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Effects of Ambient Temperature on 2016 Chevrolet Volt Performance and Battery Temperature

Aaron Loiselle-Lapointe[1], Hajo Ribberink[2]

[1]*Environment and Climate Change Canada (corresponding author), 335 River Road, Ottawa Ontario, K1V 1C7, Canada, Aaron.Loiselle@Canada.ca*

[2]*SNatural Resources Canada, 1 Haanel Drive, Ottawa, Ontario, K1A 1M1, Canada, Hajo.Ribberink@Canada.ca*

Summary

Environment and Climate Change Canada and Natural Resources Canada are collaborating to test a 2016 Chevrolet Volt extended range electric vehicle on-road in the winter and summer months in Ottawa, Canada. Testing was conducted solely in EV-mode with SAE J1711 cabin heating settings applied while power measurements of the electric drive train and select CAN signals were recorded. Preliminary results indicate that the similar to a recent 2012 Volt study presented at EVS28 [1], the electric performance of the 2016 Volt powertrain degrades as ambient temperatures decrease, but are improved significantly over its 1st generation predecessor.

Keywords: energy consumption, range, EREV, vehicle performance, BMS

1 Introduction

Since the introduction of the first plug-in hybrid electric vehicles (PHEVs) in the global vehicle market, the number of original equipment manufacturers (OEMs) producing these vehicles and the variety of available PHEV models has multiplied significantly. The impetus for this expanding availability of PHEVs (and extended range electric vehicles – EREVs) is due in part to increasingly stringent emission regulations, including new greenhouse gas limits, around the globe, forcing manufacturers to offer this clean technology to consumers. Monetary upfront incentives, conventional vehicle purchase penalties and the allure of driving petrol-free are some of the motivations propelling consumers to adopt PHEVs worldwide.

In Canada, and in other northern countries, there is concern that cold temperatures will adversely affect the performance of PHEVs, and other xEVs (hybrid electric, PHEVs, EREV and battery electric vehicles), by reducing driving range and requiring precious traction battery energy to be used to heat the cabin of the vehicle. The effects of cold ambient temperatures and driving conditions on older model PHEV performance have been investigated to some extent by government bodies [1 and 2] and fleet operators [3]. To the best of the authors' knowledge, the latest iterations of xEV technology have not been studied to the same extent as previous models [1], in the context of cold ambient temperature effects. The study presented here is a first opportunity for Environment and Climate Change Canada (ECCC) and Natural Resources Canada (NRCan) to conduct a repeat study on a 2nd generation EREV tested on-road. In addition to the comparative nature of this study between the most current generation of an EREV and its predecessor, this study further aims to explore the profiles of the traction battery temperature in relation to driving events, charge events, cold-soaking and ambient temperatures. The test program is structured to include winter and summer on-road testing in Ottawa, Canada, as well as in-lab chassis dynamometer testing at temperatures ranging from -40°C to 40°C. To date, winter on-road testing and summer on-road testing have been conducted. This paper presents the preliminary results from the on-road winter tests.

2 Test Method

The Emissions Research and Measurement Section (ERMS) of Environment and Climate Change Canada (ECCC) conducted on-road tests of the 2016 Volt between the months of January and Marth, 2017 over a prescribed route developed in the City of Ottawa to encompass multiple modes of driving. As in past studies [1] the ERMS and the NRCan collaborated once again to jointly conduct an on-road study on an xEV.

2.1 Test Vehicle Specifications

The 2016 Chevrolet Volt is the test vehicle for this project, as it represents the state-of-the-art in EREV technology available in Canada. The Volt offers 85km of all-electric range and 676km of gasoline range using a 34L fuel tank, virtually eliminating any cause for range-anxiety. A select list of the Volt's specifications is presented in Table 1.

Table 1: 2016 Volt Specifications

Identification		**Motors**	
Make	Chevrolet	Total Motoring Power [**kW**]	110
Model	Volt	Total Generating Power [**kW**]	45
Year	2016	Total Torque [**Nm**]	398
Battery		**Performance**	
Mass [**kg**]	183	Drive	FWD
TMS	Active liquid control	AER [**km**]	85
Cells	192 prismatic	0-60mph Time [**s**]	8.4
Capacity [**kWh**]	18.4	Fuel Consumption [**L/100km**]	5.74
Engine		**Capacities**	
Type	1.5L DOHC I-4 DFI	Curb Weight [**kg**]	1607
Displacement [**cc**]	1490	Generator Cooling [**L**]	7
Max speed [**rpm**]	5600	Battery pack cooling [**L**]	4.25
Max Power [**kW @ rpm**]	75	Power electronics cooling [**L**]	4.8
Fuel	Regular unleaded	Fuel Tank [**L**]	33.7

2.2 Test Fuel

Testing was conducted using North American regulatory-compliant research fuel; Tier 2 gasoline. This fuel was used for all on-road tests, both winter and summer. The primary fuel properties are shown in Table 2. The properties derived from analysis conducted by the Alberta Innovates Technology Futures laboratory on samples from Environment and Climate Change Canada's fuel storage tanks.

