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Impacts of Mileage Accumulation and Fast Charging on EV Range and Energy Usage: 50,000 km Interim Results

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Summary

Two battery-electric vehicles (BEV) were driven for 50,000 km on a controlled route in Canadian climate conditions to determine the impact of charge rate and mileage accumulation on vehicle range and usable battery energy (UBE). The vehicles were tested on a dynamometer at 15,000 km intervals.

Results demonstrate degradation in driving range and UBE. After 50,000 km, driving range decreased by between 6.1% and 12.5%, and usable battery energy decreased by between 6.8% and 10.0%, depending on the test cycle. The BEV that was regularly fast charged on 50 kW had up to 5.0% lower UBE and driving range compared to the BEV that was regularly charged on a 7.2 kW AC Level 2 charger.

Keywords: Battery Electric Vehicle (BEV), Fast-Charge, Range, Energy Consumption, Vehicle Performance

Nomenclature

ACL2	–	Alternating Current, Level 2
BEV	–	Battery Electric Vehicle
BMS	–	Battery Management System
CAN bus	–	Controller Area Network bus
CVUS	–	Canadian Vehicle User Survey
DCFC	–	Direct Current, Fast-Charge
ECCC	–	Environment and Climate Change Canada
ECdc	–	Direct Current Energy Consumption
EPA	–	Environmental Protection Agency
ERMS	–	Emissions Research and Measurement Section
eTV	–	Transport Canada's ecoTECHNOLOGY for Vehicles program
FDT	–	Full-Depletion Test
FRE	–	Full Recharge Energy
FRE _{DC}	–	Direct Current Full Recharge Energy
MCT	–	Multi-Cycle Test
OBDII	–	2 nd Generation On board diagnostics
R _{cycle}	–	All-electric range of a BEV extrapolated for a given 'cycle'
UBE	–	Useable Battery Energy

1 Introduction

Vehicle electrification has the potential to significantly reduce air pollution and greenhouse gas emissions. As battery electric vehicle (BEV) sales continue to increase worldwide, and as major OEMs announce future shifts to EV-centric production [1], it becomes essential to understand how battery deterioration affects vehicle energy consumption and range. Considering the wide range of ambient temperatures experienced regionally in North America, it is also important to determine the impacts of seasonal operation.

BEVs commonly use lithium-ion (Li-ion) cell chemistries to store and release energy to power the vehicle's motor(s). These batteries are known to degrade and perform differently as they age, and with repeated charging and discharging. Manufacturers strive to optimize vehicle performance, longevity, and cost through their choice of battery chemistry, and through their battery management systems (BMS). This optimization can involve trade-offs between performance, longevity, and cost.

In 2015, Transport Canada's ecoTECHNOLOGY for Vehicles Program (eTV) and Environment and Climate Change Canada's (ECCC) Emissions Research and measurement Section (ERMS) collaborated to initiate a multi-year, 8-round study to investigate the effects of mileage accumulation and charge rate on BEV driving and charging performance while operated in Canadian climate including winter conditions. Two 2015 model year BEVs of identical make and model, with air-cooled battery packs, are undergoing mileage accumulation in Ottawa, Canada, up to 105,000 km, with laboratory testing at 15,000 km intervals and on-road monitoring through CAN bus data logging. BEV1 is primarily charged using a 50 kW DC "Fast-Charge" station (DCFC), and BEV2 is charged exclusively using a 7.2 kW AC "Level 2" station (ACL2). To-date, the vehicles have accumulated 50,000 km and undergone 5 rounds of laboratory testing.

Previous studies by Idaho National Laboratory reported a 25-40% loss in battery capacity, and a 19-34% reduction in driving range after 80,000km of operation in a hot climate on a test track [2]. Also, a greater degradation in the battery performance was measured with the use of DCFC, compared to AC Level 2 (ACL2). In contrast, the current study investigates the impacts in a combination of hot and cold weather Canadian climate conditions.

