Informal Document

Validation of a Test Procedure for Determination of HEV System Power: Report on Testing of a 2013 Malibu Eco and 2013 Chevrolet Volt at the U.S. Environmental Protection Agency

United Nations Economic Commission for Europe (UN ECE)
Informal Working Group on Electrified Vehicles and the Environment
(EVE IWG)

December 4, 2018

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1. Introduction

This report describes hybrid vehicle tests that were performed at US EPA to support the development of a test procedure for hybrid vehicle system power determination by the United Nations Economic Commission for Europe (UN ECE) Electric Vehicles and the Environment Informal Working Group (EVE IWG).

As part of a program to validate the proposed procedure, EPA applied the draft procedure to two hybrid vehicles that were available at the EPA laboratory. These are: (1) a 2013 Malibu Eco belt-alternator-starter (BAS) mild hybrid (NOVC-HEV), and (2) a 2013 Chevrolet Volt plug-in hybrid (OVC-HEV). Test plans for each vehicle are provided in the attachments to this report.

The 2013 Malibu Eco mild BAS hybrid and the 2013 Chevrolet Volt were the only vehicles available to be tested at short notice. Conveniently, they happen to represent relatively extreme cases of the various HEV architectures to which the proposed test procedure would apply. The Malibu Eco is dominated by the power of the engine (135 kW vs. 11 kW), while the Volt is powered by electric power alone (in CD mode). Therefore, differences between the result of TP1 and TP2 for the Malibu Eco may highlight differences in the capability of each TP to account for the engine component of total power. Similarly, any difference between TP1 and TP2 for the Chevrolet Volt may highlight differences in the ability to account for the electrical power component of total power.

2. Vehicle Preparation

2.1 Signals collected

The draft UN ECE procedure outlines two test procedures (TP), named TP1 and TP2.

TP1 is based on the sum of engine power and an adjusted battery power. Engine power is determined by reference to ISO 1585 or UN Regulation 85 engine test results, using measured engine speed as an indicator of power output. Intake manifold pressure and/or fuel flow rate are used as a check to confirm the engine power. Battery power is measured in the form of current and voltage, and adjusted to account for accessory power and losses in the electric motor.

TP2 is based on power at the axle, measured by means of axle (or wheel) torque and speed, and adjusted for losses in the gearbox (and the tires if applicable).

Both TP1 and TP2 also call for monitoring of component temperatures and state of charge (SOC). Other parameters are also useful for data processing.

The data requirements for both TP1 and TP2 may be satisfied by running a single set of tests on an appropriately instrumented vehicle. The specific instrumentation plan for each vehicle is outlined in the test plan attachments.

2.2 Instrumentation Method

EPA utilizes a contractor, Southwest Research Institute (SwRI), for various support tasks including vehicle instrumentation. SwRI was supplied with the test plans and was asked to instrument the vehicles as described in the test plans. SwRI instrumented the vehicles for data collection using their proprietary Rapid Prototyping Electronic Control System (RPECS), a data acquisition system capable of recording CAN bus information and signals from analog sensors.

SwRI reported that collection of available CAN signals, as well as the requested analog signal for manifold absolute pressure (MAP), at 10 Hertz would be straightforward. However, collection of battery voltage and current signals at a higher frequency, by use of current clamps and a Hioki meter, would be more difficult because a standard operating procedure has not yet been established for invasive instrumentation of high voltage components, particularly where cable shielding may have to be removed in order to collect accurate data. To prevent delay, it was decided to rely on CAN data for current and voltage, by the reasoning that this may be sufficient to establish electrical power during the 10-second power tests which represent a relatively steady-state condition. CAN signal identification and RPECS installation was completed by the end of August 2018.

2.3 On-road trials

Prior to dynamometer testing, each vehicle was driven on a road trial with the data collection system active to confirm proper data collection and recording by the data acquisition system. SwRI provided for the RPECS to be powered by the vehicle 12V power bus during road trials. The Malibu Eco was road driven on August 24 and the Chevrolet Volt on September 6. The Malibu Eco trial revealed that it would be desirable to add the CAN bus signal for vehicle speed (kph) to allow comparison with dynamometer-reported speed. The Volt test revealed that the CAN signal for drive motor temperature reported a constant temperature and so was likely an inactive signal. SwRI added vehicle speed to the CAN channels to be recorded, and identified additional temperature signals for the Volt and added them to the system. No other significant problems were found.

3. Data Collection

Dynamometer time was scheduled in EPA Dynamometer Cell 5 for the week of September 4-7, 2018.

3.1 General protocol

For both vehicles, the first test session was devoted to determining the speed at which maximum power occurs. This was done by running a sweep of constant speeds between 50 kph and 130 kph, inclusive. At each constant speed, two pulses of maximum power were performed for 15 seconds each, by rapidly pressing the accelerator to the floor. The power measured by the dynamometer was then analyzed to make an informed guess for the exact speed where maximum power might occur. The second test session was devoted to identifying this speed, again with two pulses at each speed but within a narrower range of speeds. A conditioning cycle was run at the start of each test session.

For all tests, the test vehicle was secured by rigid restraints at front and rear, and the exhaust connected by Marman flange to the building exhaust system (see Figure 1).

Because the nature of the test was exploratory, an engineer who was knowledgeable about the procedure drove the vehicle, in place of a staff driver. One engineer was assigned to drive the vehicle during all testing, while another engineer controlled the RPECS system in the rear seat and monitored temperatures and other data. The RPECS engineer communicated with the dynamometer control room by portable radio.

3.2 Dynamometer testing of 2013 Malibu Eco

3.2.1 Installation and trial – Malibu Eco

On the afternoon of Tuesday September 4, the Malibu Eco was placed on the dynamometer, with the front wheels on the rolls and the rear wheels stationary. A fixed speed US06 fan was aimed at the front of the vehicle. The RPECS system resided in the left rear seat and was powered by line current from the test cell to avoid adding to the accessory load of the vehicle. Tests were performed with the hood open and with traction control turned off by means of a dashboard button.

A preliminary run was performed in constant-speed mode (at 80, 50, and 30 kph) to test the ability to collect and retrieve data files, to get some understanding of the vehicle's SOC behavior, and to experiment with regenerative braking as a means to manipulate SOC.

It was discovered that braking sometimes generated a burning odor, probably due to braking beyond the capacity of the regeneration system, and insufficient cooling of the brake pads due to low air flow. Later tests were conducted with additional fans pointed at the front wheels to provide cooling.

The SOC appeared to vary in a narrow band between about 50% and 60% and showed some ability to be controlled, but only moderately, often appearing to stabilize at a somewhat arbitrary level within the band.

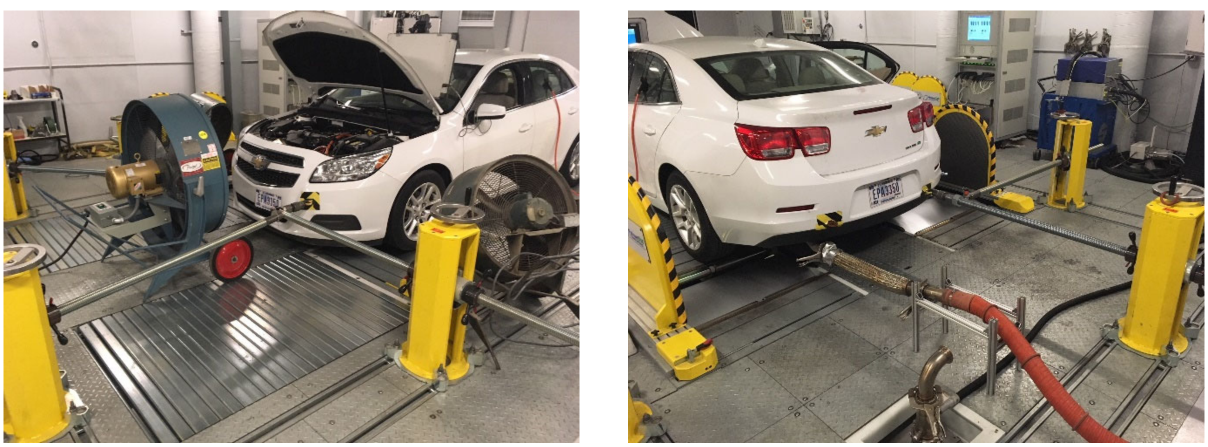

Figure 1. 2013 Malibu Eco installed on chassis dynamometer

3.2.2 Test Session 1 - Initial speed sweep – Malibu Eco

The Malibu Eco remained installed in the test cell overnight. On Wednesday September 5, an exploratory speed sweep was conducted to help identify the speed of maximum power.

First, a conditioning cycle was run in road load mode at 60 kph for slightly more than 20 minutes. Temperatures reported by CAN for the engine coolant, transmission oil, drive motor coolant, and high voltage battery (max and min cell temperature) were observed and recorded at the end of conditioning. During conditioning, SOC quickly dropped from an initial 50% and stabilized into a narrow window between about 39% to 41% for most of the conditioning cycle. This phase of the test took approximately 30 minutes and generated about 22 minutes of 10 Hz log data.

The dynamometer was then switched to constant speed mode, and testing was conducted at a series of fixed speeds ranging from 50 kph to 130 kph, in ascending sequence at 10 kph intervals. At each speed, two acceleration pulses were performed, with the accelerator pressed rapidly to maximum for an interval of 15 seconds, measured by a timer. Each pulse was separated by sufficient time to allow for recovery of the battery SOC, which was monitored on the RPECS system. Temperatures were also monitored. SOC varied in a narrow band between 59% and 64% (nominal, as reported by the CAN bus) and each acceleration pulse was targeted to occur at about 64%. Very light braking was occasionally applied at lower speeds, but was not necessary at higher speeds.

This phase of the test took approximately 45 minutes and generated about 40 minutes of 10 Hz log data.

3.2.3 Identification of maximum power – Malibu Eco

After the speed sweep was complete, the dynamometer data file was examined to determine where the greatest power was generated. The dynamometer data file was collected and imported into Microsoft Excel. The file includes a field that reports power (kW) at the dynamometer rolls, and this field was plotted for all of the speeds. The plot is shown in Figure 2 (for the range between 60 and 130 kph).

