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Electric Vehicles: Impacts of Mileage Accumulation and Fast Charging

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Abstract

The impact of mileage accumulation and fast charging on driving range and battery energy of a light-duty battery electric vehicle (BEV), commercially available in North America, is being investigated. Two identical model BEVs are undergoing mileage accumulation on-road in Ottawa, Canada as well as testing on a chassis dynamometer in accordance with the SAE J1634 recommended test procedures. BEV1 is charged exclusively on DC fast-charging (DCFC) and BEV2 is charged exclusively on SAE AC Level 2 (ACL2). At the time of writing, the BEVs have been tested initially at 1,600 km, and then again after mileage accumulation to 15,000 km. Baseline results indicate that the two BEVs had a similar initial performance, and after 15,000 km the vehicles continue to have a similar driving range and useable battery energy despite the different charging methods. Both vehicles did, however, show decreased useable battery energy and recharge energy after 15,000 km of mileage accumulation and the resulting decrease in driving range varied between 0.4 and 13% depending on test conditions; these changes were not always statistically significant. Further testing is planned at approximately 15,000 km intervals up to 105,000 km. The next round of testing, at 34,000 km, will follow mileage accumulation at cold temperature, during an Ottawa, Canada winter.

Keywords: Battery Electric Vehicle, Range, Mileage, Fast Charging

1 Introduction

Battery electric vehicles have the potential to significantly reduce urban air pollution as well as greenhouse gas (GHG) emissions depending on the source of the electricity supply [1]. Manufacturers have significantly increased the number of BEVs available for sale in North America in recent years. Purchase incentives in various Canadian and U.S. jurisdictions have facilitated consumer adoption [2, 3, 4, 5, 6 and 7]. As BEVs become more widely available in the U.S. and Canada, it is important to quantify the effects of battery aging and degradation on energy consumption and range. Considering the wide range of ambient temperatures experienced regionally in North America, it is also important to determine the effects of seasonal operation and accessory usage patterns.

Vehicle grade Li-ion battery pack technology is continually developing, but even in its infancy OEMs offering this technology were willing to provide warranties on the battery packs of up to 160,000km or 8 years. To OEMs, this commitment represented a risk of between $18,000 USD [8] and $40,000 USD [9], and this shows that OEMs must be reasonably confident in their ability to satisfy consumer expectations with respect to battery durability. It is worth considering, however, that changes in driving range or energy performance may not always be obvious to consumers.

Previous research has shown a 25-40% loss in battery capacity and a driving range reduction of 19-34% within 80,000 km of mileage accumulation in a hot climate [10]. The greatest impact occurred with the use of DCFC compared to SAE AC level 2 (ACL2) charging [10]. In contrast, the current study investigates the impacts of mileage accumulation and DCFC in cold weather climate conditions.

2 Experimental Method

Two 2015 model year BEVs were tested in-lab at odometer reading of 1,600 km and 15,000 km on chassis dynamometers. During accumulation, BEV1 was charged exclusively on DCFC, and BEV2 was charged exclusively on ACL2. During chassis dynamometer tests, both BEVs were charged on ACL2 because the test facility is not equipped with a DCFC station. Both BEVs were mileage accumulated and tested concurrently and/or within a two week time period to ensure that they were exposed to similar seasonal climates.

Round 1 of the in-lab testing was extensive, in order to capture a full perspective of the BEVs' performance at the baseline condition. Round 2 in-lab testing was conducted less extensively (i.e. excludes cold-temperature testing) in order to expedite the project schedule. Rounds 3 to 7 will be conducted likewise, while Round 8 testing will emulate the baseline testing, to allow a more complete comparison of the performance of the two BEVs between the start and end of the program.

2.1 Vehicle Specifications and Dynamometer Loading

The specifications of the two BEVs are provided in Table 1. During in-lab testing, road load was simulated using a chassis dynamometer. Target coast down coefficients from U.S. EPA Certified Vehicle Test Result Report Data [7] were used to derive dynamometer-specific set coefficients using the SAE J1263 recommended practice [11]. The Dynamometer set coefficients for low temperature (<0°C) testing were determined by increasing the target coefficients by a factor of 1.1 (as per the U.S. Code of Federal Regulations [12]) and deriving set coefficients using a coast down procedure at -7°C.

Table 1: Specifications of the two MY2015 BEVs

ERMS ID	BEV1	BEV2
Model Year	2015	← SAME
Charging Method	DCFC	ACL2
Drive Type	FWD	← SAME
ETW (**kg**)	1650	← SAME
ESS Nominal Capacity [**kWh**]	24	← SAME
Charge Time	25min for 80%	5hr
Electric Range [**km**]	110-200	← SAME
Motor	AC synchronous	← SAME
Odometer Start Round 1 (Mar 2015) [**km**]	1663	1655
Odometer Round 1 End (May 2015) [**km**]	4684	3978
Odometer Round 2 Start (Aug 2015) [**km**]	15049	15025
Odometer Round 2 End (Oct 2015) [**km**]	16177	16539
Current Odometer (April 2016) [**km**]	34936	32800