2 Method

Testing consisted of an on-road mileage accumulation component, and an in-lab component. Before any testing was performed, both vehicles underwent a break-in period of 1,650 km (~1,000 mi.). Vehicles were tested on a chassis dynamometer at approximately 15,000 km intervals. While at the lab, both vehicles were charged on ACL2 since the test facility is not equipped with a DCFC charging station.

2.1 On-Road Mileage Accumulation

Route, Drivers, and Schedule:

The on-road driving routes included a mix of driving speeds, as well as a mix of heavy and light traffic conditions on pre-defined routes. The summer route consisted of a 28.6 km loop with an elevation variation of 334 m, while the winter route consists of a 20.4 km loop with an elevation change of 233 m. The winter route is slightly shorter, to account for the reduction in the vehicles' ranges. Each weekday consisted of a morning drive, followed by a mid-day charge, an afternoon drive, and finally a full charge in the evening. The driving routes are shown in Figure 1.

Table 1 shows the yearly distance, average speed, and idle time for each test vehicle as well as for the average passenger car in Canada. The Canadian Vehicle Use Study (CVUS) is a survey that tracked driving data on a sample representative of the national Canadian fleet of light vehicles [3]. The test vehicles were on an accelerated mileage accumulation schedule, so had higher annual driving distances compared to the CVUS average distance. The test vehicles also spent slightly less time idling and had a slightly higher average speed compared to the CVUS data.

Table 1. Driving rates compared to Canadian averages

	Average distance [km/year]	Average speed [km/h]	Idle time [%]
CVUS (2015), Passenger cars	15,894	40.9	22.0
BEV1	28,549	47.2	18.3
BEV2	29,521	47.1	18.8

Two professional drivers were assigned to accumulate mileage on the vehicles. To reduce driver behavior bias on results, the drivers alternated between vehicles. They completed consecutive loops until the available range displayed on the dash board did not reasonably guarantee the completion of a full loop. The drivers reported any changes in the route (e.g. due to construction), or any irregularities in vehicle operation.

BEV1 was charged exclusively on an EATON DCFC equipped with a CHAdeMO connector. The charger was set up for a maximum output voltage of 400 Volts DC and a maximum output current of 125 Amps. BEV2 was charged using a ChargePoint ACL2 7.2 kW charger. The charger is set up for a maximum output voltage of 240 Volts AC and a maximum current of 30 amps. Following the afternoon accumulation, BEV1 was fully charged on DCFC, and then both vehicles were placed on ACL2 charging to condition the battery overnight.

Climate control for both BEVs was set to 22°C with the fan set to “auto”. During very cold days, the drivers would decide on a common temperature and fan set point, then would log these changes into their log books. The vehicles were always operated in “eco-mode”.

Maintenance was performed according to the vehicle owner’s manual, every 12,000 km. Winter tires were installed near the beginning of November, and summer tires were installed in the beginning of April.