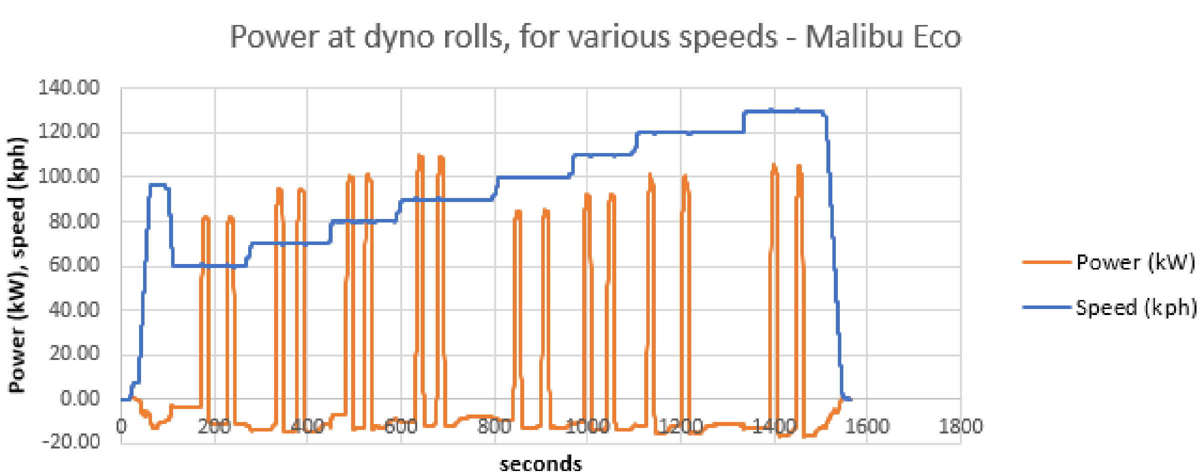

Figure 2. Initial speed sweep, 60 to 130 kph, Malibu Eco

The power measured at the dynamometer rolls increased steadily at each speed up to 90 kph, where it peaked at about 110 kW. At this point, the measured engine speed (about 5800 rpm) was slightly below the speed of its rated power (the rated peak power of the Malibu engine is 137 kw at 6200 rpm). At speeds above 90 kph, the automatic transmission shifted to a lower gear, resulting in lower measured power. At 130 kph, engine speed was again approaching maximum (about 5300 rpm), but measured power was not greater than at 90 kph. Data was not taken beyond 130 kph because higher speeds are seldom encountered in normal operation and would not be relevant to the purpose of classification and downscaling in the context of WLTP.

Because the shift results in reduced power, it was concluded that the highest power would likely occur at a speed prior to the shift, somewhere between 90 kph and 100 kph.

3.2.4 Test Session 2 – Second speed sweep – Malibu Eco

The Malibu Eco remained installed in the test cell overnight. On the morning of Thursday September 6, a second speed sweep was conducted between 90 and 100 kph, at 2 kph intervals, to identify the speed of maximum power more precisely.

A conditioning cycle was run prior to the test, as before. Each speed included two acceleration pulses, with SOC recovery, as before.

When performing the second speed sweep, the shift event was found to first occur at 94 kph, as seen in Figure 3. Although the shift was clearly evident to the driver during the test, for completeness, the speed sequence was continued to 100 kph.

The test was then continued at 93, 93.5, and 94 kph to more closely identify the shift point. Engine speed reached about 6000 rpm at 93 and 93.5 kph, and as seen in Figure 4 and Figure 5, the shift again occurred at 94 kph.

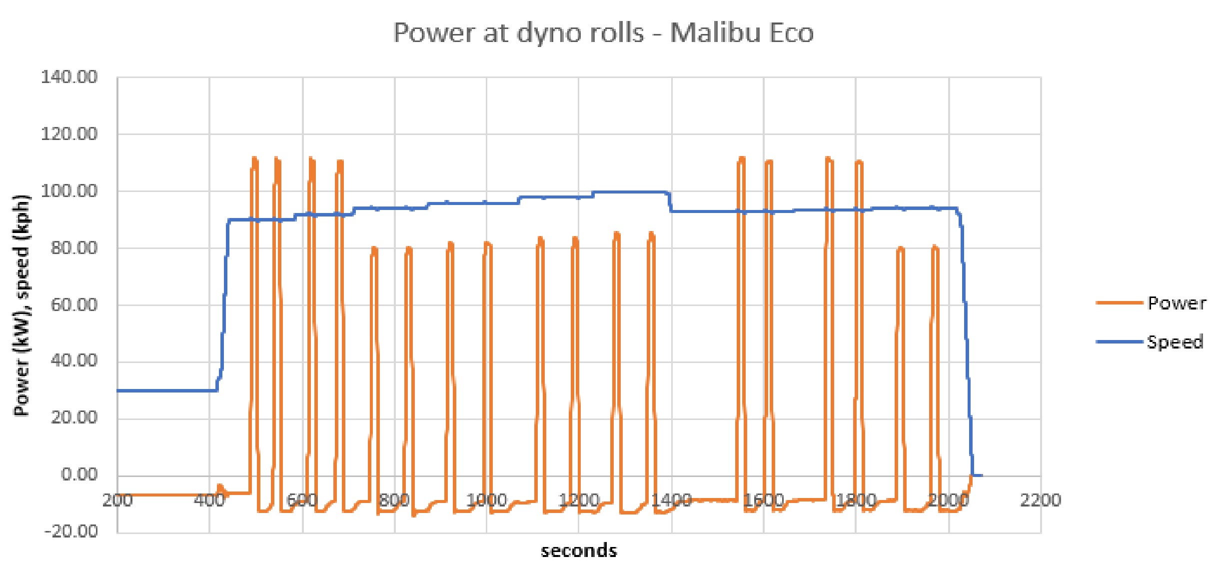

Figure 3. Second speed sweep, 90 to 100 kph and 93, 93.5, 94 kph, Malibu Eco

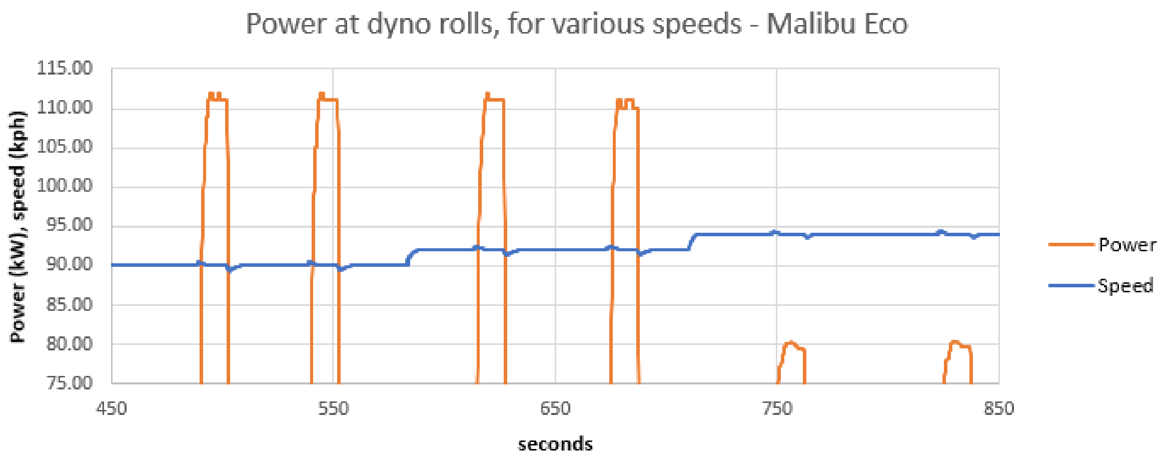

Figure 4. Occurrence of gear shift at 94 kph, Malibu Eco

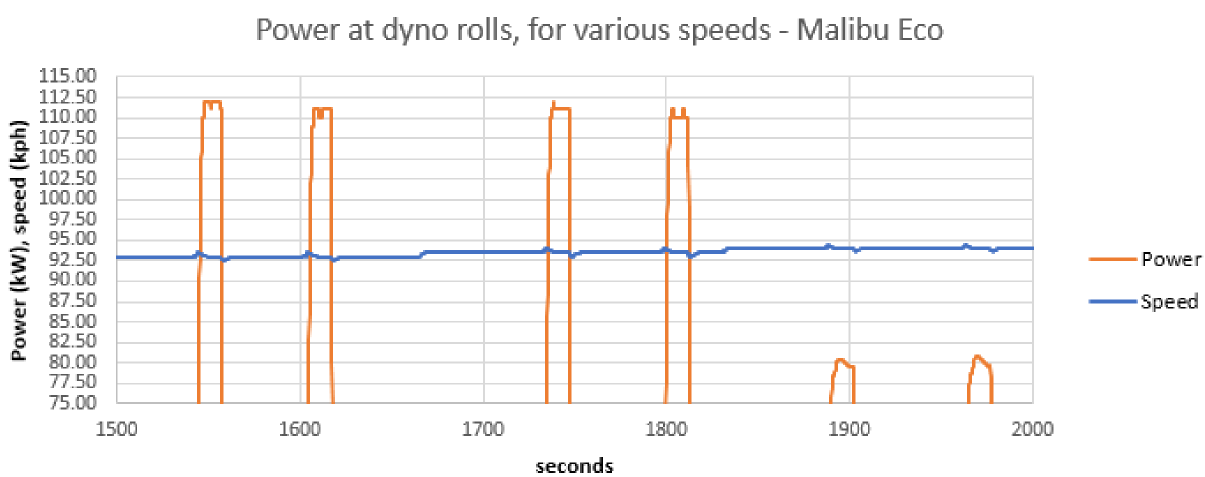

Figure 5. Power at 93 kph and 93.5 kph, Malibu Eco

Testing was then halted with the expectation that maximum power would have occurred at about 93 to 93.5 kph. This phase of the test generated about 35 minutes of 10 Hz data.

Since all data necessary to perform the power determination calculation had been collected while exploring these speeds, no further testing of the Malibu Eco was required.

Figure 6 shows behavior at 93 kph, where measured power at the rolls was 112 kW (first pulse) and 111 kW (second pulse). The difference may be due to the poor resolution of the power data reported by the dynamometer at power values above 100 kW. Otherwise, the pulses are very consistent in shape and magnitude.

