CHEVROLET VOLT ON-ROAD TEST PROGRAMS IN CANADA PART 1: EFFECTS OF DRIVE CYCLE, AMBIENT TEMPERATURE AND ACCESSORY USAGE ON ENERGY CONSUMPTION AND ALL-ELECTRIC RANGE

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ABSTRACT—Environment Canada (EC) and Natural Resources Canada (NRCan) separately tested two 2012 Chevrolet Volts between 2013 and 2014 in Ottawa, Ontario on public roads in the summer and winter months using realistic cabin-climate control settings. More than 1300 trips were conducted over nine routes: three city, one congested, two arterial, one highway and two expressway routes. EC tests recorded cabin conditioning, traction battery and 12 V accessory power, select vehicle component temperatures, regulated emission rates and exhaust flow, and DC charge energy. Both NRCan and EC tests measured cumulative electrically driven distance (all-electric range), select CANbus signals and AC grid supply charge energy. Results from these studies were analysed to evaluate the overall performance of the Chevrolet Volt on public roads in climates representative of most of Canada (−27 °C to 37 °C) using realistic accessory settings. At 25 °C the Chevrolet Volt’s on-road all-electric EPA-method adjusted range is generally less than the U.S. EPA sticker rating (57.9 km). Cabin conditioning energy was found to be directly related to the difference between ambient and cabin temperature, except at low temperatures (< 0 °C) when the 1.4 L engine activates to assist the thermal management system. On average, heating the cabin in the winter months consumed significantly more electric energy than cooling the cabin in the summer months. Summer city and highway driving resulted in the lowest energy consumption (Wh/km), while congested and expressway driving cycles resulted in the highest. In the winter months, many differences between the drive cycles were not discernible due to the high cabin conditioning energy consumptions.

KEY WORDS: PHEV, On-road, Range, Energy, Volt

NOMENCLATURE

$D_{cycle/ i}$: distance travelled in a charge depleting test repeat $i$ during which the vehicle was propelled solely by the traction battery energy, km

$E_{12V}$: energy draw measured at the auxiliary battery terminals leading to the 12 V accessory inverter, Wh

$E_{battery}$: energy discharge measured at main traction battery terminals, Wh

$EC_{dc, cycle}$: battery energy consumption for a specific cycle, DC kWh

$ED_{cc, cycle}$: cabin conditioning energy consumed during a specific cycle, DC kWh

$ED_{x, cycle}$: energy consumed by load ‘$x$’, DC kWh

$L_i$: drive cycle repeat count

$t_{cycle}$: duration of a specific cycle, min

$I_{cycle}$: instantaneous amperage reading from load ‘$x$’, A

$V_x$: instantaneous voltage reading from load ‘$x$’, V

$x$: an electric load on the traction battery of the Volt (ex. motor, 12 V accessories, cabin heating and air conditioning compressor)

$P_{TMS}$: power demand from the thermal management system for heating or cooling the cabin, kW

$R_{CC}$: calculated all-electric range using the total battery energy consumed during the test, km

$R_{cycle}$: calculated all-electric range over a specific drive cycle, km

$R_{loss}$: estimated all-electric range lost due to the use of cabin conditioning, km

$R_{no-CC}$: calculated all-electric range using the total battery energy minus the cabin conditioning energy consumed during the test, km

$SOC$: battery state-of-charge, %

$SOC_{start}$: battery state-of-charge at the start of a charge depleting mode test, %

$SOC_{end}$: battery state-of-charge at the start of a charge-sustaining mode, %

$SOC_{start}$: battery state-of-charge at the start of a charge depleting mode test, %
1. INTRODUCTION

National emission and fuel consumption standards are becoming ever more stringent worldwide. Plug-in hybrid electric vehicle (PHEV) sales are one of several critical methods for vehicle manufacturers to meet the next round of emissions and fuel consumption regulations in North America (Brooke, 2012). PHEVs are capable of emitting zero in-use exhaust pollutants and consuming no petrol, but have an internal combustion engine (ICE) to propel the vehicle when the battery is depleted, mitigating range anxiety and increasing the likelihood of consumer acceptance.

Nevertheless, like all vehicles, the performance of a PHEV is not fully captured in compliance tests, which are conducted in an environmentally controlled chamber. As such, PHEV owners may not realize the optimal performance of their vehicle, depending on their driving habits and local environmental conditions. Comprehensive studies have been undertaken to fill gaps in the performance matrix for PHEVs, most by utilizing on-board CANbus data loggers (Douba et al., 2009; Smart et al., 2009). These studies serve to shed light on the performance a consumer can expect from their PHEV during different scenarios, but as yet, there are few published studies (Smart et al., 2009; Allen, 2013) that explore real-world performance of a PHEV in Canadian driving conditions.

In 2013, Natural Resources Canada (NRCan) and Environment Canada (EC) concurrently and independently started testing two 2012 Chevrolet Volts PHEVs in Canadian climate encountered throughout the year. Testing of both vehicles was completed by 2014. While the test methods for both projects were slightly different, many similarities existed. Furthermore, the analysis of the combined results was both suitable and advantageous, due to the increased sample size and more numerous test conditions to analyse.

Any differences in experimental method between the EC and NRCan projects will be noted in the following sections.