2.2 On-Road Mileage Accumulation and Charging

The two BEVs are typically driven five days per week on public roads in Ottawa, Ontario, Canada on the routes shown in Figure 1. Two driving routes are used: a 34.6 km summer route (blue) and a 23 km winter route (yellow). Driving typically begins at 08:00 and is repeated two to four times per day to take into account changes in range due to ambient conditions, while maximizing accumulation distance. The vehicles are driven concurrently and at all times follow the posted speed limits. Morning accumulation is followed by a midday charge, and afternoon accumulation is followed by an overnight charge. Each vehicle is charged on its respective electric vehicle supply equipment (EVSE). BEV1 is charged exclusively on an EATON DCFC equipped with a CHAdeMO connector. The charger is set up for a maximum output voltage of 400 Volts DC and a maximum output current of 125 Amps. BEV2 is charged using a ChargePoint ACL2 7.2 kWh charger.

The Charger is set up for a maximum output voltage of 240 Volts AC and a maximum current of 30 Amps. The morning accumulation routes are repeated at approximately 15:30. Drivers are also alternated between vehicles to minimize any bias in driving styles. The mileage accumulation route is detailed in Table 2. Commencing in December 2015, cabin preconditioning was performed remotely using the ACL2 chargers. Following the afternoon accumulation, BEV1 was charged to 93-94% on DCFC then placed on ACL2 to condition the battery overnight and allow both vehicles' cabins to be heated prior to departure.

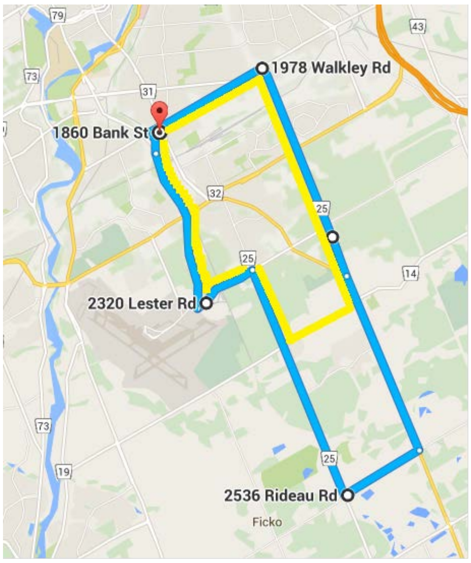


Figure 1: Mileage Accumulation Routes in Ottawa, Ontario Canada

The climate controls for both BEVs is set to 22°C with AUTO fan. Winter climate control settings were initially to be the same as in summer, however the cold climate forced the drivers to change the settings to maximum heat and fan when ambient temperatures were below 0°C. Given the variation in daily temperatures, drivers decided on a temperature and fan setting each day, and ensured that both vehicles operated in the same manner throughout the day's accumulation.

2.3 Dynamometer Testing

The BEVs were tested on the dynamometer using drive cycles meant to simulate a range of driving styles: free-flow highway driving (HWFCT), urban driving (LA4), aggressive driving (US06), accessory usage (SC03 - AC01 method), and congested urban driving (NYCC). Vehicles were also tested at a steady-state speed of 89 km/h (CSC). Brief descriptions of these drive cycles are provided in Table 2 and specifications are presented in Table 3. These drive cycles, except for the NYCC, are part of the U.S. Federal 5-Cycle Test Procedure. Table 2 also includes average parameters for the on-road mileage accumulation route. It should be noted that Table 2 contains a metric called kinetic intensity, which was proposed by O'Keefe *et al.* [13] as a basis of comparing acceleration intensity to aerodynamic speed. Hence, low speed cycles with moderate accelerations tend to have higher kinetic intensities, while high speed cycles with low or even aggressive accelerations have lower kinetic intensities.

Table 2: On-road mileage accumulation route and in-lab chassis dynamometer drive cycle specifications

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)**
Accumulation Route	60	21	88	1.2	1.8	15	-1.4	1.9	-14	0.1	1347	18	46	105	126
LA4	39	20	91	1.8	1.6	5.3	-2.1	1.9	-5	0.8	259	19	17	12	23
HWFCT	78	15	96	0.7	0.8	5.2	-0.8	1.0	-5	0.1	6	0.8	1.0	17	13
US06	83	34	129	2.4	2.9	14	-2.6	2.7	-11	0.3	44	7.3	5.0	13	10
NYCC	18	12	45	2.4	2.1	10	-2.3	2.0	-9	5.1	226	38	10	1.9	10
SC03	43	20	88	1.8	1.8	8.2	-2.2	2.2	-10	0.9	115	19	6.0	5.8	10
CSC	89	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table 3: Chassis dynamometer drive cycle descriptions

Drive Schedule	**Description**
LA4	moderate speed city cycle: part of the Canadian and U.S. 5-cycle fuel economy test
HWFCT	Highway fuel consumption test: part of the Canadian and U.S. 5-cycle fuel economy test. Simulates free-flow high driving
CSC	Constant speed driving at 55mph. Used to deplete the battery between transient cycles
US06	Aggressive high-speed driving cycle: part of the Canadian and U.S. 5-cycle fuel economy test
NYCC	New York City Cycle: Simulates congested urban driving
SC03	low speed city cycle with high ambient temperature: part of the Canadian and U.S. 5-cycle fuel economy test. Used to simulate cabin air cooling driving conditions

The drive cycles listed in Table 3 were used in full-depletion tests (FDTs), as detailed in Figure 2 to Figure 5. In this study, each FDT began with a cold start. The FDTs continued until the BEV could no longer maintain the drive trace, as per the procedures laid out in [14].