Table 2: Test Fuel Specifications

Fuel	**NHV ($MJ \cdot kg^{-1}$)**	**Octane (RON+MON)/2**	**Density ($kg \cdot m^{-3}$)**	**Sulphur (ppm)**	**Fuel Fraction (%)**		
					Carbon	**Oxygen**	**Hydrogen**
Tier 2 Gasoline	43.15	93.2	742	31	86.6	0	13.79

2.3 Instrumentation

On-road tests utilized specialized equipment (portable emission measurement system – PEMS) in order to measure the criteria emission concentrations of CO, THC, NO_x and CO_2, which were converted to emission rates and used to calculate fuel consumption through a carbon balance. This equipment is illustrated in Figure 1, along with the PEMS' auxiliary equipment, which includes an environmental sensor, GPS unit, power inverter, exhaust flow meter (EFM) and a heated line from the EFM to the PEMS unit. Aside from the PEMS related instruments, a HIOKI power analyser, clamp-on amp probes and voltage leads were used to measure electric drivetrain component power flow (described in section 2.3.1). Further, an OBD CAN logger was used to measure otherwise unobtainable signals from the vehicle's electronic control modules (see section 2.3.2). An aftermarket hitch and stainless steel platform were installed to secure a gasoline generator to the rear of the vehicle, which was used to power all instrumentation. The weight of the vehicle, including the equipment and the driver, was measured as 1906 kg, which is 149kg more than the equivalent test weight (ETW) at which the Chevy Volt is tested for certification; this should be considered when interpreting the results of this study.

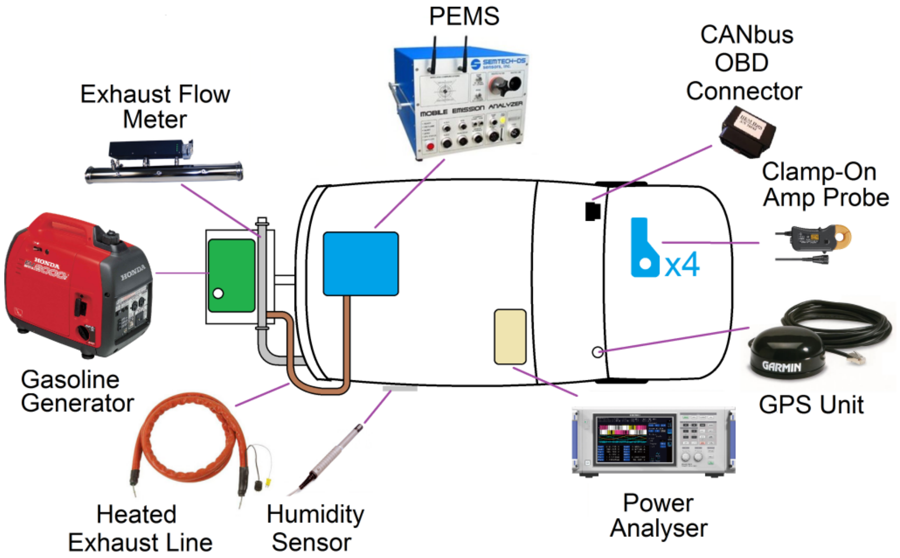

Figure 1: Instrumentation used for On-Road Testing

2.3.1 Power Measurements

Six locations in the Volt's powertrain were measured for amperage and voltage during all tests: namely, (1) between the battery terminals and the high-voltage junction box, (2) from the 12V battery to the accessory load, (3) between the battery and the heater, (4) between the battery and A/C compressor, (5) between the on-board DC charger and the battery terminals, and (6) between the AC grid supply and the Electric Vehicle Supply Equipment (EVSE) (all of which are presented in Figure 2. HIOKI amp probes were used to measure amperage and a HIOKI power analyser was used to process the measured voltage and amperage signals into useful amperage, voltage, power, and energy metrics.