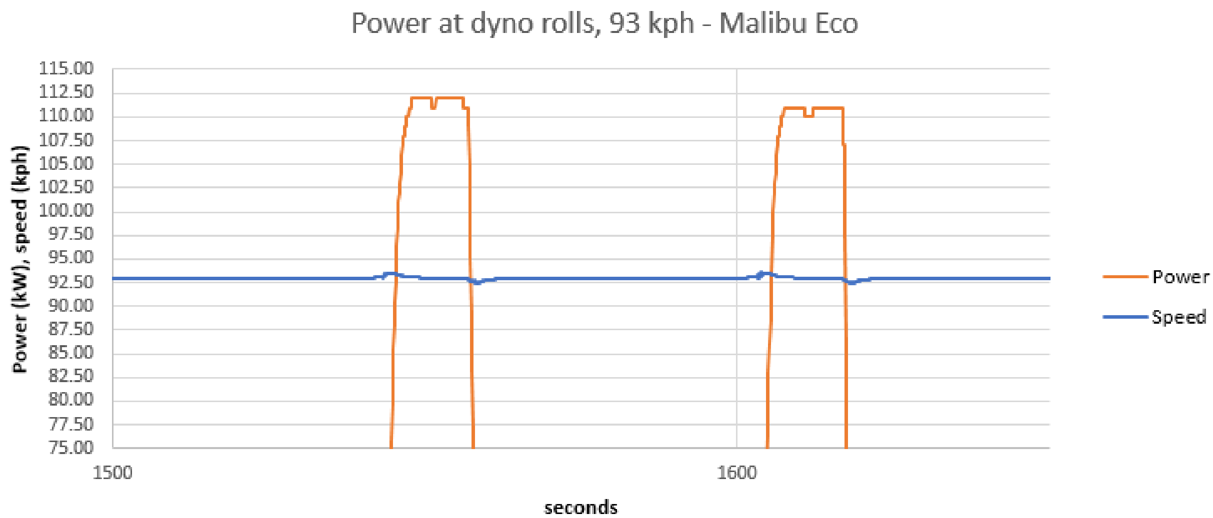

Figure 6. Close-up view of wheel power at 93 kph, Malibu Eco

Figure 7 shows behavior at 93.5 kph, where measured power at the rolls was about 111 kW (first pulse) and 110 kW (second pulse). Again, the difference may be partly due to the poor resolution of the power data reported by the dynamometer. Otherwise, the pulses are very consistent in shape and magnitude.

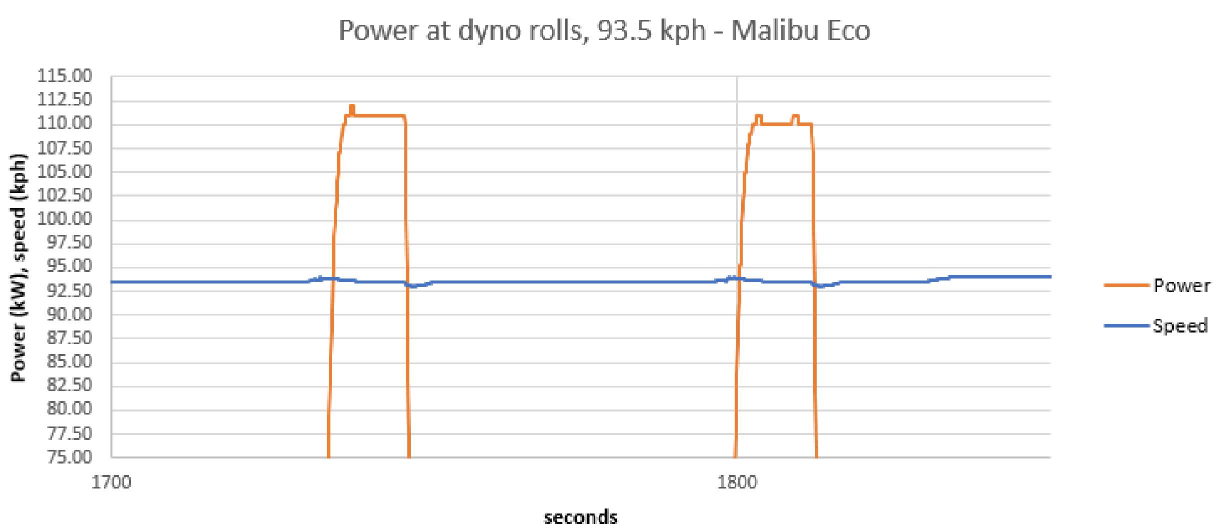

Figure 7. Close-up view of wheel power at 93.5 kph, Malibu Eco

Calculation of power according to TP1 and TP2 is described in Section 4.

3.3 Dynamometer testing of 2013 Chevrolet Volt

3.3.1 Installation and trial – Chevrolet Volt

On the afternoon of Thursday September 6, the Chevrolet Volt was placed on the dynamometer, with the front and rear wheels on the rolls (4WD mode) as shown in Figure 8. Although the Volt is a

2WD vehicle, previous EPA experience with testing this vehicle had indicated that testing in 4WD mode is preferable.

The vehicle had been fully charged the previous night. The RPECS system resided in the left rear seat. The same engineers who tested the Malibu also tested the Volt, serving the same roles as before.

There were several minor differences in how the Volt was tested as compared to the Malibu. First, a road speed fan was used for the Volt testing, in contrast to the US06 fan used for the Malibu Eco. While the ISO standard on which the procedure is based does not call for the fan speed to match the dynamometer speed, it has been proposed that the procedure should align with GTR No. 15, which does. Second, the use of a road speed fan meant that the testing had to be performed with the hood closed, due to the higher wind speed. Third, the Volt's RPECS system was powered by the vehicle rather than the test cell (as configured for the road test) due to an oversight in requesting installation of a stationary connection prior to the first test session. The current draw from the 12V power bus is estimated at about 4 Amps and was deducted in the power calculation. Finally, the brake cooling fans were not used, given the greater capacity for regenerative braking on the Volt.

Figure 8. 2013 Chevrolet Volt installed on chassis dynamometer

3.3.2 Test Session 1 - Initial speed sweep – Chevrolet Volt

On the afternoon of Thursday September 6, an exploratory speed sweep was conducted.

First, a conditioning cycle was run in road load mode at 60 kph for slightly more than 20 minutes. The vehicle was placed in "Hold Mode" for this phase of the test, which causes the vehicle to operate in charge sustaining mode. This was done to prevent the battery SOC from depleting during the conditioning phase. Temperatures reported on CAN for the engine coolant, transmission oil, drive motor, and high voltage battery (max and min cell temperature) were observed and recorded at the end of conditioning. During conditioning, SOC remained in a tight band between 81.5 and 82.5 percent as reported by the CAN signal. This phase of the test took approximately 30 minutes and generated about 30 minutes of 10 Hz log data.

The dynamometer was then switched to constant speed mode, and the vehicle was switched to Normal Mode. This causes the vehicle to run in charge depleting mode, powered exclusively by the battery. Testing was conducted at a series of fixed speeds ranging from 50 kph to 130 kph. Because it was uncertain how long the regeneration of SOC would take on this vehicle, the speeds were traversed by larger increments to ensure that a wide range could be covered, in case there was insufficient time to complete the test. In a first pass, speeds ranged from 50 to 130 kph in 20 kph increments. Finding that SOC regeneration was not an issue, a second pass completed the sweep from 60 to 120 kph in 20 kph increments.

As before, at each speed, two power pulses were performed, with the accelerator pressed fully and rapidly to maximum. Each pulse was separated by sufficient time to allow for recovery of the battery SOC, which was monitored on the RPECS system. Between each pulse, SOC was recovered by having the driver lightly press the brake pedal until a charge rate of approximately 1C to 2C was observed on the data acquisition system. This was difficult to control accurately because the driver did not have direct sight of the SOC readout. The SOC was recovered to at least 78 percent for each pulse. Battery temperatures were closely monitored. At higher speeds, braking was not necessary as the constant speed of the dynamometer generated up to about 30 amps of current into the battery, which often was sufficient to recover the target SOC in a reasonable time. This phase of the test took approximately 60 minutes and generated about 55 minutes of 10 Hz log data.

3.3.3 Identification of maximum power – Chevrolet Volt

After the speed sweep was complete, the dynamometer data file was examined to determine where the greatest power was generated. The dynamometer data file was collected and imported into Microsoft Excel. As before, the power (kW) at the dynamometer rolls was plotted for all of the speeds as shown in Figure 9.

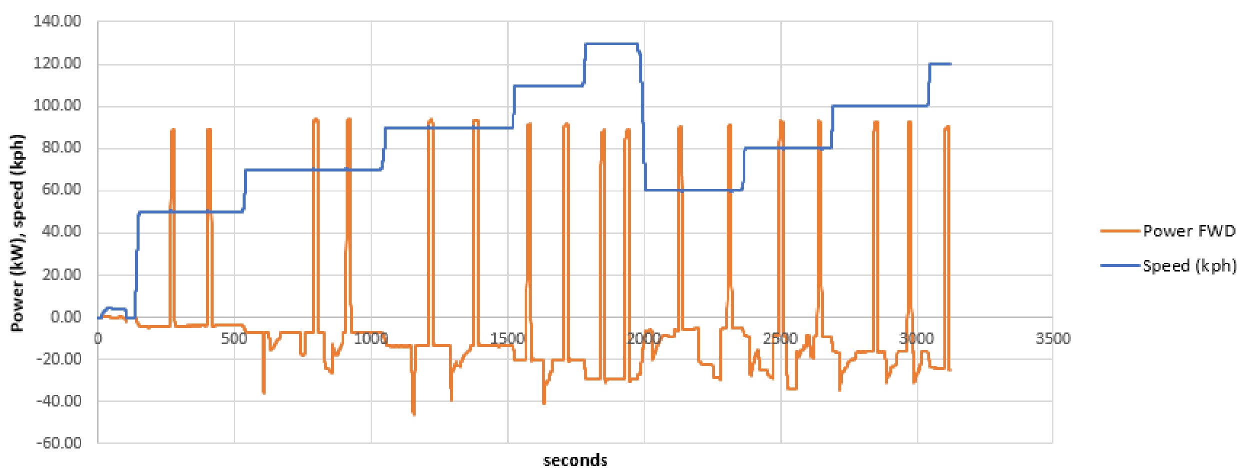

Figure 9. Initial speed sweep, Chevrolet Volt

As can be seen, the power for this vehicle was relatively constant across all of the test speeds, hovering around 90 kW. This is not surprising given that the Volt is powered electrically through a single transmission gear ratio while in charge depleting mode. However, it makes it difficult to identify the speed of peak power.

As seen in Figure 10, it is unclear exactly where the peak may occur. However, it appears possible that a maximum power might be found somewhere between 60 and 90 kph.