Table 1. Specifications of the EC (Volt 1) and NRCan (Volt 2) Chevrolet Volts.

| Parameter          | EC Volt | NRCan Volt |
|--------------------|---------|------------|
| Vehicle name       | Volt 1  | Volt 2     |
| Model year         | 2012    | Same       |
| Modal and trim     | Volt    | Same       |
| Make               | Chevrolet | Same     |
| VIN                | 1G1RA6E45CU103150 | 1G1RA6E41CU100911 |
| Engine             | ECOTEC DOHC I-4 | Same       |
| Power train        | FWD     | Same       |
| Engine size [cm³]  | 1398    | Same       |
| Power [kW@rpm]     | 63@4800 | Same       |
| Speed [rpm]        | 4800 (est.) | Same     |
| Fuel tank volume [L]| 35     | Same       |
| All electric range [km] | 58 (EPA), 40–80 (Manuf.) | Same   |
| GVWR [kg]          | 2053    | Same       |
| Curb weight [kg]   | 1721    | Same       |
| Est. test weight [kg] | 2035 | 1806 (est.) |
| Battery energy [kWh]| 16     | Same       |
| Available modes    | EV, EREV, Hybrid | Same     |
| Drive motor power [kW] | 111    | Same       |
| Generator motor power [kW] | 55     | Same       |
| Odometer at start of program [km] | 7500   | 8000       |
| Odometer at end of program [km]   | 10200  | 18000     |

Due to the volume and breadth of data accumulated from the NRCan and EC studies, two papers have been written. This paper (Paper 1) provides a detailed account of the experimental method and an overall summary of the all-electric range (AER) (i.e. vehicle range for which the Volt was propelled solely by the traction battery energy), discharge energy and energy consumption results in relation to driving pattern, ambient temperature, U.S. Environmental Protection Agency (EPA) sticker range and accessory usage. Paper 2 describes a novel approach to quantifying a gasoline displacement factor based on electricity use, as well as a detailed analysis of the performance of the Volt as a function of ambient temperature, and a comparison of the temperature dependent performance to that of other vehicle technologies. The results from these studies have already been provided to several entities conducting grid impact modelling and may be made available for further distribution upon request.

2. EXPERIMENTAL METHOD

In 2013, EC and NRCan independently undertook concurrent projects to test identical model Chevrolet Volts under Canadian conditions on roads in Ottawa, Ontario. Testing of both vehicles was completed by 2014. While the test methods for both projects were slightly different, many similarities existed. Furthermore, the analysis of the combined results was both suitable and advantageous, due to the increased sample size and more numerous test conditions to analyse.

Any differences in experimental method between the EC and NRCan projects will be noted in the following sections.
2.1. Vehicle Specifications
The specifications of the two Volts are provided in Table 1. Note that the starting odometer readings are quite similar, but the ending odometer readings differ by 7,800 km. This is due to the NRCan Volt (Volt 2) having been driven more extensively in order to fulfill its test matrix.

2.2. Drive Schedules
Volt 1 was tested over 7 different routes, each representing a different driving style and all within close proximity to the EC laboratory. These 7 drive routes include two city routes (City 1 and 2), two primary arterial routes (Artery 1 and 2), one Congested route, one Highway route, and one expressway route (417Express). The 417Express, Artery 1, Artery 2, City 2, and Congested drive cycles were combined into one large test cycle to create the COMBO cycle. The drive cycles for Volt 2 were chosen to maximize repeatability, and consisted of one city route (City 3) and one expressway route (416Express). Using GPS measurements, the average

| Drive cycle | Average Non-zero speed (kph) | St. Dev Non-zero speed (kph) | Max speed (kph) | Average accel (kph/s) | St. Dev accel (kph/s) | Max accel (kph/s) | Average decel (kph/s) | St. Dev decel (kph/s) | Max decel (kph/s) | Kinetic intensity | Idle time (s) | % Idling | No. of idle periods | Distance (km) | Time (min) | Sample count |
|-------------|-----------------------------|-------------------------------|----------------|----------------------|----------------------|------------------|----------------------|----------------------|------------------|-----------------|---------------|----------|---------------------|---------------|------------|--------------|
| 417Express  | 70                          | 31                            | 105             | 1.0                  | 1.0                  | 8                | -2.0                 | 2.0                  | -12              | 0.23            | 99            | 11       | 6                   | 15            | 16        | 12           |
| 416Express  | 1                           | 19                            | 14               | 1                    | -                    | -                | -                   | -                   | -                | -               | -             | -        | -                   | -             | -         | -            |
| Artery 1    | 45                          | 22                            | 75               | 1.6                  | 1.5                  | 7                | -2.1                 | 2.1                  | -11              | 0.70            | 136           | 18       | 6                   | 7             | 13        | 12           |
| Artery 2    | 54                          | 24                            | 87               | 1.5                  | 1.4                  | 7                | -1.8                 | 1.9                  | -9               | 0.47            | 169           | 15       | 7                   | 13            | 19        | 12           |
| City 1      | 44                          | 20                            | 77               | 1.5                  | 1.5                  | 9                | -1.8                 | 2.0                  | -11              | 0.76            | 204           | 13       | 7                   | 16            | 26        | 24           |
| City 2      | 41                          | 18                            | 65               | 1.4                  | 1.5                  | 9                | -1.8                 | 2.0                  | -11              | 0.78            | 64            | 13       | 5                   | 4             | 8         | 12           |
| City 3      | 2                           | 7                             | 48               | 1.7                  | 1.6                  | 9                | -1.9                 | 1.9                  | -12              | 3.45            | 95            | 18       | 8                   | 3             | 9         | 12           |
| Highway     | 65                          | 20                            | 83               | 0.9                  | 1.1                  | 6                | -0.9                 | 1.3                  | -9               | 0.18            | 9             | 1        | 2                   | 10            | 11        | 32           |