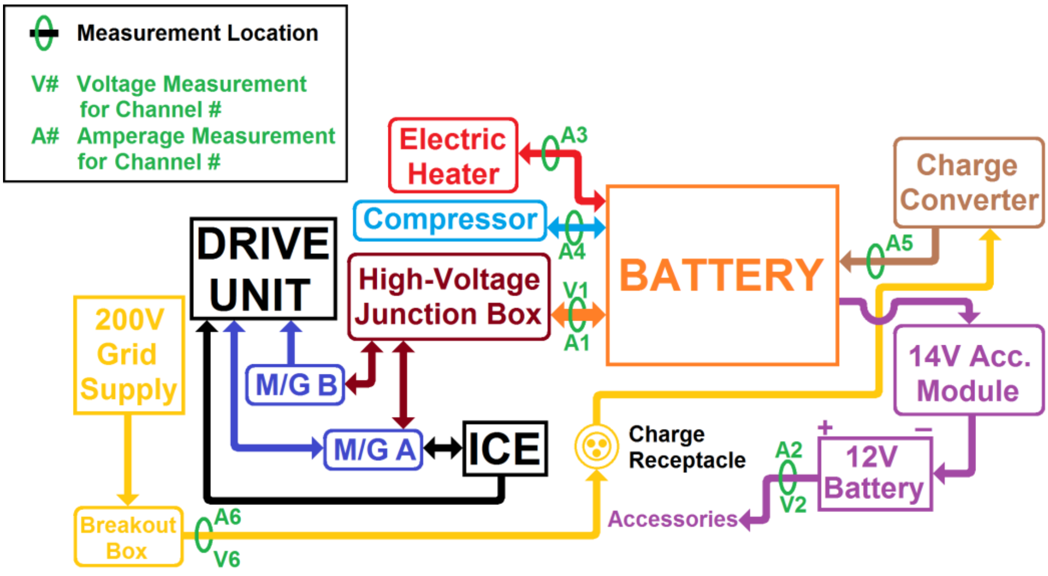

Figure 2: Locations of power measurement sensors along the 2016 Volt powertrain

2.3.2 CAN bus Signals

In order to cross-check other measurements, and to provide information that would otherwise be too resource-intensive to obtain, select CAN bus signals were recorded with the use of an OBD logger, provided by HEM Data Inc. Most of the information from this CAN logger relates to battery performance and temperatures, as measured/calculated by on-board vehicle sensors. The complete list of signals collected during all tests is provided in Table 3. In general, these diagnostic signals were broadcast and collected at a frequency of 1 Hz.

Table 3: CAN signals collected via the diagnostics system of the 2016 Chevy Volt

CAN Signal	Units
Minimum Hybrid/EV Battery Module Temperature	°C
Maximum Hybrid/EV Battery Module Temperature	°C
Engine Torque	Nm
Axle Torque	Nm
Motor 1 Torque Command	Nm
Motor 2 Torque Command	Nm
Drive Motor 1 Speed	rpm
Drive Motor 2 Speed	rpm
Hybrid/EV Battery 1	°C
Hybrid/EV Battery 2	°C
Hybrid/EV Battery 3	°C
Hybrid/EV Battery 4	°C
Hybrid/EV Battery 5	°C
Hybrid/EV Battery 6	°C
Electric A/C Compressor Power Request for Hybrid/EV Battery Pack Cooling	kW
Electric A/C Compressor Power Request for Passenger Compartment Cooling	kW
Hybrid/EV Battery Pack Heater Power Request	kW
Hybrid/EV Battery Pack Coolant Temperature Sensor 1	°C
Hybrid/EV Battery Pack Coolant Temperature Sensor 2	°C
State of Charge	%
HV Battery Temp - Min	°C
HV Battery Temp - Max	°C
Average Hybrid/EV Battery Pack Temperature	°C

2.4 Combination Route

Each EV-mode on-road test commenced at the ERMS premises and concluded upon returning to the laboratory. The on-road route circled through a large portion of the City of Ottawa, covering a total distance of 43km. Five distinct segments were characterized in this route by speed limit, number of lanes, traffic light frequency and congestion. During testing, each segment was separated by bringing the vehicle to a full stop and cycling the key off and back on while the instrumentation was reset. These five segments include Artery-1 (Segment 1), City (Segment 2), Congested (Segment 3), 417Express (Segment 4), and Artery-2 (Segment 5). These sections are shown on the map in Figure 3, and the specifications of each of these sections are listed in Table 4. While most of the metrics in Table 4 are widely understood, kinetic intensity (KI) is a relatively new driving metric. Kinetic intensity is described by O'Keefe et al. (2007) as the "ratio of characteristic acceleration to the square of the vehicle aerodynamic speed" [4]. This parameter, along with average speed and acceleration values, can be used to characterize the drive cycle in question. A driving route with a high KI will generally allow an xEV to more effectively exploit regenerative braking opportunities and favourable driving speeds in order to use significantly less energy than a conventional internal combustion vehicle. Conversely, a driving route with a low KI may not be an ideal duty cycle for operating an xEV, although exceptions exist. [4]