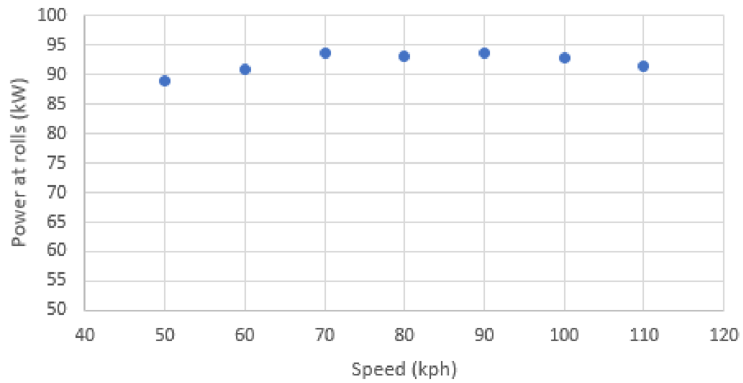

Figure 10. Variation in measured power, Chevrolet Volt

3.3.4 Test session 2 – Second speed sweep – Chevrolet Volt

The vehicle remained installed in the test cell overnight. On Friday September 7, a second, more focused speed sweep was conducted. A conditioning cycle was run prior to the test, as before.

This speed sweep progressed through speeds from 66 to 90 kph, at 4 kph intervals. As before, two acceleration pulses were conducted at each speed, with SOC recovery in between. This phase of the test generated about 47 minutes of 10 Hz data.

As seen in Figure 11, the results were very similar to each other and to the results from the day before, between about 90 and 95 kW. It remained difficult to discern a precise speed of maximum power, suggesting that within this range of speeds, the speed is not a significant determinant of the maximum power output of this vehicle.

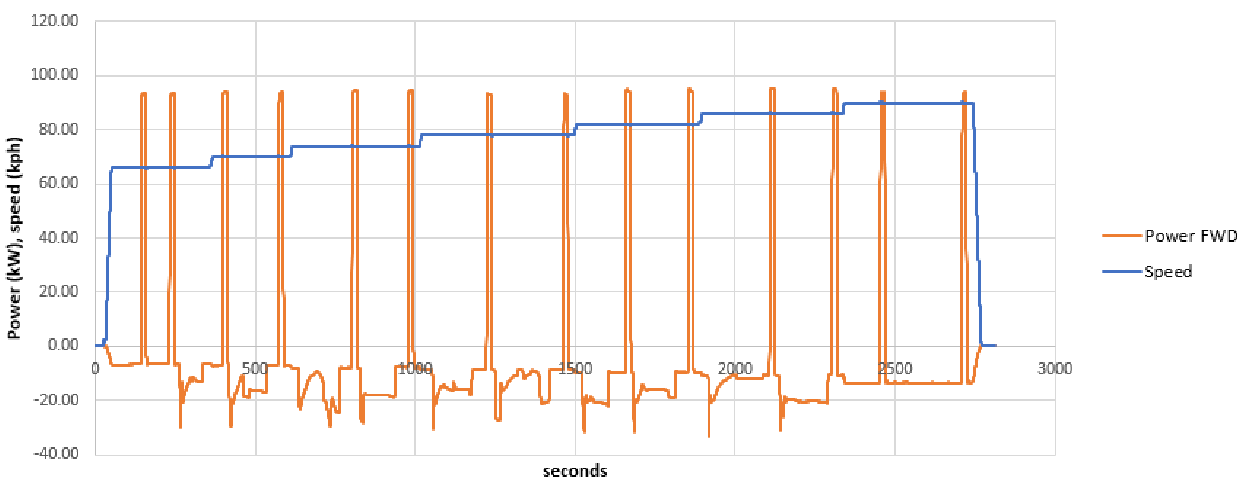

Figure 11. Second speed sweep from 66 to 90 kph, Chevrolet Volt

Figure 12 shows behavior at 82 kph, where measured power at the rolls peaked briefly at 95.2 kW (both pulses) and then settled to 94.4 kW (first pulse) and 94.3 kW (second pulse). It can be seen that the pulses are very consistent in shape and magnitude.

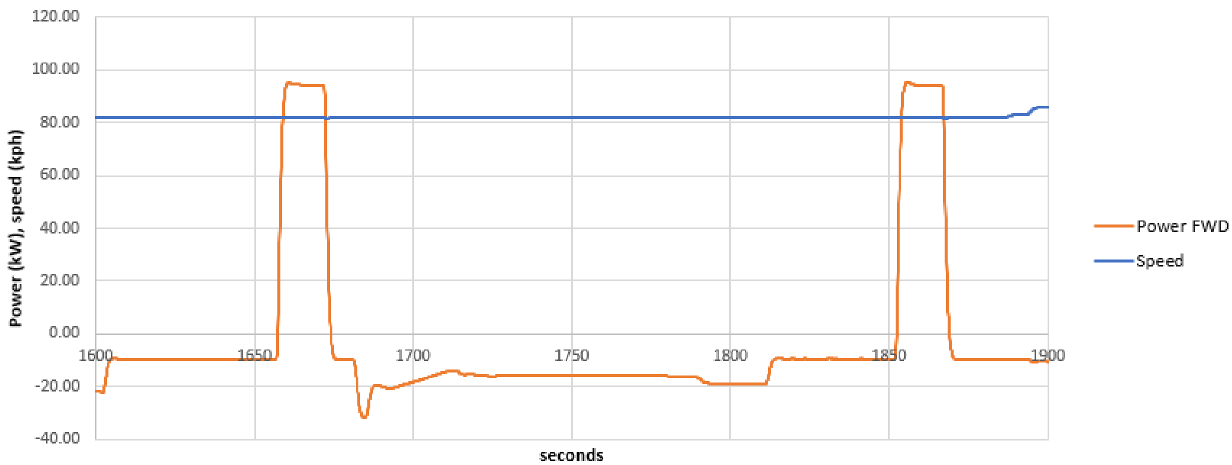

Figure 12. Close-up view of wheel power at 82 kph, Chevrolet Volt

Figure 13 shows behavior at 86 kph, where peak measured power at the rolls was 95.2 kW (first pulse) and 95.4 kW (second pulse). Again, the pulses are very consistent in shape and magnitude.

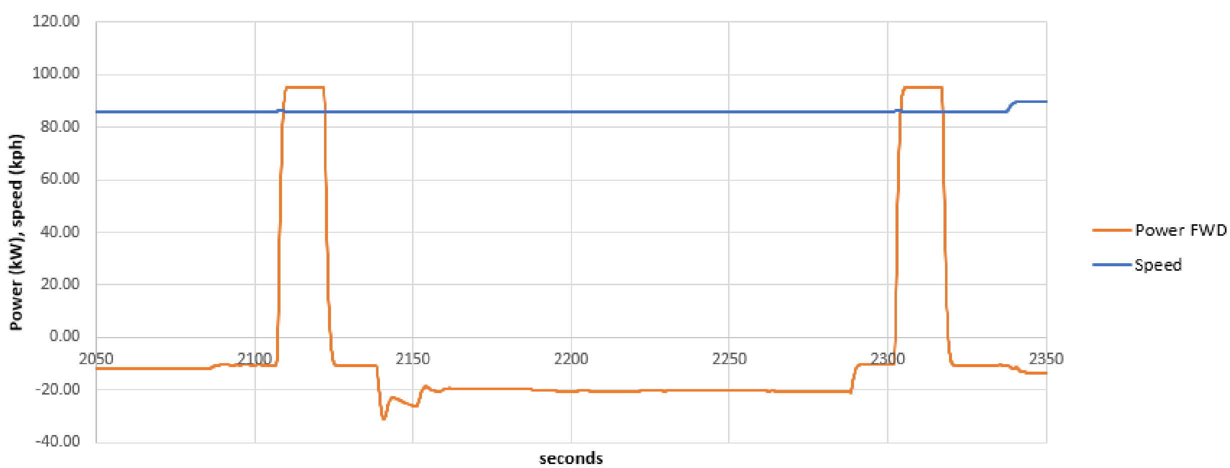

Figure 13. Close-up view of wheel power at 86 kph, Chevrolet Volt

4. Power calculation

4.1 General

According to the draft test procedure, “peak” power is defined as the maximum value obtained by applying a 2-second moving average filter to the total power measured over a 10-second measurement window beginning at the time of maximum power command. “Sustained” power is defined as the average of the total power measured between the 8th and 10th second of the 10-second window.

TP1 specifies that the total power is calculated as the sum of engine power and converted battery power. Engine power is determined by reference to the peak power curve of the engine at the observed engine speed. Converted battery power is the measured power at the battery, adjusted to account for power consumed by the DC/DC converter and 12V accessories, and by losses in the electric motor.

TP2 specifies that the total power is calculated as the power measured at the axle (or the wheels), adjusted to account for losses in the gearbox. If power is measured at the wheels instead of at the axle, additional adjustment is necessary to account for losses in the tires.

4.2 Limitations

4.2.1 Availability of ISO 1585 engine test data

TP1 depends on the availability of engine test data from ISO 1585 or UN Regulation 85. This data is typically not available for engines used in North American vehicles, and was therefore not available for the vehicles tested.

For the Chevrolet Volt, engine data was not needed because the engine does not operate during the test, which was performed in CD mode. However, engine data would have been necessary if the vehicle had been tested in CS mode.

For the Malibu Eco, which has a 2.4L EcoTec engine rated at 182 horsepower, data was instead taken from an EPA benchmarking study of a highly similar engine (a 2.5L EcoTec rated at 197 hp). The WOT data for power output and intake manifold pressure are shown in Figure 14 and Figure 15. The engine power obtained from the 2.5L engine data was scaled by a factor of 182/197 to represent the 2.4L engine.

This approximation may limit the ability to draw firm conclusions about the comparison between the results of TP1 and TP2 for this vehicle. It should also be noted that the engine data was generated on regular E10 fuel, while the validation tests were conducted on Tier 2 (E0) fuel, and no correction has been performed.