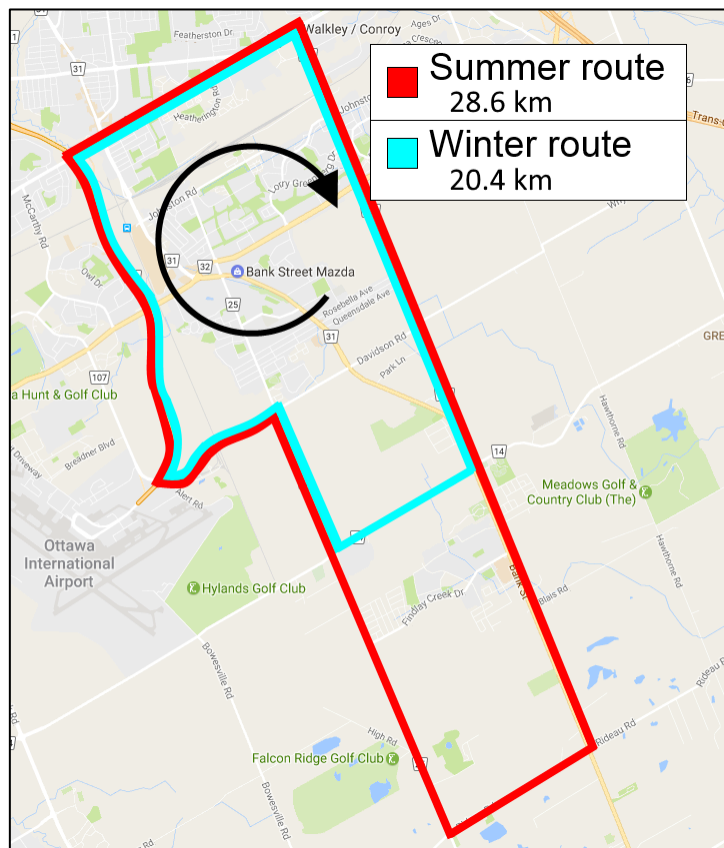


Figure 1. Winter and summer routes in Ottawa, Ontario, Canada

The speed profiles for each vehicle, averaged over the 2 year accumulation period, are shown in Figure 2.

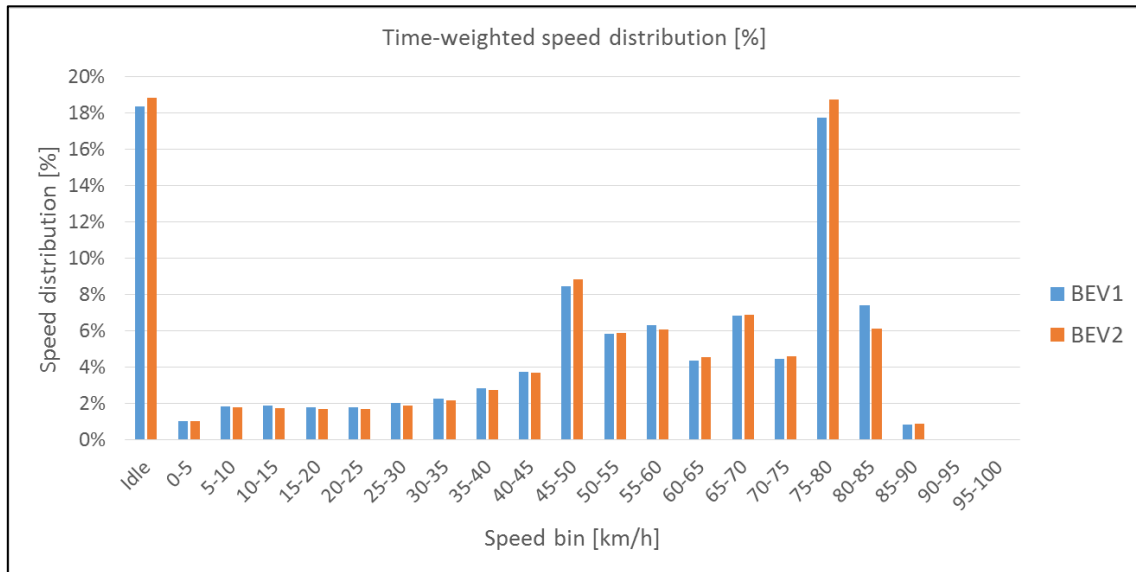


Figure 2. Speed distribution for the average accumulation route. The 0-5 km/h bin excludes idling (0 km/h)

On-Road Data Acquisition:

During on-road mileage accumulation and in-lab testing, CAN bus data was collected through the on-board diagnostics (OBDII) port. FleetCarma’s fleet management equipment was used to read and collect internal diagnostics CAN bus signals (see Table 2) from the BEVs, which allowed eTV and the ERMS to log data on temperatures, high voltage battery parameters, and motor power during accumulation and testing.