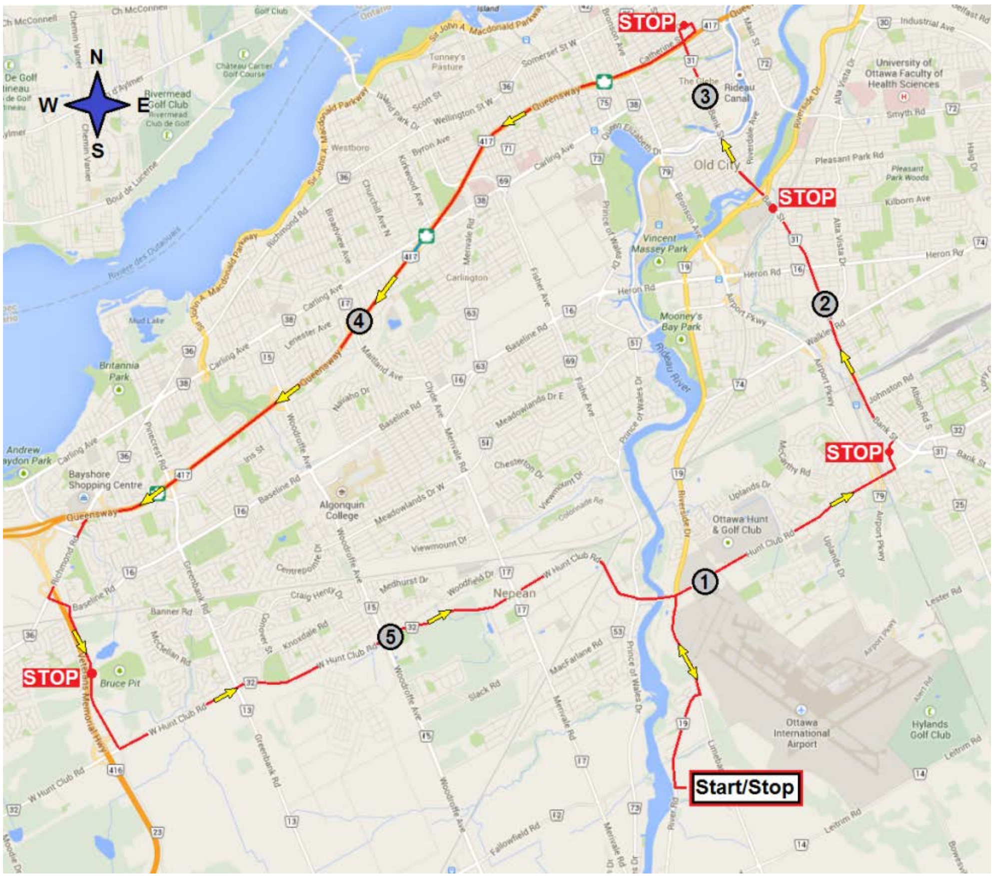

Figure 3: Ottawa, Canada on-road test route for the Chevy Volt

Table 4: On-road route specifications

Segment	Drive Cycle	Average Non-Zero Speed ($m{\cdot}s^{-1}$)	Max Speed ($m{\cdot}s^{-1}$)	Average Accel ($m{\cdot}s^{-2}$)	Max Accel ($m{\cdot}s^{-2}$)	Average Decel ($m{\cdot}s^{-2}$)	Max Decel ($m{\cdot}s^{-2}$)	Kinetic Intensity	Idle Time (s)	% Idling	No. of Idle Periods	Distance (m)	Time (s)
1	Artery-1	12 ± 6.8	23	0.64 ± 0.49	2.3	-0.70 ± 0.57	-2.8	0.64	144	21	6	6680	681
2	City	11 ± 5.2	19	0.67 ± 0.46	2.4	-0.74 ± 0.56	-2.7	1.04	168	26	7	5008	635
3	Congested	8 ± 3.9	15	0.61 ± 0.40	2.0	-0.60 ± 0.43	-2.4	2.04	98	21	6	2634	448
4	417Express	20 ± 9.0	31	0.59 ± 0.42	2.2	-0.64 ± 0.51	-2.9	0.24	116	13	6	15643	920
5	Artery-2	14 ± 7.2	25	0.64 ± 0.52	2.9	-0.66 ± 0.56	-3.1	0.50	173	16	9	12894	1070

3 Results

All test results discussed below pertain to winter on-road tests, which occurred between January 2017 and March 2017, during which the solar radiant conditions were cloudy or snowy. For all tests, cabin heating was set to 22°C with AUTO fan setting and defrost without recirculation. The Chevy Volt was started in EV mode for all tests, and the battery was only depleted during the second loop of the COMBO route during two testing days (January 19 and January 20), for which the ambient temperatures were above 0°C. On the other 5 testing days, the Volt intermittently operated the gasoline engine to support the battery. All tests were conducted by the same driver. The energy metrics discussed below in section 3.1 are from battery-propelled test segments only, unless otherwise noted. Section 3.2 presents results based upon all tests on all seven test days.

3.1 Energy and Range Performance

The energy-related performance of the 2016 Volt was characterized using several metrics, including propulsion-related energy flow, accessory power, and all-electric range. The propulsion energy consumption rate was calculated using the sum of the net energy out of the battery to the high-voltage junction box, divided by the distance travelled for the electric-only driven route segments. The accessory power was calculated by dividing the sum of the non-propulsion energies by the route segment distance. These calculations excluded all tests with gasoline engine use. The percentage of the window sticker all-electric range achieved (all-electric range percent – AER%) was determined by adding up the distance travelled for which the engine RPM and instantaneous fuel consumption were measured as zero from the CAN logger, and diving this distance by the window sticker range of the Volt.

Figure 4 shows the amount of energy consumed by the propulsion system of the 2016 Volt over each of the five segments of the COMBO route. Note that for most segments, multiple repeats were conducted in pure-electric mode only, for which standard deviation bars are displayed. In this same graph, the propulsion energy consumption of the 2012 Volt is also shown, based on previous research presented at EVS28 in 2015 [1]. The same COMBO driving route was used for both programs, except for a small change in segment 2, which increased its distance by 1km in order to ensure a safe environment for the test technicians to reset instrumentation; this change in the segment also included a 155s increase in duration and 100s increase in idle time. As can be observed in Figure 4, the propulsion energy required by the 2016 Volt is on average only 88% of the energy required by the 2012 Volt. These findings are in agreement with Conlon B. et al. (2015), who outlined the new design features of the 2nd generation Volt, such as reduced accessory loads and aerodynamic drag, higher energy density traction battery and a smaller, more advanced transaxle, which collectively increased the EV range by 30%, charge sustaining fuel economy by 11% and generally improved the EV mode performance [5].