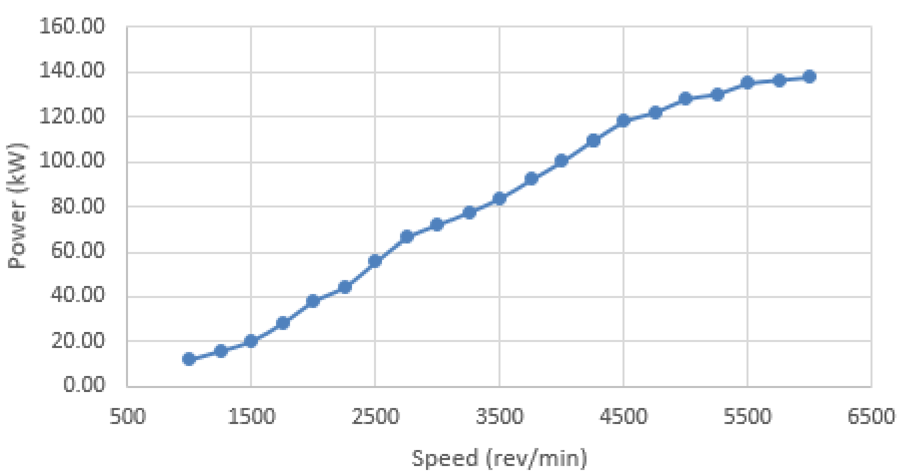

Figure 14. WOT power output, 2.5L EcoTec (Regular E10 fuel)

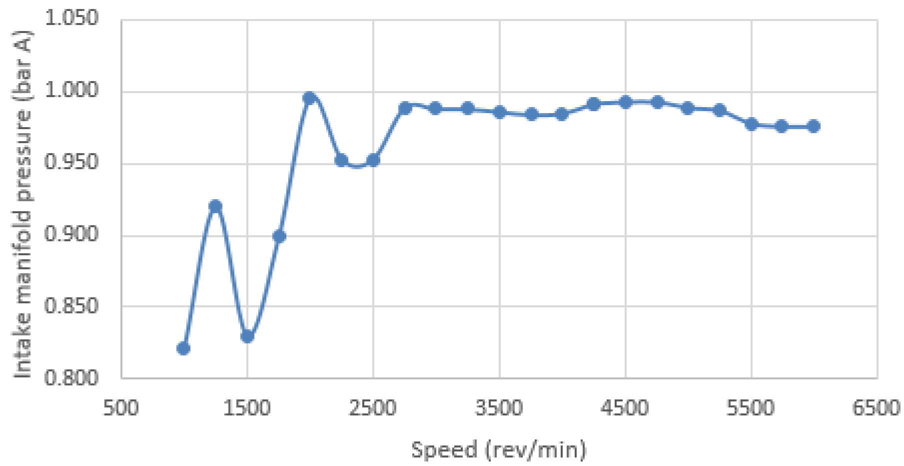

Figure 15. WOT intake manifold pressure, 2.5L EcoTec (Regular E10 fuel)

4.2.2 Availability of tire correction factor

Due to the unavailability of a hub dynamometer or wheel torque sensors at the EPA laboratory, the TP2 calculation utilized torque and speed data collected at the rollers of the chassis dynamometer. This requires correction for losses in the tires. The test procedure does not specify a procedure for making this correction. The correction was made using an estimated tire rolling resistance and vehicle weight on each axle.

4.2.3 Environmental corrections

Because the testing of the Malibu 2.5L EcoTec was performed in the same laboratory and same environmental conditions as the vehicle test, environmental corrections for the engine data were not necessary.

4.3 Power calculation – Malibu Eco

For the Malibu Eco, the tests indicated that maximum power at the dynamometer rolls was delivered at 93 kph, at about 112 kW. The first pulse collected at this speed was selected for calculation of maximum power under TP1 and TP2. It begins at 1510.32 seconds. The 10-second window of consideration for peak power thus runs from 1510.32 seconds to 1520.32 seconds. The 8th to 10th second for sustained power runs from 1518.32 to 1520.32 seconds.

4.3.1 TP1 Peak Power – Malibu Eco

Signals of interest for calculation of TP1 are plotted in Figure 16. (MA = 2-sec moving average)

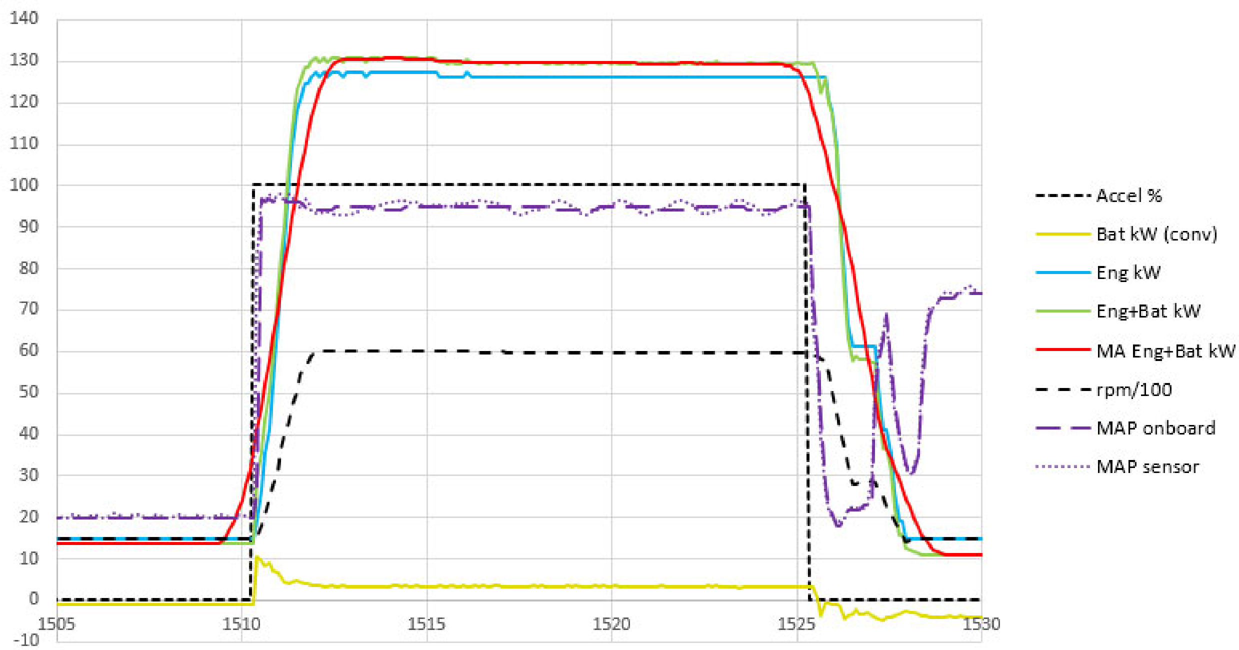

Figure 16. Peak and sustained power, TP1, Malibu Eco

Engine power was estimated by looking up the engine speed against a plot of peak power output from the 2.5L EcoTec engine (see Figure 14), and scaled by a factor of 182/197 as previously described.

The engine speed quickly reached a plateau at 6000 rpm. The intake manifold pressure sensor indicated a pressure between 0.93 and 0.96 bar during the acceleration, while the onboard data was more stable at about 0.95 bar. These pressures are similar to, but slightly lower than, the 0.976 bar reported in the engine test data at this speed (see Figure 15).

Converted battery power was computed as the product of measured battery voltage and current, from which was subtracted the product of 12V battery voltage and current to represent accessory draw, and 1.0 kW for DC-DC converter as specified by the test procedure. The resulting battery power was then multiplied by K = 0.85 as directed by the test procedure.

During the 10-second interval, the peak value of the 2-second moving average of the sum of engine power and converted battery power is **130.73 kW**.

4.3.2 TP1 Sustained Power – Malibu Eco

The average value of the sum of engine and converted battery power in the interval between the 8th and 10th second is **129.57 kW**.

4.3.3 TP2 Peak Power – Malibu Eco

TP2 can be performed by measuring power at the dynamometer rollers and adjusting for gearbox efficiency and tire losses.

As tested, there are two options for measuring power at the rollers. The dynamometer directly records roller power; however, this signal is not an ideal source because it appears to be filtered at an unknown rate. The other option is to compute roller power using dynamometer-recorded torque and estimated wheel speed. While roller speed is not recorded by the dynamometer, roller speed can be estimated from vehicle speed and wheel diameter, knowing that the roller diameter is 48 inches. As seen in Figure 17, the peak power computed by this method is slightly higher than the filtered value collected from the dynamometer.

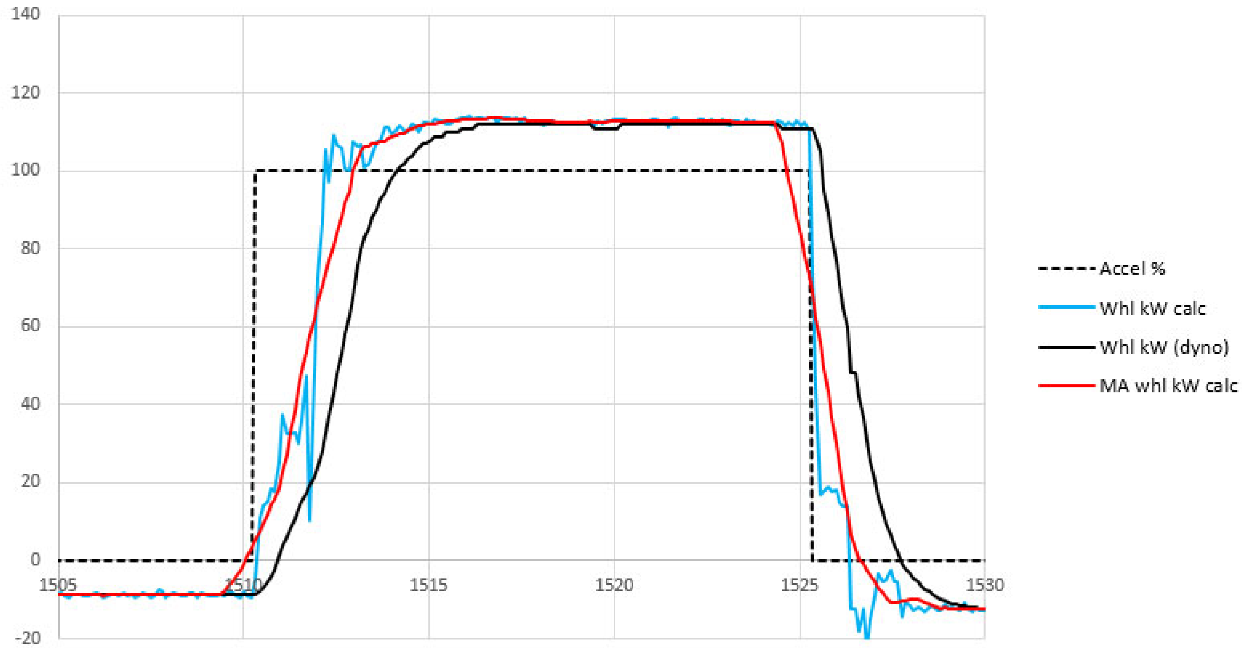

Figure 17. Peak and sustained power, TP2, Malibu Eco

During the 10-second interval, the peak value of the 2-second moving average of the roller power is 113.615 kW.