Table 4. U.S. Environmental Protection Agency vehicle compliance drive cycle characteristics.

| Drive cycle | Average Non-zero speed (kph) | St. Dev Non-zero speed (kph) | Max speed (kph) | Average accel (kph/s) | St. Dev accel (kph/s) | Max accel (kph/s) | Average decel (kph/s) | St. Dev decel (kph/s) | Max decel (kph/s) | Kinetic intensity | Idle time (s) | % Idling | No. of idle periods | Distance (km) | Time (min) | Sample count |
|-------------|-----------------------------|-------------------------------|----------------|----------------------|----------------------|------------------|----------------------|----------------------|------------------|-----------------|---------------|----------|---------------------|---------------|------------|--------------|
| LA4         | 39                          | 20                            | 91              | 1.8                  | 1.6                  | 5                | -2.1                 | 1.9                  | -5               | 0.80            | 259           | 19       | 17                  | 12            | 23        |              |
| HWFCT       | 78                          | 15                            | 96              | 0.7                  | 0.8                  | 5                | -0.8                 | 1.0                  | -5               | 0.14            | 6             | 1        | 1                   | 17            | 13        |              |
drive cycle characteristics for winter and summer tests are presented in Table 2 and Table 3. Due to limited GPS data from Volt 2 some information is not available for the 416Express and City 3 routes.

The 417Express, 416Express, and Highway routes are characterized by high average speeds. However, the maximum speed for the Highway route is slightly lower than the 417Express (416Express maximum speed was not measured). The Congested route has the lowest average speed, as well as the highest percentage of idle time. The Artery 1 and all City routes have slightly higher average speeds in comparison to the Congested route, as well as less idling. The Artery 2 route is similar to the City routes in terms of average speed and idling time, but with a slightly higher average and maximum speed. The Artery 1 and 2 routes were driven on the same road in Ottawa, but in different sections.

It is interesting to note that for almost all drive cycles the average speed in the winter is higher in comparison to summer. Similarly, the average number of idle periods increased in several summer tests. This is likely a result of increased pedestrian traffic and construction projects in the summer months compared to the winter months.

### 2.3. Test Setup

Because the Volt 1 and Volt 2 projects were conducted independently and without initial collaboration, there were inherent differences in the test setup and procedure used; as listed in Table 5. While both sets of test conditions were meant to emulate those prescribed by the U.S. Environmental Protection Agency (EPA), some differences in testing could not be avoided due to practical considerations. For instance, the vehicle test weight was determined by the collective mass of instrumentation and the passengers. The fan setting was left untouched in order to decrease the number of pre-test and in-test procedures, and ultimately increase consistency between tests (i.e. reduce potential for human error).

Volt 1 was preconditioned 12 – 36 hours before each test by driving it over the intended test route in either charge-sustaining (CS) or charge-depleting (CD) mode. Afterwards, and after all tests, Volt 1 was charged outside without any external pre-warming equipment (except for the protection of on-board instrumentation). Each test began immediately upon starting the vehicle and each repeat of all cycles were separated from the next repeat with a 12 minute soak period. In between each section in a cycle Volt 1 was soaked for approximately 2 minutes, while technicians made notes and reset instrumentation. Testing was aborted in adverse weather conditions (i.e. snow, icy roads and rain). Vehicle temperature settings remained the same throughout both the summer and winter tests at 22°C and a medium fan setting with auto defrost enabled. Test routes were conducted first in CD mode for as many times as required to deplete the battery, and then in CS mode for one full test repeat.

Volt 2 was not preconditioned before a test and was driven 4 km and 12 km away from the NRCan facility before the City 3 and 416Express tests were started, respectively. As such, Volt 2 was at least partially warmed up by the time the City 3 or 416Express test was initiated. The 416Express tests were voided or aborted if the wind speed was high enough to significantly increase the power requirements. Tests were conducted by cold-starting in CD

| Test condition                        | Volt 1                  | Volt 2                  | U.S. EPA                  |
|---------------------------------------|-------------------------|-------------------------|---------------------------|
| Cold-start in CD mode                 | Yes                     | No                      | Yes                       |
| Single-cycle full depletion tests     | City 1 and highway only | No                      | Yes                       |
| Preconditioned with test cycle        | Yes                     | Mostly No               | Yes                       |
| Tests run in all weather conditions   | No (avoided adverse weather) | No (avoided high winds and precipitation) | 25 °C ± 5 °C (no solar load or simulated wind) |
| Accessory temperature settings        | Winter: Auto defrost Medium Fan @ 22 °C | Winter: Auto defrost Auto Fan @ 22 °C | Off                      |
|                                       | Summer: Medium Fan @ 22 °C | Summer: Auto Fan @ 23 °C |
| Drive to route start point            | No (start at facility) | Yes (4 km and 12 km distances) | N/A                       |
| Section-to-section soak duration      | 2 – 3 minutes           | 2 – 3 minutes           | N/A                       |
| Repeat-to-repeat soak duration        | 12 minutes              | 2 – 3 minutes           | LA4: 10 min               |
|                                       |                         |                         | HWFCT: 15 s               |
| Vehicle test weight                   | 2,035 kg                | 1,806 kg est.           | 1,814 kg                  |
| Number of passengers (including driver) | 2                      | 1 or 2                  | 1                         |
mode. Once the battery charge was fully depleted, CS tests were conducted if time permitted. For longer duration tests, the CS mode was tested on a separate day. Charge-sustaining testing of Volt 2 included at least 4 repeats of the City 3 or 416Express routes (unless limited by weather), while CS tests of Volt 1 often only had one repeat of the City 1, City 2, Artery 1, Artery 2, Congested, Highway or 417Express routes. The CD City 3 tests with and without cabin cooling were conducted on the same day on the same charge, while the 416Express tests with cabin cooling were conducted on different days than those without cabin cooling (i.e. using a different charge). Tests conducted without cabin cooling were run on days with ambient temperatures matching those of the test days with cabin cooling.