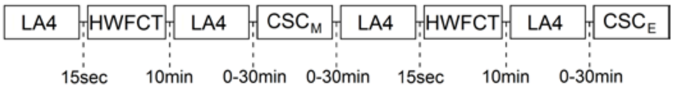


Figure 2: SAE J1634 multi-cycle full depletion test

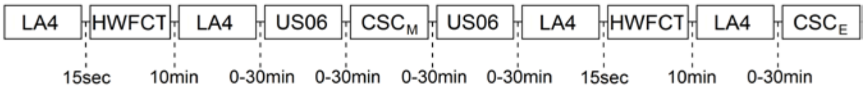


Figure 3: SAE J1634 US06 multi-cycle full depletion test

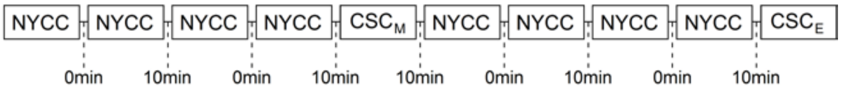


Figure 4: NYCC single-cycle full depletion test

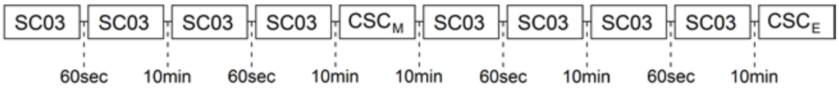


Figure 5: SC03 single-cycle full depletion test

The CSC was also run as a FDT, for preconditioning the BEV before a test day. This test also served as a means to establish the baseline useable battery energy (UBE) of the BEV, a parameter that is used to estimate the durations of the CSC_M and CSC_E portions of the test sequences shown above. This CSC FDT was conducted as follows:

(1) Accelerate to 89 km/h within 30 seconds
(2) Drive at 89 km/h until the vehicle is unable to maintain the speed tolerance outlined in [14]
(3) Decelerate to a stop within 30 seconds
(4) Shut-off vehicle
(5) Commence charge event within 3 hours (for 25°C ambient temperature) or 1 hour (for -7°C ambient temperature)

2.3.1 Instrumentation and Measurements

HIOKI clamp-on and solid-core AC/DC amp probes were used to measure the power draws shown in Figure 6 while the BEVs were under test on the chassis dynamometer. These include the traction battery (see Figure 7), PTC heater, A/C compressor and the 12V accessory draws. As well, during charging events, the AC grid supply was also monitored with the use of a solid-core amp probe on a breakout box. The voltages and currents were measured and recorded with a HIOKI 3930-10 high-precision power analyser. Instantaneous measurements of current, voltage, power, integrated current and integrated energy were collected over the duration of each chassis dynamometer test.

During in-lab testing and on-road mileage accumulation a select list of CAN bus signals were recorded on both BEVs with the use of OBD dataloggers. The specific signals captured during all testing, charging and mileage accumulation events are shown in Table 4. Raw data was collected on the dataloggers, uploaded to a restricted access cloud and then processed by FleetCarma before the test files were made available.

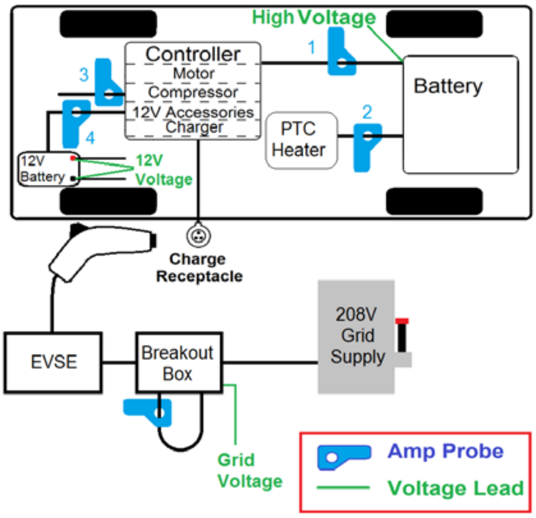


Figure 6: Current and voltage measurement locations along BEV1 and BEV2 drivetrains

Figure 7: Picture of the disconnected high-voltage battery main cable with a high current fuse looped through a 500A solid-core amp probe

Table 4: List of CAN bus signals collected during all vehicle activity of BEV1 and BEV2

Parameter	**Units**	**Parameter (Cont'd)**	**Units**
Battery Module Temperature 1	°C	Motor1 Speed	rpm
Battery Module Temperature 2	°C	Motor1 Torque	Nm
Battery Module Temperature 4	°C	Motor Propulsion Power	kW
Board Temperature	°C	Motor Regenerative Power	kW
Cabin Temperature	°C	Motor Temperature	°C
Dash Odometer	km	Outside Air Temperature	°C
Main Battery Current	Amp	Plug Status	0 or 1
Main Battery SOC	%	Vehicle Speed	km/h
Main Battery Voltage	Volt	Whee lSpeed Front Driver	km/h
Input Voltage	milli volt	Wheel Speed_Front Passenger	km/h
Inverter DC Voltage	Volt	Wheel Speed Rear Driver	km/h
Charging?	0 or 1	Wheel Speed Rear Passenger	km/h
Charging DC?	0 or 1		