This figure was adjusted for tire losses in the following manner. The weight on the front axle, as tested, was 2250 pounds (1020.6 kg) and on the rear axle, 1744 lb (791.1 kg). Only the front wheels were in operation on the dynamometer. Assuming a typical rolling resistance coefficient for a light-duty vehicle tire at 0.01, the rolling force on each of the two driven wheels would be:

0.01*(2250/2) lb = 11.25 lb = 50 N (a total of 100 N for two driven wheels)

Assuming a wheel radius of 0.3396 m (see Malibu test plan attachment), the rolling force of 100 N amounts to a torque of 33.96 Nm. At 93 kph roller speed, the onboard system indicated a vehicle speed of 94 kph (possibly due to wheel slippage). At 94 kph, the rotational speed of the wheels would be:

(94 km/hr)(1000 m/km)(1 rev/(2*3.1416*0.3396 m))(1 hr/3600 sec) = 12.237 rev/sec

Tire losses therefore amount to:

(33.96 Nm)(12.237 rev/sec)(3.1415927*2) = 2.611 kW

Adding this power back to the wheel power yields the axle power:

Axle power = 113.615 kW + 2.611 kW = 116.23 kW

Using a gearbox efficiency of 0.96 (for parallel hybrid), this yields:

116.23 kW / 0.96 = **121.07 kW**

4.3.4 TP2 Sustained Power – Malibu Eco

The average value of the roller power in the interval between the 8th and 10th second is 112.73 kW. Adding the tire losses brings this to 115.34 kW. Dividing by 0.96 gearbox efficiency results in:

115.34 kw / 0.96 = **120.15 kW**

4.3.5 Implied downstream efficiency – Malibu Eco

As a check, we calculated the implied downstream efficiency of the powertrain, by comparing the computed TP1 and TP2 sustained power values to the power recorded at the dynamometer rollers (thus representing losses in the transmission, bearings, and tires).

As reported in Section 4.3.4, sustained power at the rollers was measured as 112.73 kW. According to the sustained TP1 power at 129.57 kW, the implied downstream mechanical efficiency of transmission, bearings and tires is:

112.73 kw / 129.57 kW = **87.0%.**

According to the sustained TP2 power at 120.15 kW, the implied downstream mechanical efficiency of transmission, bearings and tires is:

112.73 kw / 120.15 kW = **93.8%.**

4.3.6 Summary of Results – Malibu Eco

Similar calculations were performed for the second acceleration pulse in the pair of pulses that were performed at 93 kph. The results for both are summarized here.

As seen in Table 1, the variation between TP1 and TP2 peak and sustained power is significant.

Table 1. Peak and sustained power, TP1 and TP2, Malibu Eco

	Peak power			Sustained power		
	TP1	**TP2**	**Difference**	**TP1**	**TP2**	**Difference**
First pulse	130.73 kW	121.07 kW	-9.66 kW	129.57 kW	120.15 kW	-9.42 kW
Second pulse	130.04 kW	119.87 kW	-10.17 kW	129.54 kW	118.99 kW	-10.55 kW
Difference	-0.69 kW	-1.2 kW		-0.03 kW	-1.16 kW	

Table 1 also shows that the results for each TP were reasonably consistent between the first and second pulse.

The implied downstream efficiency for the power measurements of TP1 and TP2 also varies substantially. The TP1 calculation suggests an efficiency of 87.0% while TP2 suggests 93.8%.

Table 2. Implied downstream efficiency of transmission, bearings and tires, Malibu Eco

	Sustained	
	TP1	**TP2**
First pulse	87.0%	93.8%
Second pulse	86.2%	93.8%

In considering the TP1 result, it should be noted that the Malibu Eco represents an extreme case, in that the rated power of the electric motor is a very small fraction of the rated power of the engine. The accuracy of the engine power estimate may therefore exert a strong influence on the accuracy of the TP1 result. Unfortunately, the use of substitute data in place of ISO 1585 or UNR 85 test results prevents the drawing of a firm conclusion here.

In considering the TP2 result, a possible source of error is in the assumed efficiency of the transmission. A mild hybrid is likely to have a transmission efficiency similar to that of a conventional vehicle, which might be less efficient than the assumed value of 0.96. Assuming a lower efficiency would bring the TP2 result closer to TP1.

Another possible source of error for TP2 is wheel slippage. As seen in Figure 18, some wheel slippage appears to have occurred during the acceleration pulses. Before and after each pulse, the speed measured by the dynamometer rolls and the speed measured by the vehicle onboard system are in agreement. However, during each pulse, the speed measured by the vehicle onboard system is about 1 kph higher than the dynamometer speed, indicating slippage. The exact magnitude of the difference is uncertain due to the low resolution of the onboard signal. However, it is likely that some amount of power is being lost to wheel slippage, which would mean that the vehicle is performing more work than reported by the dynamometer roller surface torque. This would reduce the amount of power reported by TP2.

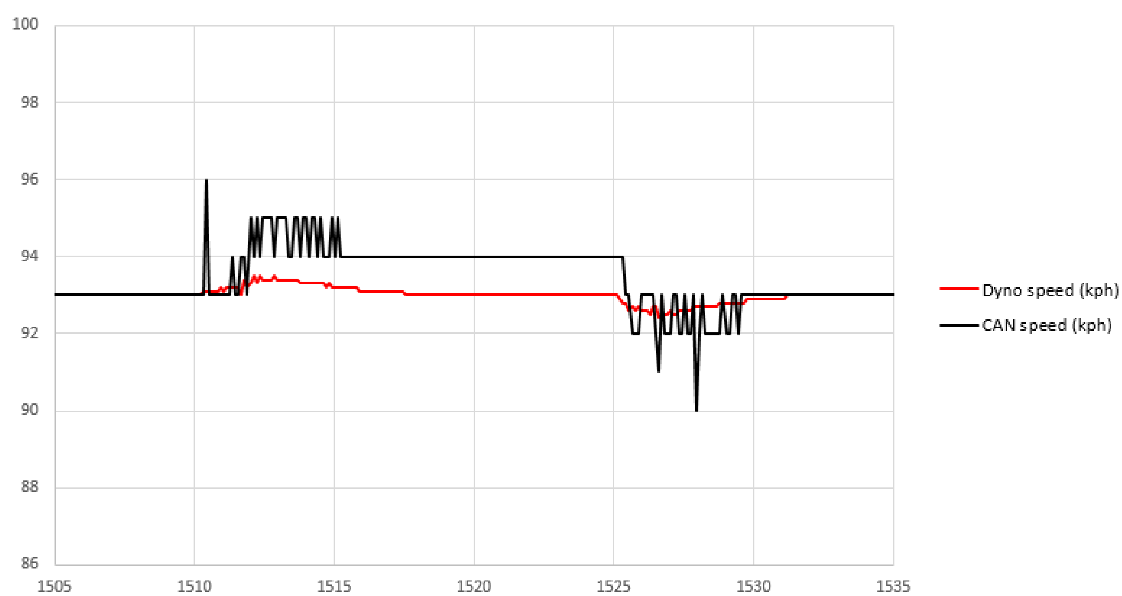

Figure 18. Wheel slippage indicated by measured speed differences, Malibu Eco

4.4 Power calculation - Chevrolet Volt

For the Chevrolet Volt, the tests indicated that maximum power at the dynamometer rolls was relatively constant and varied little for many of the speeds tested.

86 kph was selected for application of the test procedure calculations, where the power at the dynamometer rolls was 96.3 kW. The first pulse collected at this speed was analyzed for power calculation. The selected acceleration pulse begins at 2108.21 seconds. The 10-second window of consideration for peak power thus runs from 2108.21 seconds to 2118.21 seconds. The 8^{th} to 10^{th} second for sustained power runs from 2116.21 seconds to 2118.21 seconds.

4.4.1 TP1 Peak Power - Chevrolet Volt

Signals of interest for performing TP1 are plotted in Figure 19. Engine power is not plotted because the engine did not operate during the test.

Figure 19. Peak and sustained power, TP1, Chevrolet Volt

Converted battery power was computed as the product of measured battery voltage and current, from which was subtracted the product of 12V battery voltage and current to represent accessory draw, and 1.0 kW for DC-DC converter (the default value). The Volt data acquisition system was powered by the vehicle, drawing an estimated 4 amps. Therefore the measured 12V battery current was reduced by 4 amps for purposes of calculation. The result was then multiplied by K = 0.85 as directed by the test procedure.

During the 10-second interval, the peak value of the 2-second moving average of the sum of engine power (zero) and converted battery power is **94.31 kW**.

4.4.2 TP1 Sustained Power - Chevrolet Volt

The average value of the sum of engine (zero) and converted battery power in the interval between the 8th and 10th second is **92.91 kW**.

4.4.3 TP2 Peak Power - Chevrolet Volt

TP2 can be performed by measuring power at the dynamometer rollers and adjusting for gearbox efficiency and tire losses.

As previously noted with respect to the Malibu Eco, there are two options for measuring power at the rollers. The dynamometer directly records roller power, but this was not used because it is filtered at an unknown rate. The other option is to compute roller power using dynamometer-recorded torque and estimated wheel speed. While roller speed was not recorded, roller speed can be estimated from vehicle speed and wheel diameter, knowing that the roller diameter is 48 inches. As seen in Figure 20, the latter option yields a slightly higher peak power within the 10 second window of consideration.