The Volt 2 was soaked for 2 to 3 minutes in between each repeat test and in between each section of a cycle. Vehicle cabin temperature settings were 22 °C with automatic fan speed during the winter tests and 23 °C with automatic fan speed during summer tests.

2.4. Correlation to the U.S. Federal Test Procedure

2.4.1. Accessory settings and ambient temperatures

The U.S. EPA requires that all vehicle accessories be turned off during compliance testing; except during the supplemental test procedure (STP) SC03 cycle, which includes testing the performance of said vehicle at 35 °C with a solar load of 850 W/m² and air conditioning set to 22 °C. The STP also includes testing the vehicle at –7 °C with the use of cabin heating set at 22 °C. However, the AER of a battery electric vehicle (BEV) or PHEV can be based solely on the test results conducted at 25 °C without the use of vehicle accessories.

While this study was intended to assess the performance of the 2012 Volt at realistic in-use environmental conditions, some summer tests did fit the accessory and ambient temperature settings prescribed by the U.S. EPA. These particular tests were conducted at 25 °C ± 5 °C and the range lost due to any accessory usage during these tests was discounted to allow for a reasonable comparison to the U.S. Department of Energy (DOE) sticker range of 57.9 km (United States Department of Energy and Environmental Protection Agency, 2015).

2.4.2. Drive cycles

The U.S. EPA typically uses the LA4 and highway fuel consumption test (HWFCT) cycles to determine fuel consumption and AER of PHEVs. The characteristics of these drive cycles are shown in Table 4 as a basis of comparison to the on-road drive cycles used in this study. The kinetic intensity, shown in these tables, was determined according to the calculations of O’Keefe et al. (2007) for each on-road test and then averaged over the number of repeats for each test condition. O’Keefe et al. (2007) proposed this metric as a basis of comparing acceleration intensity to aerodynamic speed. Further, a simple comparison was conducted whereby the percent differences between each variable listed in the tables were calculated between the U.S. EPA compliance cycles and the on-road cycles. Based on the kinetic intensity and percent difference calculations, it was determined that the City 1, Artery 1 and City 2 cycles are most similar to the LA4 drive cycle, respectively. The on-road Highway cycle is the most similar to the HWFCT drive schedule, followed by the 417Express.

The U.S. EPA sticker range (AER) for PHEVs, electric range extended vehicles (EREVs) and BEVs is determined by using a weighted average of 70% of the AERs determined for the LA4 and HWFCT test cycles conducted on chassis dynamometers (see Equation (1)).

\[
AER [km] = (0.7 \cdot AER_{LA4}) \cdot 0.55 + (0.7 \cdot AER_{HWFCT}) \cdot 0.45
\]

2.5. Instrumentation and Data Acquisition

Volt 1 was outfitted with a portable emission measurement system (PEMS), high-speed exhaust flow tube, GPS unit and relative humidity sensor, a power analyser and amp probes, a CANbus datalogger, a digital datalogger and a gasoline generator, to supply the electricity demand of the instrumentation (see Figure 1).

Table 6 presents the specifications of the instrumentation (Figure 1) used to measure the parameters in Table 7 during the EC Volt project.

While the EC project (Volt 1) relied heavily on external sensors and instrumentation, the NRCan project (Volt 2) took advantage of the available information from the vehicle dash, a ChargePoint web application, and from a FleetCarma C5 datalogger. The C5 datalogger was programmed to record summary information from each trip.

Figure 1. Instrumentation and equipment for Volt 1 (graphics adopted from (a) Honda Canada, 2015; (b) Sensors Incorporated, 2015; (c) Direct Industry, 2015; (d) Graphtec Corporation, 2015; (e) AutoEnginuity, 2015; (f) HIOKI E.E. Corporation, 2015; (g) OMEGA Engineering Incorporated, 2015; (h) GPSCity, 2015; (i) Fotronic Corporation, 2015; (j) iProcesSmart Incorporated, 2015; (k) Apex Instruments Incorporated, 2015).
Table 6. Specifications of all instrumentation used to test the Volt 1.