2.3.2 Calculations

The SAE J1634 recommended practice provides procedures for conducting electric vehicle chassis dynamometer testing, as well as calculations to assess BEV performance [15]. Several parameters defined in this recommended practice are used in this study to characterize the performances of BEV1 and BEV2: all-electric vehicle range for a given cycle (R_{cycle}), AC full recharge energy (FRE), DC full recharge energy (FRE_{DC}), DC discharge energy (E_{DC}), UBE, and DC energy consumption rate (EC_{dc}). The UBE is defined as the total discharge energy over the duration of an entire FDT. The energy measured at the grid supply (see Figure 6) at the breakout box over the duration of a charge event is the FRE, while the charge energy measured at the terminals of the main battery is the FRE_{DC}. The DC energy discharged from the battery during test is ECdc. ECdc values for each set of unique drive cycles within a FDT are calculated using phase scaling factors ($K_{[cycle]\_i}$), as defined in SAE J1634. The use of a phase scaling factor is meant to weight the cold-start and full-charge impacts relative to the entire depletion range of the vehicle. More details on the calculations used to process the results described in this paper may be found in SAE J1634.

2.3.3 Test Matrices

The Round 1 and Round 2 test matrices for BEVs 1 and 2 are shown in Table 5. It should be noted that each test repeat identified in Table 5 represents a set of cycle repeats in one unique FDT. Thus, while there are four LA4 and two HWFCT tests in the J1634 MCT, this FDT would yield one LA4 range and EC_{DC}, and one HWFCT range and EC_{DC}. The number of repeats differs between BEVs 1 and 2 because of multiple factors including, but not limited to: timing, scheduling, tangent investigations and data verification purposes.

Table 5: Drive cycle repeat count for BEVs 1 and 2 during (a) Round 1 and (b) Round 2 of testing

Drive Cycle	**BEV**	**Ambient Temperature [°C]**		
		35	**25**	**-7**
LA4	1	-	4	6
	2	-	4	5
HWFCT	1	-	4	6
	2	-	4	5
US06	1	-	1	2
	2	-	3	0
NYCC	1	-	1	1
	2	-	1	0
CSC	1	2	9	7
	2	1	7	5
SC03	1	2	-	-
	2	1	-	-

(a)

Drive Cycle	**BEV**	**Ambient Temperature [°C]**		
		35	**25**	**-7**
LA4	1	-	3	0
	2	-	3	1
HWFCT	1	-	3	0
	2	-	3	1
US06	1	-	3	0
	2	-	3	0
NYCC	1	-	1	0
	2	-	1	0
CSC	1	2	6	0
	2	3	7	2
SC03	1	2	-	-
	2	3	-	-

(b)

3 Results and Discussion

3.1 On-Road Mileage Accumulation and Charging

3.1.1 Battery Temperature

Figure 8 details the average daily battery temperature for both BEV1 and BEV2 during periods of charging and driving. BEV1 was charged outdoors where the DCFC station is located. BEV2 was charged indoors during the first round of accumulation (May to December), and was subsequently charged outdoors. The average battery temperatures during accumulation were an average of 5.7°C higher for BEV1 compared to BEV2 during driving and 4.5°C higher during charging. Table 6 lists average battery temperatures for each season. During the seasonal winter months there was a greater difference in the average battery temperatures between BEV1 and BEV2. BEV1 reported an average battery temperature of 13.2°C (charging) and 10.3°C (driving) whilst BEV2 reported 5.2°C (charging) and 4.6°C (driving), a difference of 7°C and 5.7°C, respectively. The larger difference in charging temperatures between BEV1 to BEV2 may be attributed to the DCFC charger rapidly charging the vehicle battery, heating the battery up with the rapid transfer of energy from charger to battery pack. Battery temperatures will continue to be recorded as the study progresses into its second year.

Table 6: Average Battery Temperatures

Season	Battery Temperatures [°C]			
	Charging		Driving	
	BEV1	BEV2	BEV1	BEV2
Spring (Apr-Jun)	32.94	26.88	27.61	24.79
Summer (Jul-Sep)	35.35	29.68	33.25	27.76
Fall (Oct-Dec)	23.65	20.52	22.44	18.63
Winter (Jan-Mar)	13.15	5.21	10.26	4.57