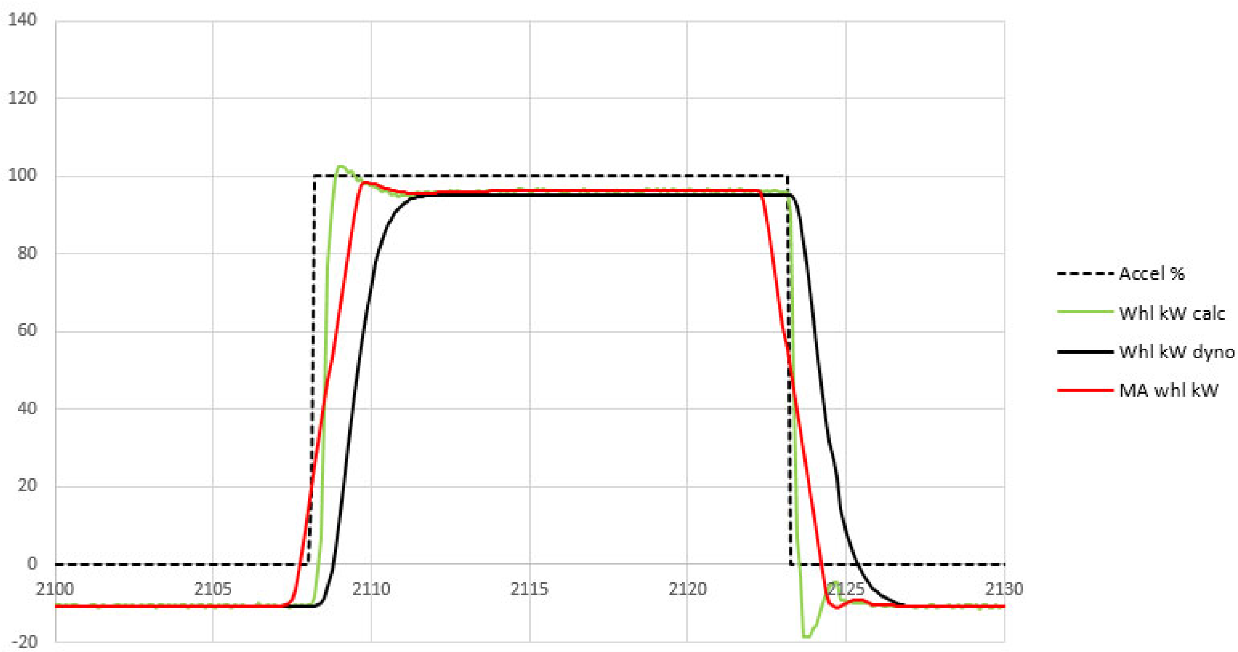

Figure 20. Peak and sustained power, TP2, Chevrolet Volt

During the 10-second interval, the peak value of the 2-second moving average of the roller power is 98.57 kW. This figure was adjusted for tire and bearing losses in the following manner.

The rolling resistance coefficient (RRC) for the Volt tire is not known. However, because the vehicle was tested in 4WD mode, the dynamometer recorded a power drag on the rear roller resulting from the combination of tire rolling resistance and bearing losses of the rear wheels. This makes it possible to estimate an RRC that includes tire and bearing losses.

At 86 kph, the rear roller drag was 1.8 kW. The weight on the rear axle, as tested, was 1704 lb (773 kg). The nominal wheel radius is 0.33414 m (See Volt test report attachment). No wheel slippage is assumed on the rear wheels because they are not driven. At 86 kph the wheel rotational speed would be 11.37857 rev/s.

RRC = rolling force / normal force

Rolling force = roller torque / wheel radius

Roller torque (Nm) = ((1.8 kW)(1000)) / (2*3.1416)(11.37857 rev/s) = 25.17 Nm

Rolling force = 25.17 Nm / wheel radius = 25.17 N / 0.33414 m = 75.35 N (total for both wheels)

75.35 N / (4.44822 N/lb) = 16.94 lb rolling force (total for both wheels)

Normal force = 1704 lb (both wheels)

RRC = 16.94 lb / 1704 lb = 0.009941 (i.e. approximately 0.01)

This RRC was assumed to be applicable to the front tires as well (only the front wheels are powered on the Volt). The weight on the front axle, as tested, was 2465 lb. Assuming RRC = 0.01, the rolling force (including tire and bearing losses) on the two driven wheels together would be:

0.01*(2465) lb = 24.6 lb = 109.6 N

Assuming a wheel radius of 0.33414 m, the rolling force of 109.6 N amounts to a torque of 36.64 Nm. At 87 kph (as measured by the onboard system rather than the dynamometer, to include the speed increase due to any slippage), the rotational speed of the wheel would be 11.51 rev/sec. Tire losses in the two tires therefore amount to:

(36.64 Nm)(11.51 rev/sec)(3.1415927*2)/1000 = 2.65 kW

Adding this power back to the peak wheel power yields the peak axle power:

Axle power = 98.57 kW + 2.65 kW = 101.22 kW

Several K factors may be applicable to the Volt, depending on driving mode. Because the drive unit has a planetary power-split design, it may be appropriate to classify it as a power-split hybrid, with K = 0.93. However, in all-electric mode, the Volt utilizes a relatively simple power path through two fixed gear reductions. This would suggest a series hybrid configuration, for which K = 0.98, may be more appropriate. Assuming K = 0.98, the TP2 result becomes:

101.22 kw / 0.98 = **103.29 kW**

4.4.4 TP2 Sustained Power - Chevrolet Volt

The average value of the roller power in the interval between the 8^{th} and 10^{th} second is 96.33 kW. Adding the 2.65 kW tire losses brings this to 98.98 kW. Dividing by K = 0.98 results in:

98.98 kw / 0.98 = **101.0 kW**

4.4.5 Implied downstream efficiency – Chevrolet Volt

As a check, we calculated the implied downstream efficiency of the powertrain, by comparing the computed TP1 and TP2 sustained power values to the power recorded at the dynamometer rollers (thus representing losses in the transmission, bearings, and tires).

As reported in Section 4.4.4, sustained power at the rollers was measured as 96.33 kW.

According to the sustained power measured by TP1, the implied downstream mechanical efficiency of transmission, bearings and tires is:

96.33 kw / 92.91 kW = **103.7%.**

According to the sustained power measured by TP2, the implied downstream mechanical efficiency of transmission, bearings and tires is:

96.33 kw / 101.0 kW = **95.37%.**

4.4.6 Summary of Results - Chevrolet Volt

Similar calculations were repeated for the second acceleration pulse in the pair of pulses that were performed at 86 kph. The results for both are summarized here.

The results for TP1 and TP2 are shown in Table 3. Again, the difference between TP1 and TP2 is significant. In contrast to the result for the Malibu Eco, where TP2 delivered a lower power than TP1, in the case of the Volt, TP2 delivers a higher power than TP1. The consistency between each pulse is similar to that observed with the Malibu Eco.

Table 3. Peak and sustained power, TP1 and TP2, Chevrolet Volt

	Peak power			**Sustained power**		
	TP1	**TP2**	**Difference**	**TP1**	**TP2**	**Difference**
First pulse	94.31 kW	103.29 kW	+8.98 kW	92.91 kW	101.00 kW	+8.09 kW
Second pulse	93.21 kW	102.31 kW	+9.10 kW	92.67 kW	101.19 kW	+8.51 kW
Difference	-1.10 kW	-0.98 kW		-0.24 kW	+0.18 kW	

It appears that TP1 is delivering a low estimate of power for this vehicle. This is because the power measured at the wheels by the dynamometer is greater than the TP1 power. Normally losses in the transmission and tires would cause the dynamometer power to be the lower of the two values. One possible explanation is that the downstream efficiency from the battery output to the motor output for the Volt is greater than the 85% default efficiency (K = 0.85) assumed by TP1. For example, using K = 0.92 instead of K = 0.85 would change the TP1 value to 100.6 kW, very close to the 101.0 kW of TP2.

The implied downstream efficiency for the power measurements of TP1 and TP2 also varies substantially. The TP1 measurement suggests greater than 100% efficiency, while TP2 suggests 95.4%, similar to the 93.8% for the Malibu Eco.

Table 4. Implied downstream efficiency of transmission, bearings and tires, Chevrolet Volt

	Sustained	
	TP1	**TP2**
First pulse	103.7%	95.4%
Second pulse	104.1%	95.4%

In considering the TP1 result, it should be noted that TP1 normally includes an engine power, but in the case of the Volt, only electric power is present. Therefore, this vehicle provides an opportunity to directly assess the ability of TP1 to account for the electric power component of total power.

As seen in Figure 21, some wheel slippage may have occurred during the acceleration pulses. Before and after each pulse, the speed measured by the dynamometer rolls and the speed measured by the vehicle onboard system are in agreement. However, during each pulse, the speed measured by the vehicle onboard system is about 1 kph higher than the dynamometer speed, indicating slippage. The exact magnitude of the difference is uncertain due to the low resolution of the onboard signal. However, it is likely that some amount of power is being lost to wheel slippage, which would mean that the vehicle is performing more work than reported by the dynamometer roller torque. This would reduce the amount of power reported by TP2.

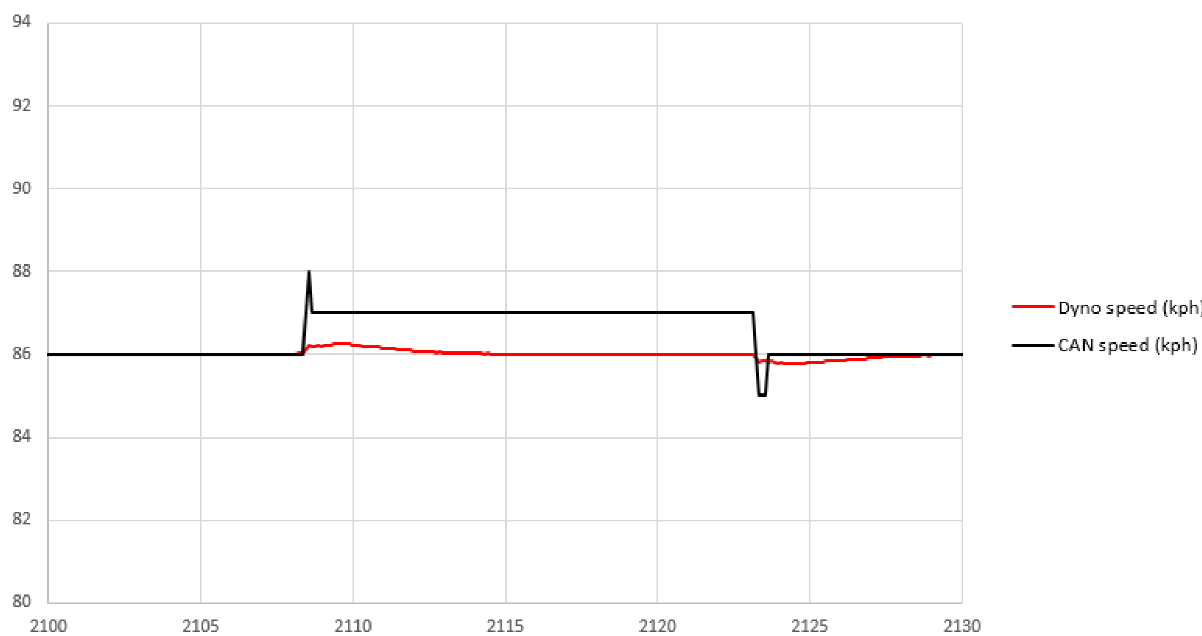

Figure 21. Wheel slippage indicated by measured speed differences, Chevrolet Volt

5. Discussion

5.1 Comparison of TP1 and TP2

For both vehicles, when using the default K factors in the TP1 and TP2 calculations, the comparative results of TP1 and TP2 are quite different, on the order of 8% to 10% apart.