Table 2: List of CAN bus signals collected during charging and driving events

Global	Temperatures	Electrical	Motor
<ul style="list-style-type: none"> • Date • Time • Odometer 	<ul style="list-style-type: none"> • Battery module temperatures • Cabin temperature • Motor temperature • Outdoor temperature 	<ul style="list-style-type: none"> • Battery state of charge • Inverter voltage • Battery voltage • Battery current • Charge type 	<ul style="list-style-type: none"> • Motor torque • Motor RPM • Regen power • Propulsion power • Vehicle speed

A data file was created every time the vehicles’ ECMs were activated (key-on, running and charging). A program was developed by eTV to analyze accumulation data. The program generates tables summarizing file-level, trip-level (subsequent driving events are chained together as one trip), and daily-level data. These summary tables are then filtered to remove non-accumulation results, such as when the vehicles were at the garage for maintenance, days spent at the dynamometer test facility, and extremely short charge or driving events. Similarly, a program was developed by the ERMS to simultaneously analyze in-lab CAN data, power analyzer data, dynamometer data and mini-logger data and synchronize the data files to allow for meaningful comparisons and analysis.

2.2 In-Lab

Chassis Dynamometer Test Cycles

Dynamometer testing was conducted every 15,000 km at ECCC’s ERMS laboratory to determine the vehicles’ driving ranges and UBEs. The vehicles were tested on a chassis dynamometer at ambient temperatures of -7°C, 25°C, and 35°C (cold temperature testing was only performed for the first round and will be conducted again at 105,000 km).

In order to simulate a wide range of driving styles, each BEV was tested on 4 different Full-Depletion Tests (FDT), including: the SAE J1634 Multi-Cycle Test (MCT), the SAE J1634 US06 MCT, the SC03 Full-Depletion Test (FDT), the NYCC FDT, and the 89 km/h Constant Speed Cycle (CSC). Each FDT is comprised of multiple test cycles. The Multi-cycle FDTs are shown in Table 3, and a brief description of each test cycle is provided in Table 4. Each FDT began with a cold start. The FDTs continued until the BEV could no longer maintain the drive trace, as per the procedures established in the U.S. Environmental Protection Agency (EPA) Code of Federal Regulations [4].

Dynamometer target coast-down coefficients were taken from the U.S. EPA Certified Vehicle Test Result Report Data [5] and used to determine the 25°C set coefficients on the chassis dynamometer according to the vehicle recommended practice of SAE J1263 [6]. Low temperature (< 0°C) set coefficients were determined by increasing the target coefficients by 10% and then running set coefficient determinations at -7°C on the chassis dynamometer, as prescribed by the U.S. Code of Federal Regulations [7].

Table 3. Multi-Cycle Full-Depletion Test sequences

SAE J1634 multi-cycle full depletion test	
SAE J1634 US06 multi-cycle full depletion test	
NYCC single-cycle full depletion test	
SC03 single-cycle full depletion test	

Table 4. Test Cycle Description

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. Simulated free-flow highway driving
CSC	Constant speed driving at 55mph. Served multiple purposes, including: Preconditioning the BEV before a test day, fully depleting the battery at the end of each test day before a full charge, and determining the baseline useable battery energy.
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 condition

Instrumentation and Measurements

A HIOKI power analyser and AC/DC amperage probes were used to measure the power flow of the Leaf’s electric drivetrain components, shown in Figure 3. These components include the traction battery (see Figure 4), electric heater, A/C compressor and the 12V accessories. As well, during charging events, the AC grid supply was monitored with the use of a solid-core amp probe outfitted on a breakout box. The voltages and currents were measured and recorded with a HIOKI 3193 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.

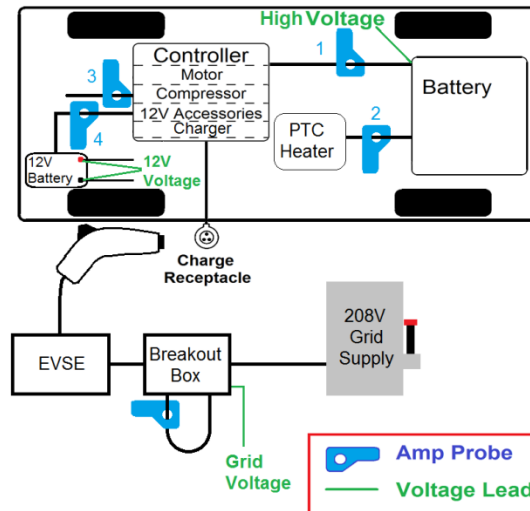


Figure 3: Current and voltage measurement locations along BEV1 and BEV2 drivetrains