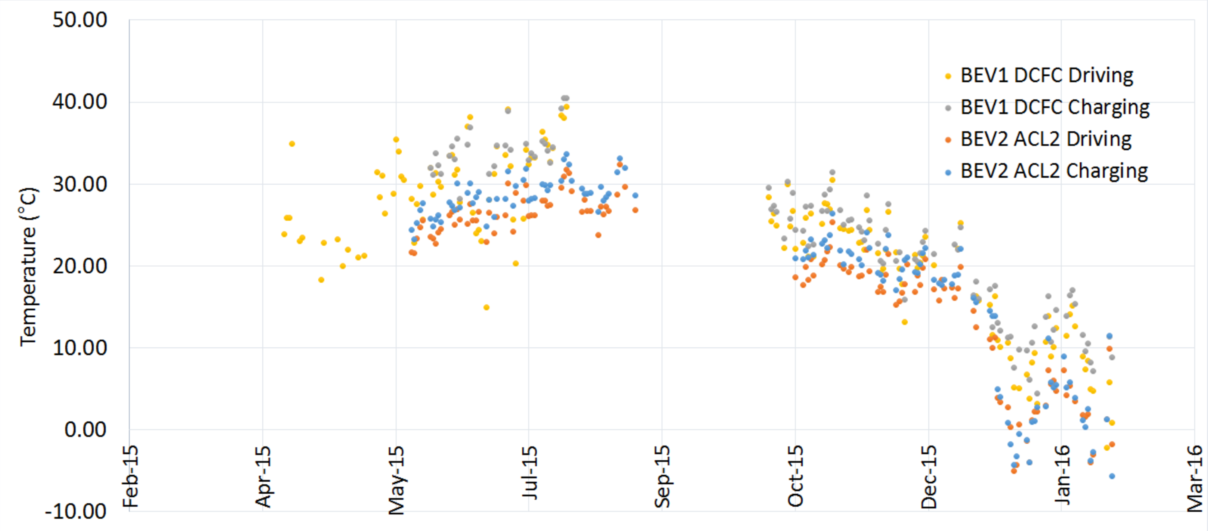


Figure 8: Average Daily Charging & Driving Battery Temperature

3.1.2 Battery Voltage

Figure 9 illustrates the charging and discharging voltages for BEV2. The average battery charging voltage over the duration of the accumulation was 384 V, and the average driving voltage was 376 V. During the winter months (Dec-Feb) the battery voltage dropped to an average driving voltage of 372 V, while the charging voltage remained essentially unchanged. The contrast between spring and summer discharge voltages compared to winter is most likely due to the air temperature cooling the battery pack and increasing the internal resistance, therefore decreasing the system voltage.

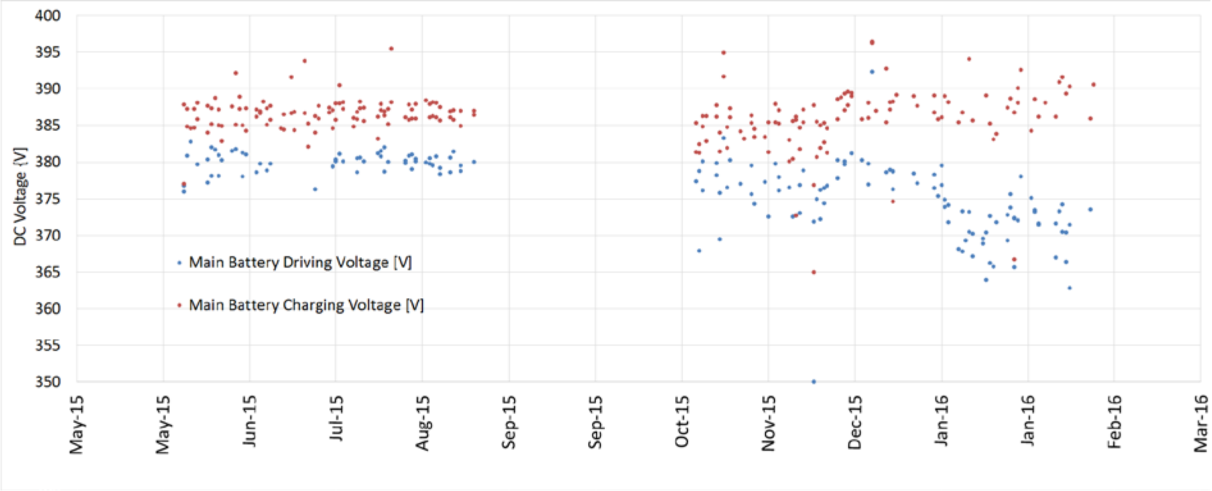


Figure 9: BEV2 Charging vs. Driving Battery Voltages

3.1.3 Charging

Figure 10 illustrates a typical charge profile for BEV1 charged using the DCFC charger (a), and BEV2 charged using ACL2 (b). A typical DCFC takes about 40 minutes with the charger automatically ending the charge at a SOC of 94% as reported by the on-board SOC indicator. During the winter season however, noticeable differences in vehicle charging times were observed, with charging times increasing to upwards of 90 minutes. A typical ACL2 charge took approximately 4 hours.