| Instrument                              | Manufacturer       | Model                  | Units |
|-----------------------------------------|--------------------|------------------------|-------|
| Portable emission measurement system   | Sensors Inc.       | SEMTECH-DS             | 1     |
| Exhaust flow meter                      | Sensors Inc.       | EFM-HS                 | 1     |
| Ambient temperature & pressure probe    | Vaisala            | HMP 45A                | 1     |
| Global positioning system               | Garmin International Inc. | GPS 16-HVS            | 1     |
| Inverter                                | Sensors Inc.       | SEMTECH P/PS 80        | 1     |
| Generator                               | Honda              | EU2000i                | 1     |
| Power analyser                          | HIOKI              | 3390-10                | 1     |
| Level 2 charger                         | ClipperCreek       | DS100                  | 1     |
| 200A clamp-on probe                     | HIOKI              | 4278                   | 2     |
| 500A clamp-on probe                     | HIOKI              | 9279                   | 2     |
| Voltage/Amperage data logger            | Graphtec           | midi LOGGER GL800      | 1     |
| Thermocouple                            | Omega              | K                      | 3     |
| Thermocouple                            | Omega              | J                      | 2     |
| Frequency transducer                     | Phoenix contact    | MCR-f-UI-DC            | 1     |
| AC-DC converter                         | SOLA               | SCP30 S 24-DN          | 1     |
| Thermocouple                            | Omega              | K                      | 2     |
| Thermocouple                            | Omega              | J                      | 2     |
| Heating pad                             | Philips & Temro Industries | 280-0055            | 4     |
| Temperature/process controller           | Omega              | CN132                  | 2     |
| CANbus decoder                          | AutoEnginuity      | ScanTool               | 1     |

Table 7. Parameters measured during Volt 1 on-road tests.

| Instrument type | CANbus datalogger | Portable emission measurement system | Power analyser | Data logger |
|-----------------|-------------------|--------------------------------------|---------------|-------------|
| Model           | AutoEnginuity     | Sensors SEMTECH-DS and HS-EFM        | HIOKI HiTester 3193 | Graphtec GL800 |

| Measurement frequency | Electric distance (miles) | Drive motor current (A) | Drive motor 1 speed (rpm) | Drive motor 1 temperature (°F) | Drive motor 2 current (A) | Drive motor 2 speed (rpm) | Drive motor 2 temperature (°F) | Engine speed (rpm) | Hybrid/EV battery pack current (A) | Ambient temperature (°C) | Hybrid/EV battery pack SOC (%) | Vehicle speed (mile·hr⁻¹) | Engine speed (rpm) | Ambient pressure (mbar) | Exhaust flow (scfM) | Exhaust temperature (°C) | Exhaust relative humidity (%) | Position (Degree latitude and longitude) | Altitude (m) | Ground speed (mile·hr⁻¹) |
|----------------------|-------------------------|-------------------------|---------------------------|-------------------------------|--------------------------|--------------------------|-----------------------------|---------------------|-----------------------------|--------------------------|----------------------------|--------------------------|-------------------------|-------------------------|------------------------|--------------------------|----------------------------|----------------------|------------------------|
(a trip is defined as the duration between the initiation and shutdown of vehicle CANbus systems). Table 8 lists the parameters measured for the NRCan Volt tests by each of these data sources.

### 2.6. Test Matrix

Table 9 presents the test matrix for Volt 1 and Volt 2 CD tests conducted with and without accessory usage. Although tests have been categorized as either winter, summer or spring/fall, the tests presented in this paper were conducted at a range of ambient temperatures, with summer test temperatures varying between 17 °C and 37 °C, and winter test temperatures varying between –27 °C and 12 °C. Volt 1 tests were aimed at capturing summer versus winter data, while Volt 2 testing was designed to capture all temperatures experienced in Eastern Ontario during a given year.

### 3. CALCULATIONS

Because different instrumentation was used to measure distance travelled and battery (as well as components) energy usage, different calculation methods were employed to arrive at the final products, i.e. AER of a specific cycle \(R_{\text{cycle}}\), useable battery energy \(UBE\), DC discharge energy \(Edc_{\text{cy cle}}\) and DC energy consumption for a specific cycle \(ECdc_{\text{cy cle}}\). The following sections detail the fundamental calculation steps used to arrive at these final products for each vehicle’s tests.

#### 3.1. Volt 1

Volt 1 DC energy discharge \(Edc_x\) of different electrical loads \(x\) was calculated from external instrumentation measuring the voltage \(V_x\) and current \(I_x\) of each of these loads, as shown in Equation (2).

\[
Edc_x [\text{Wh}] = \sum_{z=1}^{n} I_x z \cdot V_x z \cdot (t_z - t_{z-1})
\]  

In Equation (2), \(x\) is the battery, air conditioning compressor, 12 V accessory draw, electric heater, AC grid supply or DC charge received by the battery; \(z\) is any given test measurement; and \(n\) is the total number of data points recorded by the HIOKI power analyser for a given test. The DC battery energy discharged for a given repeat cycle \(i\) in a test was calculated using Equation (3).

\[
Edc_{\text{cycle }i} [\text{Wh}] = E_{\text{battery}} + E_{\text{12V}}
\]  

Where \(i\) is the cycle repeat number for any given test; \(E_{\text{battery}}\) is the energy discharged at the primary battery terminals; and \(E_{\text{12V}}\) is the energy draw measured at the secondary battery terminals leading to the 12 V inverter. The UBE for a specific cycle was then estimated as the sum of all \(Edc_{\text{cycle }i}\):

\[
UBE [\text{kWh}] = \sum_{i=1}^{n} Edc_i
\]  

Where \(n\) is the total number of cycles driven for a given test.
CD mode test and includes mixed test (i.e. CD and CS mode in the same test during transition to CS mode) energy discharge, but only from the portion of the test that is in CD mode. Note that the cycle is not specified because many Volt 1 tests included multiple drive cycles in a single repeat (i.e. COMBO drive cycle – see Section 2.2).