Figure 4: Picture of the disconnected high-voltage battery main cable, modified to include a 2AWG cable with a high current fuse through which a 500A solid-core amp probe is looped

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 3) 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 a test is EC_{dc} . EC_{dc} values for each unique drive cycle within a FDT are calculated using phase scaling factors ($K_{[\text{cycle}]_i}$), 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.

Test Matrices

The Round 1, 8 and Round 2-7, test matrices for both BEVs are shown in Table 5. The number of repeats conducted during each round and for each BEV differs because of multiple factors including, but not limited to: timing, scheduling, tangent investigations and data verification purposes.

Table 5. Test schedule for (a) Round 1 and 8, and (b) Rounds 2 through 7

Test Sequence	Ambient Temperature [°C]			Test Sequence	Ambient Temperature [°C]		
	35	25	-7 w cabin heat		35	25	-7 w cabin heat
SAE J1634 US06 MCT		3	3	SAE J1634 US06 MCT		3	
NYCC FDT		2	2	NYCC FDT		2	
SC03 FDT	2			SC03 FDT	2		

(a)

(b)

3 Results and Discussion

3.1 On-Road Mileage Accumulation and Charging

To date, the vehicles have accumulated 65,000 km between June 2015 and May 2017. While dynamometer test results only include up to 50,000 km at time of publication, the on-road results include 65,000 km of driving. On-road results presented in this paper include battery module temperatures and energy consumption rates.

Battery and ambient temperatures during mileage accumulation and charging events are shown in Table 6 and Figure 5. Temperature was only recorded during active driving or charging. The vehicles occasionally drew energy from the grid after a charge event had concluded, in order to power the battery conditioner during cold nights. These events were not included in the temperature averages since they are not characterised as a charge to recuperate energy from driving. The ambient temperatures during these cold nights occasionally reached -22°C.

Overall, BEV1 battery pack temperatures exceeded those of BEV2 during driving and charging events by approximately 2.7°C; this has been attributed to the faster charge rates of DCFC, which cause more heat to build up in the battery pack within a short amount of time. The warmest temperatures logged were 49°C for BEV1’s battery pack, and 38°C for BEV2’s battery pack.

Table 6. Temperature by vehicle and charging or driving event

Season	Average battery temperature [°C]				Average ambient temperature [°C]	
	Charging		Driving		Charging	Driving
	BEV1	BEV2	BEV1	BEV2		
Winter (Jan-Mar)	11	7	5	3	0	-4
Spring (Apr-Jun)	27	22	24	19	21	17
Summer (Jul-Sep)	32	29	28	26	29	23
Autumn (Sep-Dec)	21	18	18	15	15	6