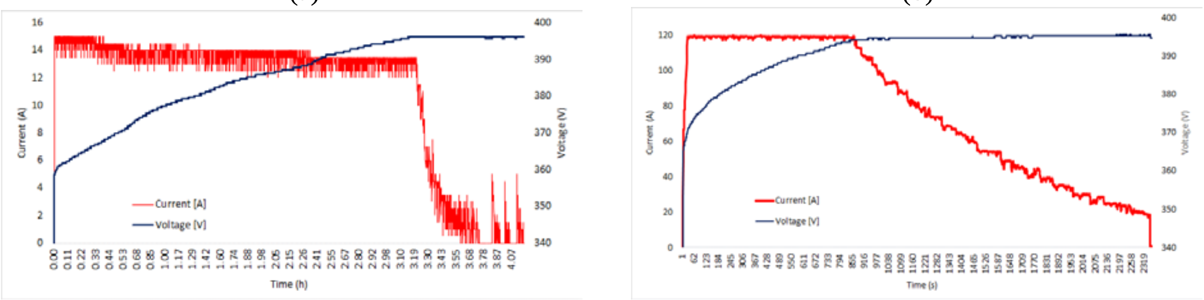

(a) (b)

Figure 10: (a) ACL2 and (b) DCFC typical charge profiles

3.2 Dynamometer Test Results

3.2.1 Dynamometer Test Results: Baseline

Baseline test results (1,600 km odometer reading) indicate that BEV1 and BEV2 performed nearly identically in terms of driving range, energy use, and charging. For instance, Figure 11 presents the average FRE, FRE_{DC} and UBE for BEV1 and BEV2 at 35°C, 25°C and -7°C. While BEV1 had slightly higher charging energy and UBE, the differences were not statistically significant. The only statistically significant differences (p=0.05) between the two BEVs were determined to be a 0.4kWh difference in the 25°C FRE and 25°C FRE_{DC}, and a 0.9kWh difference in the 35°C FRE_{DC}, likely due to the low sample count for this test condition.

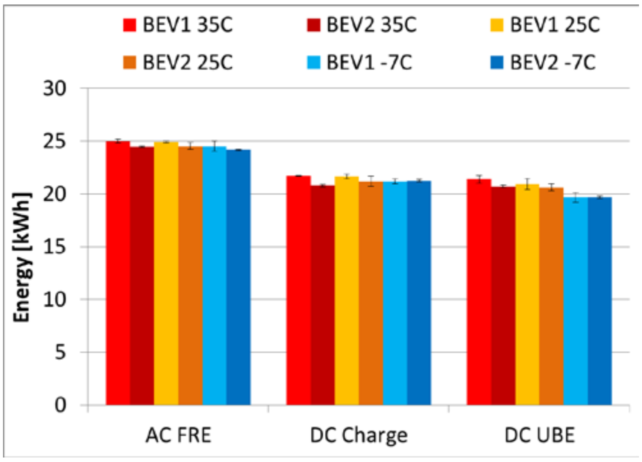


Figure 11: Average baseline BEV1 and BEV2 full recharge, DC charge and DC useable battery energies at 35°C, 25°C and -7°C

Similarly, range and EC_{DC} comparisons between the two BEVs were made for all test conditions. The results for EC_{DC} are shown in Table 7.

Table 7: Average baseline EC_{DC} for BEV1 and BEV2

Amb Temp [°C]	Vehicle	Average DC Energy Discharged per Kilometer - EC_{DC} [DC Wh/km]					
		LA4	HWFCT	US06	NYCC	CSC	SC03
35	BEV1	-	-	-	-	150 ± 16	170 ± 12
	BEV2	-	-	-	-	161 ± N/A	175 ± N/A
25	BEV1	109 ± 1	135 ± 6	182 ± N/A	118 ± N/A	141 ± 5	-
	BEV2	112 ± 4	134 ± 0	182 ± 3	124 ± N/A	142 ± 4	-
-7	BEV1	143 ± 30	158 ± 15	195 ± 5	213 ± N/A	160 ± 6	-
	BEV2	127 ± 4	147 ± 2	-	-	158 ± 2	-

The differences in EC_{DC} rates between BEV1 and BEV2 were not statistically significant. However, as shown in Table 8, under city driving conditions the driving range (R_{LA4}) was significantly higher for BEV1 compared to BEV2 (test condition is highlighted green); specifically, BEV1's (DCFC) R_{LA4} was 11 km greater than BEV2's (ACL2) R_{LA4}. All other ranges are not statistically significantly different between the two BEVs.

Table 8: Average baseline driving ranges of BEV1 and BEV2

Amb Temp [°C]	Vehicle	Total BEV Range [km]					
		LA4	HWFCT	US06	NYCC	CSC	SC03
35	BEV1	-	-	-	-	144 ± 13	126 ± 7
	BEV2	-	-	-	-	128 ± N/A	118 ± N/A
25	BEV1	194 ± 3	157 ± 7	115 ± N/A	177 ± N/A	147 ± 2	-
	BEV2	183 ± 5	153 ± 2	112 ± 1	170 ± N/A	145 ± 5	-
-7	BEV1	143 ± 25	127 ± 13	102 ± 3	90 ± N/A	119 ± 6	-
	BEV2	155 ± 5	134 ± 2	-	-	125 ± 2	-

3.2.2 Dynamometer Test Results: 15,000 km

After 15,000 km of mileage accumulation, BEV1 and BEV2 total energies (FRE, FRE_{DC} and UBE) were once again compared (see Figure 12). While none of the energies at 35°C were different between the two BEVs, the 25°C FRE, FRE_{DC} and UBE were determined to be statistically significantly different. BEV1 (DCFC) had higher FRE, FRE_{DC} and UBE, compared to BEV2 (ACL2).