The $EC_{dc,cyle,i}$ of a specific cycle in a test was calculated using Equation (5).

$$EC_{dc,cyle,i} \ [Wh/km] = \frac{\sum_{i}^n Edc_{cycle,i}}{\sum_{i}^n D_{cycle,i}} \ (5)$$

Where $D_{cycle,i}$ is the all-electric distance (km) travelled during repeat $i$ of a specific cycle in a test. For instance, if the total cycle distance was 10 km, but only 8 km were electrically propelled, $D_{cycle,i}$ would be 8 km. Again, transition cycles between CD and CS mode were included in this calculation.

Volt 1 measured distance travelled using a high accuracy GPS unit in conjunction with a Sensors Inc. PEMS. Some Volt 1 drive cycles (City 2, Artery 1, Artery 2, 417Express and Congested) were part of the multi-cycle drive cycle (COMBO) and thus the UBE was found from summing the $Edc_{cycle,i}$ values from all cycles in the COMBO test. For these tests, the cycle AER ($R_{cycle}$) was estimated as shown in Equation (6).

$$R_{cycle} \ [km] = \frac{UBE}{EC_{dc,cyle,i}} \ (6)$$

For single-cycle full-depletion tests the sum of the distance travelled with the Volt in its ‘electric mode’ for the CD mode portion of the day’s tests was equated to the cycle AER.

Finally, fuel consumption was calculated using gaseous concentration measurements of THC, CO, CO$_2$, as well as exhaust flow rate and ambient conditions. Fundamentally, the equation is based on a carbon balance between the air mass entering the engine versus the exhaust mass exiting the tailpipe. The series of equations to arrive at the final fuel consumption for each test were taken from the U.S. Code of Federal Regulations Title 40 Part 600 (40CFR§600) (United States Government Publishing Office, 2015).

3.2. Volt 2

The Volt 2 was driven to the start point of any given test while in ‘electric mode’ (no option existed to switch between ‘electric mode’ (i.e. charge depleting – CD) and ‘hybrid mode’ (i.e. charge sustaining – CS) with the 2012 model), thus partially depleting the battery from a full charge. As such, the calculations described herein extrapolate from the data collected to estimate overall energy consumption, UBE and AER for the given drive route (i.e. 416Express or City 3).

$Edc_{cycle,i}$ was recorded directly from the C5 datalogger and reported to a summary file from a web based portal. $EC_{dc,cyle}$ was then calculated using the same method as applied to Volt 1 (Equation (5)). The UBE was estimated using the starting battery state-of-charge (SOC) value from the first repeat of the test (SOC$_{start}$) and the ending SOC value from the last full-electric repeat cycle in the test (SOC$_{end}$).

$$UBE \ [kWh] = \frac{\sum_{i}^n Edc_{cycle,i}}{SOC_{start} - SOC_{end}} \times 100 \ % \ (7)$$

The AER was then found as the division of the $UBE$ by the battery energy consumption determined for the given cycle.

$$R_{cycle} \ [km] = \frac{UBE}{EC_{dc,cyle}} \ (8)$$

The fuel consumption for Volt 2 was determined using the FleetCarma C5 datalogger, which reported the overall fuel volume (litres) consumed per trip, as well as the total distance travelled per trip. The all-electric distance was recorded from the Volt’s dash.

4. RESULTS AND DISCUSSION

4.1. Driving Patterns and Ambient Temperatures

Although there are a myriad of ‘City’ type driving patterns, compliance test procedures use a standard ‘City’ driving route (ex. LA4, NEDC, JC08) to evaluate a vehicle over that type of driving for repeatability, consistency, comparability and practical reasons. This study employed 3 different city routes, 2 arterial routes, 2 express routes (416Express and 417Express), one Highway route and one Congested route to evaluate the performance of the 2012 Volt in different driving scenarios.

4.1.1. Effects of driving patterns

Table 10 presents the averages and standard deviations of $EC_{dc,cyle}$ and $R_{cycle}$ for each cycle completed in the summer and winter seasons with the effects of cabin conditioning discounted. The averages are taken across the breadth of ambient temperatures encountered during each driving route. Note that NA refers to $EC_{dc}$ values for which only 1 test was completed, and that a short dash (−) signifies that no data for this test condition exists.

Complementing Table 10, Figure 2 presents the average $EC_{dc}$ values, along with shaded rectangles representing the maximum and minimum ambient temperatures and $EC_{dc}$ values measured during each drive route during the summer season tests. Despite the ambient temperature varying in the summer months by up to 18 °C within a single set of driving route repeat tests, the standard deviation for all the average $EC_{dc}$ values remain below a coefficient of variation of 6 %. ANOVA tests were conducted between each set of drive cycle repeats for the summer $EC_{dc}$ values.
with the effects of cabin conditioning discounted, and using a p-value of 0.05. The results of this analysis are presented in Table 11. Interestingly, most drive cycle comparisons resulted in statistically significantly different ECdc values, even between variants of the same drive patterns (i.e. City 1, 2 and 3). This serves to highlight how difficult it is to develop all-encompassing drive cycles for compliance test procedures, but also how repeatable these particular tests are, despite the large ambient temperature flux in each set of cycle repeats.

