noted that the spread observed from the best-fit line represents dynamics other than the basic *Voltage = Current x Resistance* relationship. Although more accurate, dynamic estimates are possible they will likely not deviate significantly from the basic estimates shown in for most standard operating scenarios.

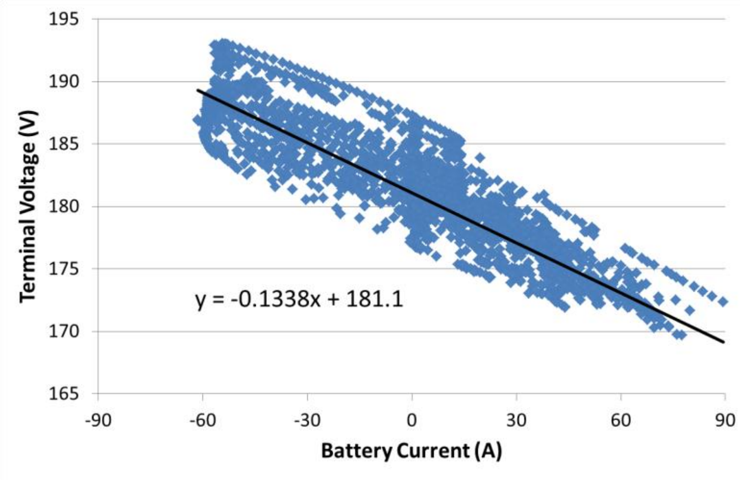


Figure 19: Battery Voltage versus Current

9 Conclusions and Future Work

Vehicle-level testing and data collection has provided insight into the the operating strategies and behavior of the Hyundai LPi Hybrid. Relevant findings include:

- Significant unfueled operation during vehicle decelerations even while operating at higher vehicle speeds and power requirements.
- Increased battery power usage for electric assist during the high vehicle acceleration events of the US06 cycle.
- Significant fuel economy degradation when operating with air-conditioning.
- Limited performance fade for roughly 7 accelerations, followed by a significant reduction in positive (assist) battery usage.
- Simple battery parameter estimates for this lithium polymer battery pack.

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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