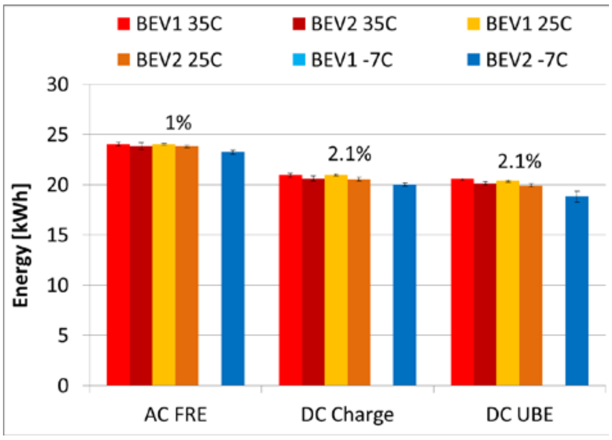


Figure 12: Average 15,000 km BEV1 and BEV2 full recharge, DC charge and DC useable battery energies at 35°C, 25°C and -7°C

The average EC_{DC} rates and R_{cycle} calculations are shown in Table 9 and Table 10. In Round 2 of testing, BEV1 and BEV2 do not have statistically significantly different EC_{DC} rates or ranges despite BEV1 having higher energy capacities than BEV2. This may be attributable to the data spread in EC_{DC} and range values diluting the differences between the BEVs. Observing the average EC_{DC} and ranges in Table 9 and Table 10, it would appear at face value that BEV1 is performing slightly better than BEV2 in Round 2 of this study.

Table 9: Average Round 2 EC_{DC} of BEV1 and BEV2

Amb Temp [°C]	**BEV**	**Average DC Energy Discharged per Kilometer - EC_{DC} [DC Wh/km]**					
		LA4	**HWFCT**	**US06**	**NYCC**	**CSC**	**SC03**
35	1	-	-	-	-	165 ± 5	185 ± 7
	2	-	-	-	-	167 ± 31	177 ± 11
25	1	110 ± 2	133 ± 3	180 ± 2	118 ± N/A	146 ± 6	-
	2	109 ± 2	133 ± 3	182 ± 7	132 ± N/A	142 ± 1	-
-7	1	-	-	-	-	-	-
	2	124 ± N/A	161 ± 15	-	-	161 ± 15	-

Table 10: Average Round 2 driving ranges of BEV1 and BEV2

Amb Temp [°C]	**BEV**	**Total BEV Range [km]**					
		LA4	**HWFCT**	**US06**	**NYCC**	**CSC**	**SC03**
35	1	-	-	-	-	125 ± 5	112 ± 5
	2	-	-	-	-	120 ± 3	114 ± 6
25	1	186 ± 4	153 ± 4	113 ± 2	172 ± N/A	141 ± 4	-
	2	182 ± 4	149 ± 2	109 ± 5	151 ± N/A	141 ± 2	-
-7	1	-	-	-	-	-	-
	2	155 ± N/A	132 ± N/A	-	-	117 ± 7	-

3.3 Round 1 versus Round 2

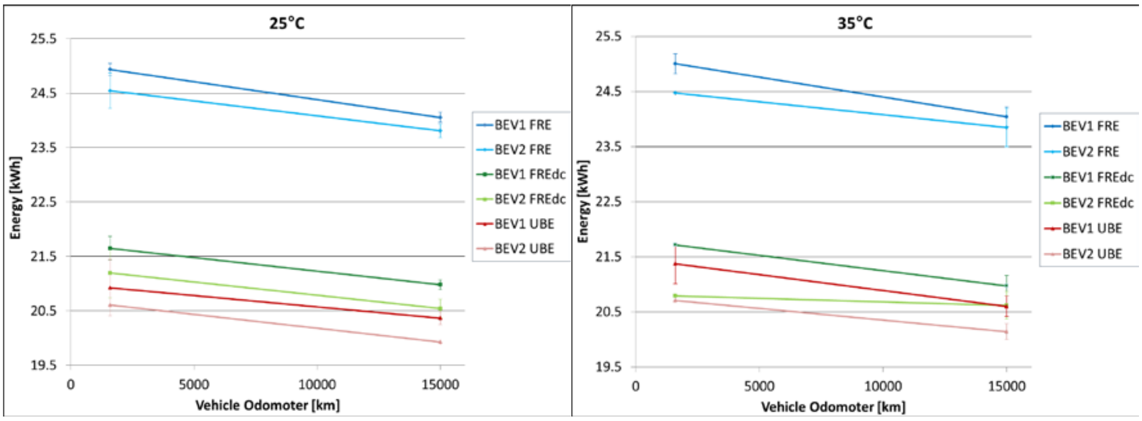
The energy capacity and performance gap between BEVs 1 and 2 generally decreases between Rounds 1 and 2, as seen in Table 11. Note that a dash (-) represents a non-statistically significant difference in the performance metric between the two BEVs for the particular Round of testing in question.