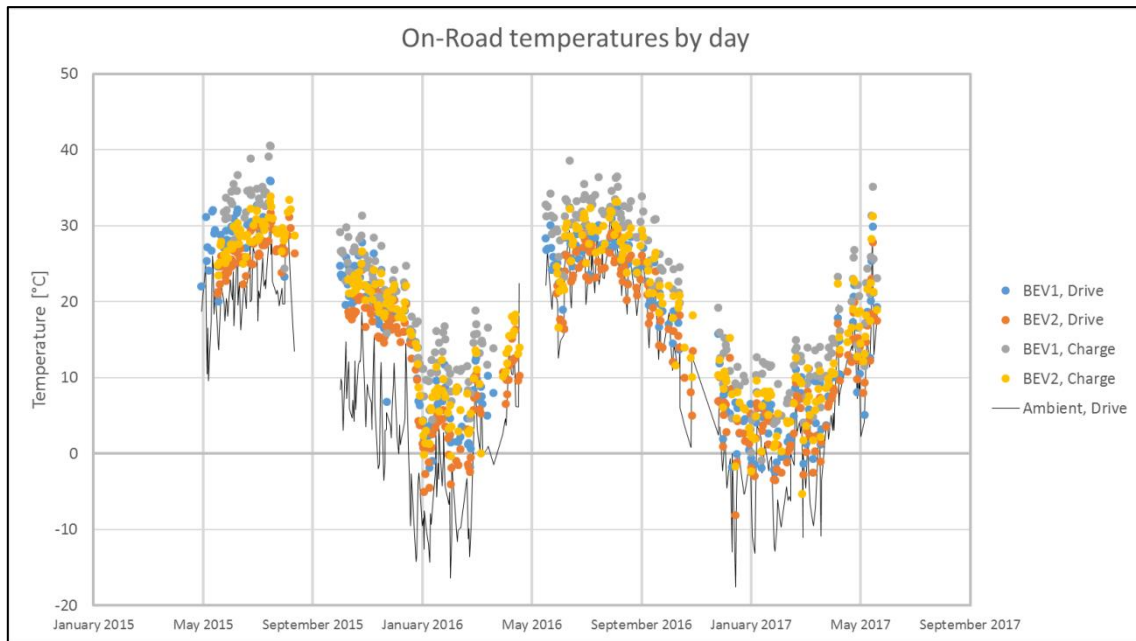


Figure 5. Daily average battery temperatures and ambient temperatures during driving and charging events

The BEVs' energy consumption rates were calculated using CAN bus battery current and voltage, performing a numeric integration over time to get the cumulative power output, then dividing by the total distance travelled; these are shown in Figure 6. Energy consumption varied with temperature and traffic conditions, and deterioration due to accumulated mileage is not apparent in the on-road results. Figure 6 also shows the average energy consumption rates on the dynamometer driving cycles. These were comparable to the on-road consumption rates in summer, but as expected, lower compared to on-road consumption rates in winter.