The Winter ECdc values could not be statistically analysed due to the very low sample count of tests that met the following conditions:

- ICE remains off during entire test
- Conducted in CD mode
- Test conducted without cabin conditioning or such that cabin conditioning discharge energy can be subtracted from the total discharge energy

4.1.2. Effects of ambient temperature

The effects that ambient temperature has on electric drivetrains are complicated when an internal combustion engine is integrated into the electric drivetrain; i.e. PHEV and EREV drivetrains.

Figure 3 presents the entire dataset of cabin conditioned CD mode tests conducted on Volt 1 and Volt 2, as well as CD mode tests for which the ICE was active (for the sake of simplicity hereinafter referred to as CD+CS mode tests). In this chart, for the ‘No Cabin Conditioning’ mode tests, any cabin conditioning energy was subtracted from the calculation of Edc cycle.

When the effects of cabin conditioning and ICE activity are removed (i.e. CD – No Cabin Conditioning curve), the effects of ambient temperature on the Volt’s energy consumption can be observed. While ECdc does decrease to a minimum value at the higher ambient temperatures (> 30 °C), it increases non-linearly as ambient temperature drops. Conversely, the CD – Cabin Conditioning ECdc...
reaches a minimum at around 26 °C, when cabin conditioning energy demand is near its lowest, and increases sharply at higher (> 30 °C) and low (< 0 °C) temperatures when cabin conditioning energy demand increases substantially.

The CD tests with ICE activity (CD+CS tests) present a different story. When cabin conditioning energy is included in the calculation of $EC_{dc}$ for the CD+CS – Cabin Conditioning series the overall result is a scattered plot of $EC_{dc}$ at low ambient temperatures and generally high energy consumption values. When the effects of cabin conditioning are removed (CD+CS – No Cabin Conditioning series) the contribution of the engine to powering the Volt at low temperatures can be observed. The overall $EC_{dc}$ values are lower than those at > 20 °C, indicating that the ICE is contributing most of the power to the Volt, while the traction battery is providing most, if not all, of the cabin heating power. The former assertion is substantiated by Figure 4, which presents the calculated fuel consumption rates of the ICE for all CD mode tests at the ambient temperatures for which their respective tests were conducted.

The calculated ranges corresponding to the $EC_{dc}$ values of the CD – No Cabin Conditioning series in Figure 3 were used to calculate the ranges for each test shown in Figure 5. As expected, without the influence of cabin conditioning or ICE activity, the range of the Volt decreases linearly with decreasing ambient temperature. The maximum calculated range of the Volt without cabin conditioning is 103 km at 27 °C and the minimum is 41 km at – 5 °C.

Figure 6 presents a slightly different story. The ranges shown in Figure 6 are for the CD – Cabin Conditioning tests and are categorized by drive cycle. In comparison to Figure 5 the effects of ambient temperature are exaggerated in Figure 6, due to the added effects of cabin conditioning at extreme temperatures. In general, the maximum AER was realised for each drive route at between 18 °C and 30 °C. The overall maximum AER when using cabin conditioning (95.1 km during a City 2 test) was achieved at 18 °C and the minimum AER (27.5 km during an Arterial 2 test) occurred at – 6 °C.

4.2. Comparison to U.S. EPA Certification Tests

Table 12 compares AER combinations from on-road city and highway tests that were conducted at 25 °C ± 5 °C to the U.S. EPA determined AER for the 2012 Volt (57.9 km) (United States Department of Energy and Environmental Protection Agency, 2015). The AER combinations of on-road drive cycles were determined using Equation (1), except that the LA4 AER was replaced by the first cycle shown in Table 12 (ex. City 1, City 2, City 3 or Artery 1) and the HWFCT AER was replaced by the Highway drive cycle. Note that outside this section only the unadjusted ranges are discussed and presented.

It is worth renoting that the U.S. EPA requires vehicle manufacturers to submit the AERs of at least the LA4 and HWFCT drive cycles. The AERs are determined by operating the vehicle on the chassis dynamometer over one drive cycle repeatedly and consecutively, until the vehicle’s engine turns on. An option exists to also test the same vehicle over three supplementary test cycles; if this is done, the AER is determined using Equation (1), except instead of the 0.7 factor for the LA4 and HWFCT, an adjustment factor is calculated using the total (i.e. gasoline + electric)
Table 12. Combined all-electric EPA method adjusted ranges from different on-road drive cycles compared to the U.S. DOE all-electric range.

| City and highway cycle combinations | Amb temp (°C) | Calculated AER (km) | % Change from U.S. DOE range |
|-------------------------------------|---------------|---------------------|----------------------------|
| City 1 + Highway 26 & 25            | 26            | 53                  | −6                         |
| City 2 + Highway 24 & 25            | 24            | 63                  | 12                         |
| City 3 + Highway 26 & 25            | 26            | 50                  | −11                        |
| Artery 1 + Highway 28 & 25          | 28            | 52                  | −8                         |

4.3. Cabin Conditioning

The power demand from the thermal management system (TMS) for cabin conditioning \( P_{TMS} \) was calculated for Volt 1 using the measured cabin conditioning energy discharge per test \( Edc_{TMS, cd} \), and using the cycle time \( t_{cycle} \), as shown in Equation (9).

\[
P_{TMS} \ [kW] = \frac{Edc_{TMS, cd}}{t_{cycle}} \times \frac{60 \text{ min}}{\text{hr}}
\]  

(9)

The cabin conditioning power demand is shown for all CD mode Volt 1 tests in Figure 7. Note that any tests for which there was ICE activity were not included in the dataset presented in Figure 7, as the engine activity reduced the electric motor and heater load, thus misrepresenting electric-only battery activity and behaviour at cold temperatures.