Table 11: Statistically significant performance metric differences between BEV1 and BEV2; BEV1 metric minus BEV2 metric

Performance Metric	**Amb Temp [°C]**	**BEV1 minus BEV2**	
		Round 1	**Round 2**
FRE **[kWh]**	25	0.39	0.24
FRE_{DC} **[kWh]**	35	0.92	-
	25	0.45	0.44
UBE **[kWh]**	25	-	0.44
R_{LA4} **[km]**	25	11	-

When comparing UBE and charging energy between Round 1 and Round 2, a trend is immediately observed; that is, the average energy capacities (FRE, FRE_{DC} and UBE) decrease between the 1,600 km odometer test condition and 15,000 km odometer test condition. This trend is observed at both 35°C (Figure 13 (a)) and 25°C (Figure 13 (b)). The error bars in these graphs represent one standard deviation from the average value to which it corresponds. At 35°C, these energy capacity reductions are statistically significant for BEV1. At 25°C the energy capacity reductions are statistically significant for both BEVs 1 and 2.

From Figure 13 it is evident that not only is the available energy for propulsion decreasing, but the AC charge energy delivered (and DC energy received by the battery) to the battery decreased as well, by approximately 3%; this, after only 15,000 km of mileage accumulation. These results are supported by a similar study conducted by Idaho National Laboratory (INL), which compared battery cycling (and/or mileage accumulation) and fast charging effects on battery performance. INL found that the battery degradation occurred most severely in the first 10,000 miles of accumulation, after which, the rate of degradation became more linear and less severe [10].



(a) (b)

Figure 13: Average FRE, FRE_{DC} and UBE energies of BEV1 and BEV2 at (a) 25°C and (b) 35°C and at 1600km and 15000km odometer

The average percent decrease in range and increase in EC_{DC} rates for test condition and BEV are shown in Table 12 (a) and (b). Although the trend in Table 12 (a) consistently points to range degradation between the 1,600 km and 15,000 km test condition, only the 25°C BEV1 LA4 and CSC, and -7°C BEV2 CSC range decreases are statistically significant (highlighted green in Table 12). The average percent increases in EC_{DC} rates exhibits less of a specific trend. None of the changes between the 1,600 km and 15,000 km EC_{DC} rates are statistically significant. At 25°C, some test conditions even resulted in a decrease in energy consumption. Clearly, energy consumption rates have not increased at the 15,000 km mark.

Table 12: Percent decrease in (a) driving range and (b) EC$_{dc}$ between Round 1 and 2 of testing for BEV1 and BEV2

Drive Cycle	**BEV**	**Percent Decrease in Range [%]**		
		35°C	**25°C**	**-7°C**
LA4	1	-	4.0	-
	2	-	0.4	-0.2
HWFCT	1	-	2.5	-
	2	-	2.5	0.9
US06	1	-	1.9	-
	2	-	2.4	-
NYCC	1	-	2.8	-
	2	-	10.8	-
SC03	1	11.5	-	-
	2	3.5	-	-
CSC	1	13.0	4.3	-
	2	6.3	2.9	5.9

(a)

Drive Cycle	**BEV**	**Percent Increase in EC$_{DC}$ [%]**		
		35°C	**25°C**	**-7°C**
LA4	1	-	0.5	-
	2	-	-2.4	-2.8
HWFCT	1	-	-1.2	-
	2	-	-0.3	9.1
US06	1	-	-0.9	-
	2	-	-0.1	-
NYCC	1	-	0.1	-
	2	-	6.8	-
SC03	1	8.7	-	-
	2	1.0	-	-
CSC	1	10.3	3.1	-
	2	3.8	0.0	1.8

(b)

4 Conclusions

This technical paper describes the first two rounds of a multi-year, eight-round study to investigate the effects of mileage accumulation and fast-charging in Canadian seasonal climates on 2015 model year BEVs, in terms of driving range, charging energy, and useable battery energy.

During baseline testing, minor differences in the performance of the two identical BEVs were measured. Specifically, BEV1 (DCFC) received more DC charge energy (FRE$_{DC}$) than BEV2 at 25°C and 35°C; 0.4 kWh and 0.9 kWh, respectively. BEV1 also had an 11 km higher range on the LA4 drive cycle than BEV2. At 15,000 km this performance gap between the two BEVs generally decreased. The difference in the LA4 range (or any other drive cycle range) was no longer statistically significant and nor was the difference in the 35°C FRE$_{DC}$. BEV1 maintained a slightly higher 25°C FRE$_{DC}$ than BEV2 (0.4 kWh) and also had 0.4 kWh higher UBE.

Between Rounds 1 and 2, the driving range and charging/useable battery energy of each BEV generally decreased. The 25°C charging and useable energy (FRE, FRE$_{DC}$ and UBE) of both BEVs decreased by approximately 3% between 1,600 km and 15,000 km. Further, the ranges of both BEVs over the majority of drive cycle-temperature combinations decreased, although this decrease varies depending on temperature, BEV and drive cycle. However, for the most part this trend is not statistically significant. Energy consumption rates (DC Wh/km) were not statistically significantly different between the BEVs for any test conditions or different for any of the two BEVs between test rounds.

Generally, results suggest that degradation in range, energy usage and energy capacity has already begun at 15,000 km mileage. Round 3 of chassis dynamometer testing will commence in January 2016. Incremental results from this study will be published and made available upon request.

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