Despite this expected improvement in the propulsion system, two other factors should be noted. Between the 2016 Volt study and 2012 Volt study, different test drivers drove the 2016 Volt; and the drive cycle metrics were compared to quantify any differences in the cycle statistics. It was determined that although the 2016 Volt driver was more aggressive during accelerations and decelerations, the average speeds for each segment differed by only 1.7%. Furthermore, the kinetic intensities did not increase in a significant or consistent manner; thus, driver bias was ruled out as a likely reason for the 2016 Volt having lower propulsion energy consumption rates. Secondly, it should be noted that while the 2016 Volt's energy propulsion numbers are derived from multiple repeats (i.e. sample counts), the 2012 Volt tests only yielded one test per section that was conducted purely in electric mode, and thus the comparisons made between the two vehicles cannot be substantiated by a statistical analysis.

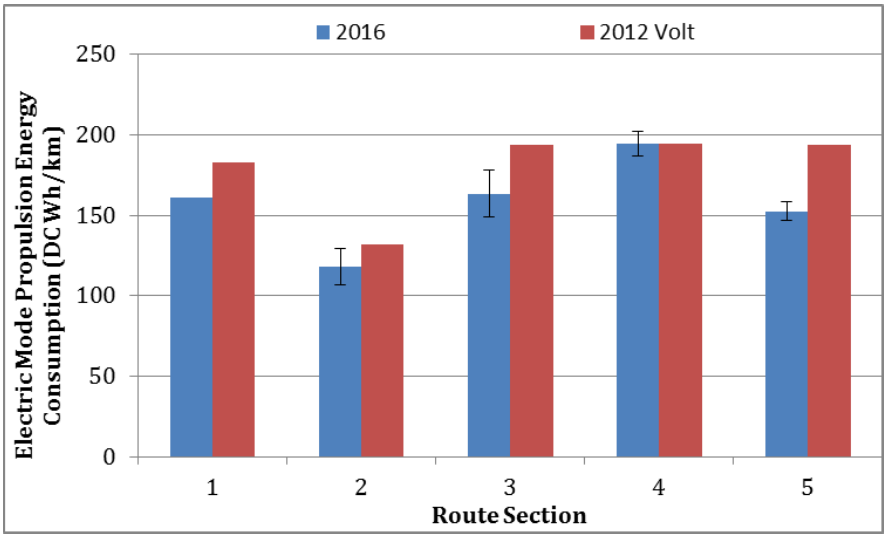

Figure 4: Battery-derived propulsion energy consumption of the 2012 and 2016 Volts over the 5 segments of the COMBO route

Figure 5 presents the average accessory power loads for each segment of the COMBO route during electric-only test segments for the 2012 and 2016 Volts. The ambient temperatures during the test days from which the bar graphs are derived are shown above the corresponding accessory power bars. For both studies, the radiant conditions for all the tests were overcast and/or snowy. While ambient temperature differences, standard deviations, and in some cases, similarity in power rates, exclude conclusive statements concerning the differences in cabin heating effectiveness between the 2012 and 2016 Volts, a power comparison for segment 1 is not convoluted by these variables. The temperature difference in segment 1 between the 2012 and 2016 Volt tests is 0.2°C. The difference in power to the accessories, namely the cabin heating, is more than 2kW. The first test of the day of an electric vehicle at cold or hot temperature will consume the most energy for cabin conditioning (assuming it is used) because the vehicle thermal mass is at a minimum or maximum. The 2kW difference between the 2012 and 2016 Volt warrants further investigation, and will be explored during summer on-road testing.

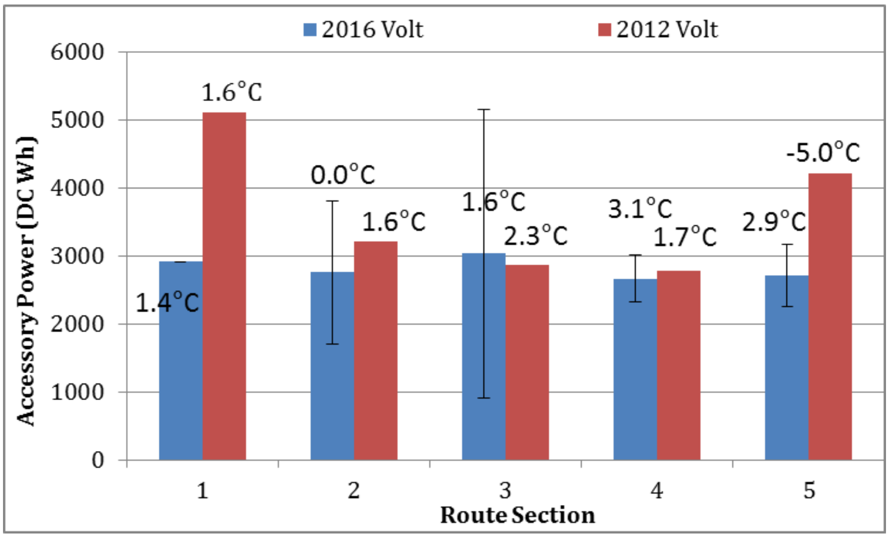

Figure 5: Accessory power usage during all segments of the COMBO route for the 2012 and 2016 Volt