For the Malibu Eco, which is dominated by engine power, TP1 returned a higher value than TP2. However, for the Volt, which was tested in all-electric mode, TP1 delivered a lower value than TP2.

In the case of the Malibu Eco, the validity of the comparison between TP1 and TP2 is uncertain because ISO 1585 or UN Regulation 85 engine test results were not available. However, this does not apply in the case of the Volt.

The TP1 value for the Chevrolet Volt is particularly questionable because it is smaller than the power known to have reached the dynamometer rollers. This might be related to the use of the default K = 0.85, which may be too conservative for this vehicle.

When TP2 is performed using dynamometer roller power instead of wheel torque sensors, tire losses and wheel slippage become included in the measurement and must be accounted for. A small amount of wheel slippage was observed during the tests. Tire losses may be accounted for if the RRC and normal force on the tire can be estimated, but it is uncertain how to account for wheel slippage.

The difference between the result of TP1 and TP2 is very sensitive to the assumed values for the K factor. In theory, if the K factors for the vehicle being tested have been accurately measured and are used in the calculations, TP1 and TP2 should deliver similar results. However, use of the current default values did not lead to similar results for the two vehicles that were tested.

5.2 Repeatability

5.2.1 Repeatability of sequential pulses

Two acceleration pulses were conducted at each speed, with recovery of SOC between each. This supports only a limited assessment of repeatability due to the small number of samples.

Table 1 and Table 3 reported the results for the Malibu and Volt, respectively. The difference between the two pulses performed for each vehicle are repeated in Table 5. Both TP1 and TP2 were reasonably consistent for each of the two pulses, matching within about 1 kW or less.

Table 5. Difference between results of first and second sequential acceleration pulse

	Peak		Sustained	
	TP1	**TP2**	**TP1**	**TP2**
Malibu Eco	-0.69 kW	-1.2 kW	-0.03 kW	-1.16 kW
Chevy Volt	-1.10 kW	-0.98 kW	-0.24 kW	+0.18 kW

5.2.2 Repeatability between test days

Although testing at the speed of maximum power was limited to two sequential pulses on the same day, a limited number of other vehicle speeds were tested on both the first and second test day, providing an opportunity to see if results are repeatable from one day to the next.

For the Malibu Eco, both days included tests at 90 kph and 100 kph. For the Chevrolet Volt, both days included testis at 70 kph and 90 kph. The results were quite consistent between each day, as seen in Table 6 through Table 9.

Table 6. Day to day repeatability, TP1, Malibu Eco, at 90 kph and 100 kph

Malibu Eco TP1	TP1 (Peak)				TP1 (Sustained)			
	Day 1		Day 2		Day 1		Day 2	
	Pulse 1	Pulse 2	Pulse 1	Pulse 2	Pulse 1	Pulse 2	Pulse 1	Pulse 2
90 kph	129.74	129.77	129.80	129.83	129.64	129.62	129.70	129.70
100 kph	98.64	98.78	98.81	98.82	98.43	98.49	98.52	98.55

Table 7. Day to day repeatability, TP2, Malibu Eco, at 90 kph and 100 kph

Malibu Eco TP2	TP2 (Peak)				TP2 (Sustained)			
	Day 1		Day 2		Day 1		Day 2	
	Pulse 1	Pulse 2	Pulse 1	Pulse 2	Pulse 1	Pulse 2	Pulse 1	Pulse 2
90 kph	118.53	117.82	120.60	120.51	118.00	117.60	119.89	119.56
100 kph	92.53	92.66	93.31	92.98	92.20	92.16	92.61	92.55

Table 8. Day to day repeatability, TP1, Chevrolet Volt, at 70 kph and 90 kph

Chevy Volt TP1	TP1 (Peak)				TP1 (Sustained)			
	Day 1		Day 2		Day 1		Day 2	
	Pulse 1	Pulse 2	Pulse 1	Pulse 2	Pulse 1	Pulse 2	Pulse 1	Pulse 2
70 kph	93.96	93.56	93.96	93.77	92.42	92.71	92.75	92.53
90 kph	91.99	91.39	91.56	91.85	91.09	90.50	91.09	91.48

Table 9. Day to day repeatability, TP2, Chevrolet Volt, at 70 kph and 90 kph

Chevy Volt TP2	TP2 (Peak)				TP2 (Sustained)			
	Day 1		Day 2		Day 1		Day 2	
	Pulse 1	Pulse 2	Pulse 1	Pulse 2	Pulse 1	Pulse 2	Pulse 1	Pulse 2
70 kph	100.14	100.41	100.17	100.90	98.95	98.99	99.58	99.74
90 kph	99.89	99.43	99.30	99.44	99.46	99.17	98.70	98.44

5.3 Conditioning cycle

A conditioning cycle of 20 minutes at 60 kph was generally adequate to raise the temperature of the engine coolant and the electrical components to within a normal operating temperature range. However, it was not sufficient to raise the temperature of the transmission oil to the temperature eventually realized during the test procedure. For example, the Malibu Eco transmission oil reached 57C after conditioning (within a normal operating range), but increased further to as high as 100C during later phases of the test (also normal, but higher than at end of conditioning).

As currently written, the test procedure would require that the conditioning cycle be repeated if the transmission oil temperature reaches a higher temperature than at end of initial conditioning. However, it is unlikely that operating at 60 kph for any reasonable amount of time would have reduced the transmission oil temperature back to 57C.

Because TP2 depends on power measured at a point past the transmission, any variability in the operating temperature of the transmission is likely to influence the variability of TP2.

One practical consideration in repeating the conditioning cycle to reduce operating temperature during a test is that it requires switching the dynamometer out of constant speed mode and into road load mode. For many dynamometer systems (as at EPA), this requires shutting down the test, and thus prevents the collection of all test data in a single data file for ease of analysis.

6. Conclusions and Observations

6.1 Speed of maximum power

The test procedure suggests a method for finding the speed of maximum power by cycling through a series of fixed speeds on a dynamometer. No difficulties were encountered in identifying the speed of maximum power by this method. In the case of the Volt, the power curve was very flat, making it more difficult to identify a specific speed. However, because the curve is so flat, any of a number of different speeds may have sufficed.

6.2 Consistency of maximum power at wheels

A fundamental aspect of the test procedure is the expectation that maximum power output can be consistently generated by rapidly pressing the accelerator while the vehicle is running on a dynamometer in constant speed mode. This method produced quite consistent results for each of the vehicles and at each of the speeds tested.

6.3 Inconsistency of TP1 and TP2

TP1 and TP2 show significant discrepancy for the tested vehicles, on the order of about 10 percent.

Directionally, the discrepancy is not consistent between the two vehicles. TP1 computes a higher power than TP2 for the Malibu Eco BAS hybrid, while it computes a lower power for the Chevrolet Volt.

This suggests that the accuracy of TP1 and TP2 may be sensitive to the HEV configuration, or more specifically, on whether the total power is dominated by engine power or by electric power.

6.4 Influence of assumed K factor

The difference between the result of TP1 and TP2 is very sensitive to the assumed values for the K factor. In theory, if the K factors for the vehicle being tested have been accurately measured and are used in the calculations, TP1 and TP2 should deliver similar results. Conversely, the result of TP1 and TP2 may always be expected to differ to the degree that the K factors used in the calculations differ from the actual powertrain efficiencies they represent.

TP1 and TP2 react differently to inaccuracies in K. For TP1, if the motor and inverter have a higher efficiency than the default K = 0.85, but the default value is used in the calculation, the TP1 power rating will be reduced. For TP2, if the gearbox has a higher efficiency than the default value, but the default value is used in the calculation, the TP2 power rating will be inflated.

Because different vehicles are likely to have different component efficiencies, some vehicles will be impacted differently than others by use of the default K. The ability to choose between providing an accurately measured K factor or using the default value could influence the test result.

6.5 Accounting for tire losses in TP2

The test procedure specifies that when TP2 is performed using dynamometer roller torque and speed, tire losses must be accounted for. Wheel slippage is another factor that should be accounted for. The test procedure does not currently specify a method for accounting for either.

For the Chevrolet Volt, data collected from the non-driven rear wheel roller made it possible to estimate an RRC that would represent the losses in the tires (excluding slippage) and wheel bearings. Estimated losses were on the order of 2 to 3 kW.

There is evidence that a small amount of wheel slippage occurred in the tests. The energy consumed was not accounted for and continues to affect the reported TP2 results by an unknown amount.

6.6 TP1 or TP2 in a GTR

The IWG has previously discussed the possibility of selecting either TP1 or TP2 alone for use in the GTR, to reduce variability and the possibility of cherry picking. It seems reasonable to expect that the results of TP1 and TP2 will always be different to some degree, if the K factors used in the calculations differ from the actual efficiencies they represent.

TP1 and TP2 both appeared to provide repeatable results for the vehicles tested. However, TP1 and TP2 varied significantly in magnitude, and in different directions depending on the hybrid architecture. The results from the other validation laboratories will provide a more complete comparison of TP1 and TP2 for other HEV architectures.

It should be noted that the ISO procedure recommends TP2 as an alternative to TP1 when the engine power under TP1 cannot be determined (e.g. because the intake manifold pressure does not agree with ISO 1585 results). Eliminating TP2 would eliminate this option, leaving manufacturer recommendation as the only recourse. However, selecting TP2 alone may impose a burden of more sophisticated hardware (hub dynamometer or wheel torque sensors) and/or a greater variability compared to TP1, if the effect of tire losses and slippage cannot be accurately accounted for.