As expected, the cabin conditioning power is at a minimum at approximately 20 °C (cabin set temperature was 22 °C) and increases linearly at an approximate rate of 53 W/°C \((R^2 = 0.71)\) as ambient temperature increases. As ambient temperature decreases, power demand increases at a rate of approximately 117 W/°C \((R^2 = 0.34)\). The low \( R^2 \) value can be attributed to several factors. Firstly, at these low temperatures, a very sunny day can provide significant radiative heat to the various heat loads of the Volt, thus lowering the delta temperature for the cabin conditioner to manage. Unfortunately, at the time of this study both NRCan and EC did not have the equipment to measure this radiative energy (direct insolation). Secondly, the data points in Figure 7 include all drive cycles, and cabin conditioning power demand was found in this study to be partially affected by driving patterns. Finally, at temperatures below 0 °C there are only 3 data points, thus reducing confidence in the observed trends at those temperatures.

The overall maximum power demand from the electric heater and air conditioning compressor during electric-only charge depleting tests are 4.3 kW (at 1.6 °C during the Artery 1) and 1.4 kW (at 36 °C during the City 1 cycle), respectively.

The estimated range lost due to cabin conditioning \( R_{est} \) was calculated using Equation (10).

\[
R_{est, cycle} \ [km] = R_{CC, cycle} - R_{CC, no-CC, cycle}
\]  

(10)

\( R_{CC} \) and \( R_{CC, no-CC} \) are the calculated AERs of Volt 1 over the same cycle and test, where \( CC \) represents cabin conditioning. The calculations for \( R_{CC} \) and \( R_{CC, no-CC} \) are shown in Equations (11) and (12), where \( Edc_{TMS, cd} \) is the energy consumption of the TMS during a cycle.

Figure 8 presents the calculated losses in AER for each test. The maximum loss in range due to cabin heating is 29 km (at 2 °C) while for cabin cooling the maximum range loss is 19 km at 36 °C. The overall minimum loss in range...
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(1 km) occurs at 19 °C. For ambient temperatures greater than 18 °C a linear trend is observed in the increase in lost AER due to cabin cooling.

For temperatures between –10 °C and 12 °C a more scattered pattern is observed between decreasing ambient temperature and increasing lost range due to cabin conditioning. The likely factors for this are discussed above for Figure 7.

5. CONCLUSION

In general, the tests from this on-road study are highly repeatable per season, despite the large ambient temperature flux within each drive cycle dataset and the extraneous variables encountered during testing (ex. traffic, pedestrians and construction). The exceptions to this observation are tests for which ICE activity was measured during CD tests. The ICE operating characteristics for these tests were not repeatable, likely due to the complex nature of the Volt’s electronic control module (ECM). This highlights the great difficulty vehicle test facilities encounter in accurately determining a PHEV’s (or EREV’s) AER during chassis dynamometer tests if modal measurements of the ICE activity are not possible. At which point does the vehicle switch from ‘hybrid mode’ to ‘electric mode’ during the test? How many kilometres, cumulatively, did the engine participate in powering the vehicle? These questions can only be answered accurately with the use of substantial instrumentation, or more practically, by utilizing CANbus signals from the vehicle’s ECM.

The effects of drive cycle characteristics on energy consumption and range were determined to be very strong, despite ambient temperature flux per season not being removed from the datasets. Specifically, all three variants of the City drive cycle were found to produce statistically significantly different $EC_{cd\_cycle}$ and $R_{cycle}$ values. This observation illustrates how difficult it is to develop ‘all-encompassing’ drive cycles, for use in compliance test procedures, or otherwise.

In comparing the combined on-road city and highway ranges of the 2012 Volt from this study to the U.S. DOE stated range for the Volt, it was found that, in general, the U.S. EPA sticker range exceeded the on-road study AERs when they were adjusted using the EPA method. Specifically, The U.S. EPA sticker AER of 57.9 km was between 12 % lower and 11 % higher than the EPA-method adjusted AERs of the on-road city/highway route combinations shown in this paper.

The results from this study indicate that even at the highest ambient temperature tested (36 °C), without accounting for the effects of cabin conditioning, $EC_{cd\_cycle}$ had not reached a minimum value. At approximately 0 °C and below the Volt intermittently utilised the ICE, despite being in CD mode, while for tests above approximately 0 °C, the ICE was never activated during CD tests. Without accounting for the effects of cabin conditioning, the minimum unadjusted range of 41 km was reached at –5 °C while the maximum unadjusted range of 103 km was achieved at 27 °C (drive patterns could not be isolated from this analysis). When cabin conditioning effects are not removed, the maximum range was achieved for each tested drive cycle between 18 °C and 30 °C.

Although ambient temperature and drive cycle characteristics play a role in determining the performance of the Volt, cabin conditioning utilization has the largest effect on energy consumption and AER. At approximately 19 °C, cabin conditioning energy is at a minimum and increases linearly for cabin cooling at 53 W per °C increase, while increasing from 12 °C at a rate of 117 W per °C decrease for cabin heating. The maximum power draws for cabin conditioning are 1.4 kW at 36 °C and 4.3 kW at 1.6 °C. The maximum loss in unadjusted range due to cabin heating is 29 km (at 2 °C), while 19 km in range is lost at 36 °C due to cabin cooling.

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