The electric-only distance travelled during each double-loop of the COMBO route was calculated for the 2012 and 2016 Volts and expressed as a normalized metric called the all-electric range percentage (AER%); namely, the total electric-propelled distance travelled for both loops of the COMBO route for a given day divided by the window sticker range for the respective vehicles (56km for the 2012 Volt and 85km for the 2016 Volt). For this analysis all tests were included, regardless if the individual segments making up the tests were battery-propelled or otherwise. These AER% numbers are plotted in Figure 6 against the ambient temperatures of the corresponding test day. As expected, as the ambient temperature decreases, the AER% decreased. The AER% dropped as low as 50% at -11°C for the 2016 Volt. In comparison, the 2012 Volt AER% at -11°C was calculated to be 11%. By normalizing the ranges to the respective sticker ranges of the vehicles, the remaining differences observed in Figure 6 is likely a result of the 2nd generation Volt's battery being allowed to discharge energy at a faster rate and a deeper DoD at cold temperatures more so than the 1st generation Volt.

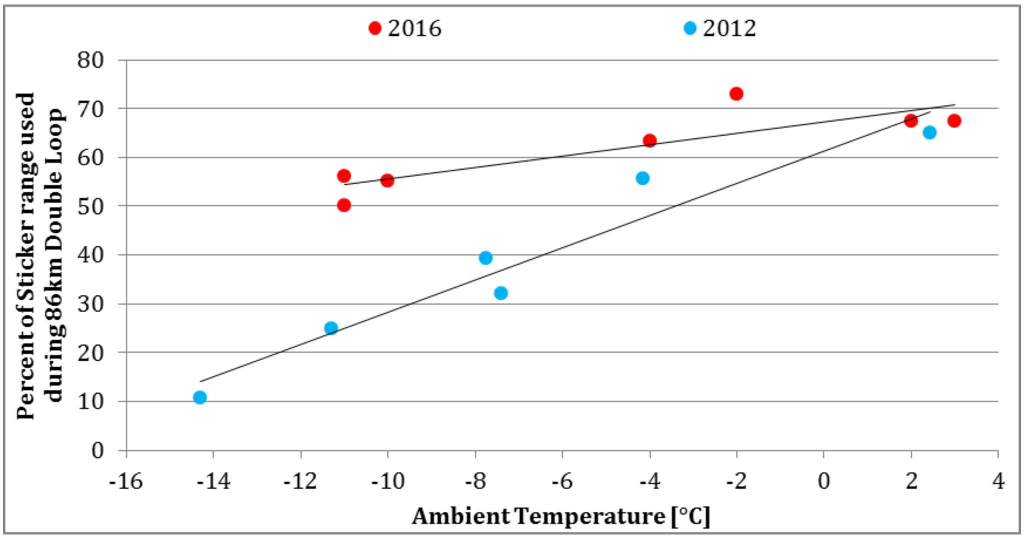

Figure 6: Percentage of the double-loop COMBO route propelled solely by the traction battery for the 2012 and 2016 Volts in relation to their respective sticker ranges at various ambient temperatures

3.2 Battery temperatures

The 2016 Chevrolet Volt's battery is equipped with 6 temperature sensors, which were monitored by the HEM data logger during all tests. Figure 7 displays the location of these sensors.

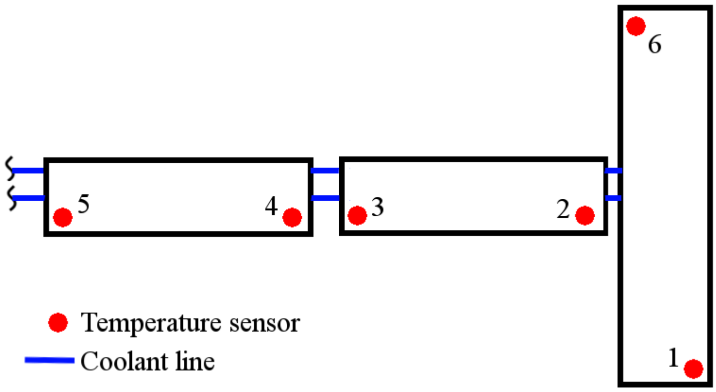

Figure 7: Location of the six temperature sensors of the 2016 Volt battery

The Volt battery did not have a uniform temperature distribution during testing. Figure 8 presents the measured battery temperatures over the first five driving segments on January 20, 2017. The temperature difference between the sensors with the highest and lowest temperatures increased from 2 °C at the start of the test to 7 °C at the end of 5th segment. All test days showed a consistent pattern in battery temperature distribution with Sensor 6 having the highest temperature, Sensors 4, 5 and 6 being close to the calculated average battery temperature, and Sensors 1 and 2 having the lowest temperature. For all testing days, the temperature difference between the sensor with the highest and lowest temperature increased over the 2.5 hour test period to reach a constant value of 7 – 8 °C. In the following graphs, the route segments of the repeat of the COMBO route on each testing day have been named S6, S7, S8, S9, and S10.

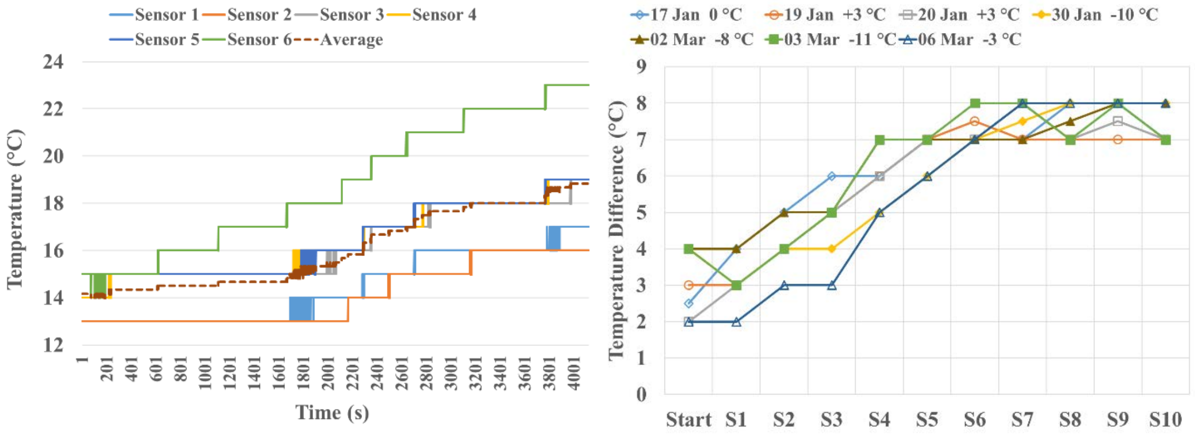

Figure 8: Evolution of the battery temperature over the first five driving segments on January 20 (left) and the difference between highest and lowest battery sensor temperatures over all test days (right)

The battery temperature of the 2016 Chevrolet Volt was influenced by a number of factors. The temperature at the start of the testing days varied significantly due to different ambient conditions, but also due to differences in what happened to the vehicle preceding the test. At the end of each testing day, the Volt would almost immediately be recharged to be ready for the next testing day. The recharge would generally take 5 hours. Then the Volt's battery thermal management system would actively keep the battery temperature at around +4 °C for approximately the next 55 hours. After that, it appears that the battery temperature would be allowed to slowly drop to the ambient temperature. This thermal management of the battery would result in battery temperatures clearly above the ambient for consecutive testing days during winter and battery temperatures closer to the ambient temperature for tests starting on Mondays. Two of the seven test days reported here were Mondays (January 30 and March 6). On these two days the battery temperature was even so low that during the first phase of testing the thermal management system of the Volt actively heated the battery until it reached +1 °C. Finally, there was a clear correlation between the intensity with which the battery was used and the increase of its temperature. It should be noted that during these testing days in January and March, the battery temperatures never reached values high enough to require active battery cooling.

Figure 9 displays the profiles of the average battery temperature for the different testing days and the temperature increase per driving segment.

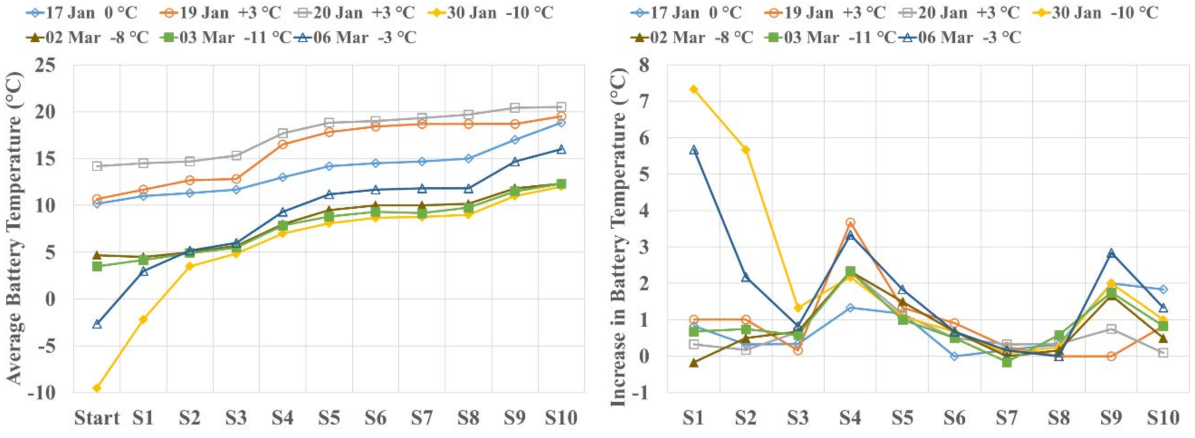

Figure 9: Evolution of average battery temperature over the driving segments (left) and temperature increase of the battery over each driving segment (right). The legend presents the average ambient temperature during testing.

In Figure 10, the increase in average battery temperature per driving segment is compared to the total battery activity over the same segment. The total battery activity is defined as the sum of all power drawn from the battery (for driving, cabin conditioning, or the 12 Volt power systems) and supplied to the battery (from regenerative braking), regardless of the direction of the power flow. Figure 10 displays a clear correlation between the total battery activity and the resulting temperature increase in the battery.

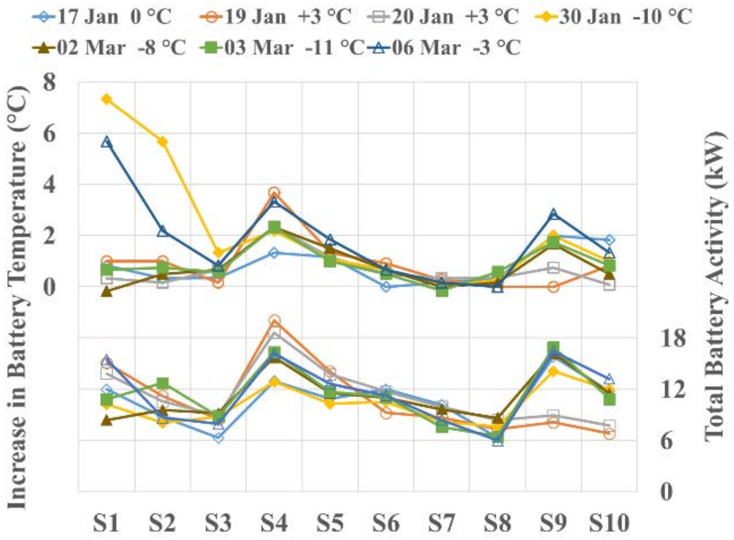

Figure 10: Comparison of Total Battery Activity and temperature increase per driving segment

Figure 9 showed that the temperature increase over the first five driving segments of a test day is generally higher than over the last five segments. This may give the impression that the battery temperature approached equilibrium conditions in comparison to the ambient after the approximately 2.5 hour duration of the total testing. In this equilibrium, the heat generated in the battery due to its internal resistance would balance the heat loss of the warmer battery to the environment. To investigate this further, the temperature difference between the average battery temperature and the ambient temperature was plotted in Figure 11. The results displayed in Figure 11 do not support this hypothesis, as it is clear that on most testing days the temperature difference between battery and environment still significantly increases over Segments 8, 9 and 10 and thermal equilibrium is not yet reached. Figure 11 also indicates that the temperature difference between battery and ambient was consistently higher on the testing days with ambient temperatures around -10 °C.

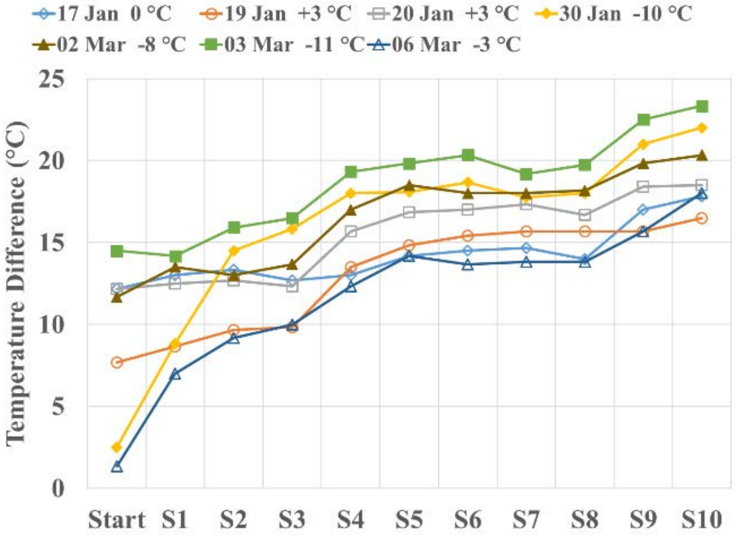

Figure 11: Temperature difference between average battery temperatures and ambient temperature over the testing period

4 Future Work

This study is on-going as of August 2017. Specifically, the on-road summer tests conducted in July 2017 will be post-processed and amalgamated with the winter on-road results, and the 2016 Volt will be tested in-lab on chassis dynamometers. This testing will include multiple ambient temperatures ranging from as low as -40°C to as high as 40°C whilst the Volt is operated in EV mode using the LA4 and US06 drive cycles. This program will provide a comprehensive dataset of performance metrics at 9 unique ambient temperatures representing both mild and extreme weather conditions. Further these tests will provide a high-resolution mapping of battery temperature in relation to ambient temperature, which will be processed by Natural Resources Canada CANMET to fine-tune an existing model of PHEV performance.

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Authors

Aaron Loiselle-Lapointe has 7 years of experience testing electric mobility technologies, both on the road and on chassis dynamometers. Previous to this, Aaron conducted in-use emission and fuel consumption tests on marine and locomotive engines. Aaron has a Masters of Applied Science degree in Environmental Engineering and a Bachelor's of Engineering degree in Aerospace Engineering.

Hajo Ribberink has a M.A.Sc. degree in Applied Physics from Delft University in the Netherlands. He has 25 years of experience in using modelling and simulation to assess new and innovative technologies in the energy field. At Natural Resources Canada, he currently leads CanmetENERGY's research related to integration aspects of electric vehicles and the electrical grid.