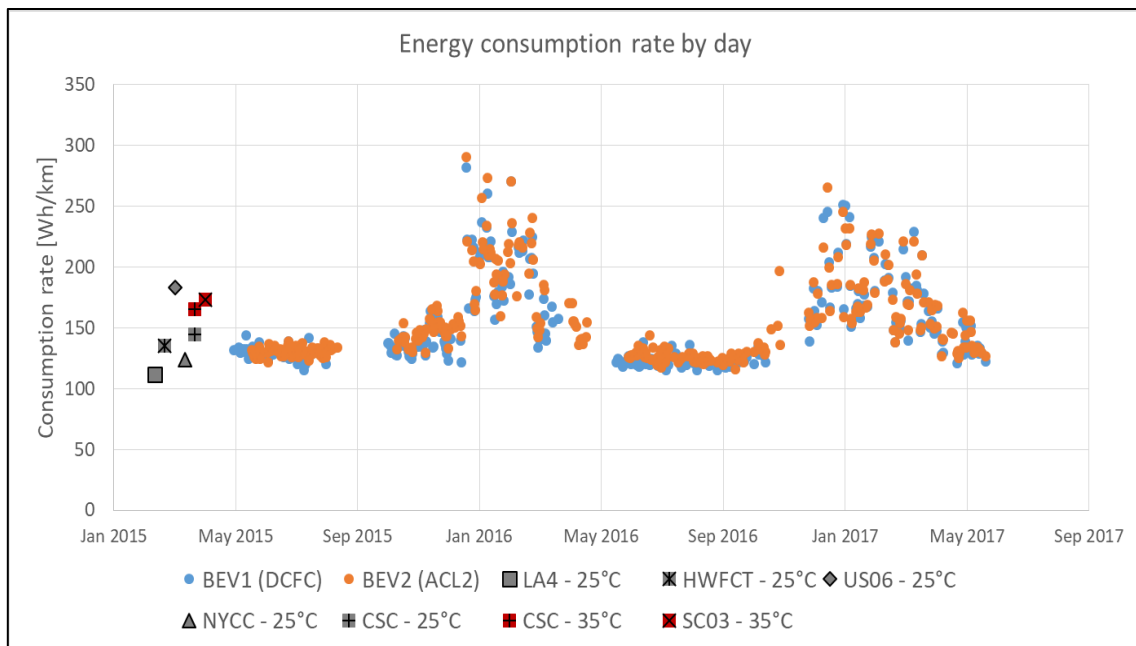


Figure 6. Energy consumption rates: on-road and in-lab

3.2 In-Lab Results

Charging and Usable Energy

As shown in Figure 7, FRE and UBE decreased at each 15,000 km test interval. By 50,000 km, the 25°C FRE had decreased by 9% for BEV1 and 6.2% for BEV2, while the UBE had decreased by 10% for BEV1 and 6.8% for BEV2. The reductions for each energy mode are shown in Table 7. BEV1, had lost 3.2% more UBE at 50,000 km than did BEV2, at a statistically significant level ($p \leq 0.05$).

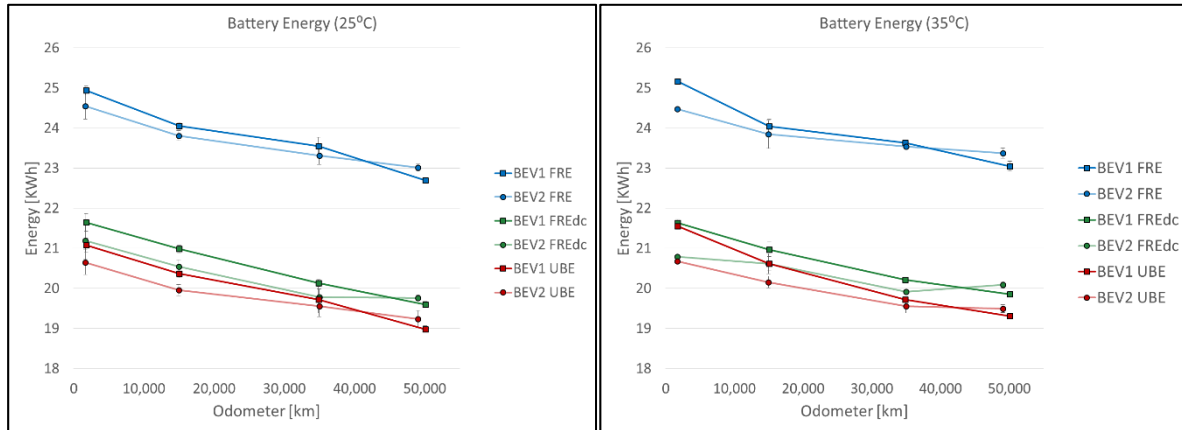


Figure 7. Battery energy at 25°C and 35°C: Usable Battery Energy (UBE), Full Recharge Energy (FRE), and FREdc \pm 1 standard deviation

Table 7. Reduction in battery energy from round 1 (1,600 km) to round 4 (50,000 km) (average of all full depletion tests)

	25°C			35°C			
	UBE	FRE	FREdc	UBE	FRE	FREdc	
BEV1 – DCFC	10.0%	9.0%	9.5%	10.4%	8.4%	8.2%	Significant ($p \leq 0.01$)
BEV2 – ACL2	6.8%	6.2%	6.8%	5.7%	4.5%	3.4%	Significant ($0.01 < p \leq 0.05$)

Driving Range

Driving range for each round 4 cycle, calculated based on the UBE and the cycle's ECdc, varied between 103 km and 167 km, depending on the driving style. Driving range was longest on the moderate speed city cycle (LA4) and shortest on the high speed aggressive cycle (US06). At 50,000 km, only considering statistically significant results, the driving range had decreased by between 10.1% and 12.5% for BEV1, and 6.1% to 8.9% for BEV2. BEV1 had a 3-5% greater reduction in driving range with mileage accumulation in comparison to BEV2, which was also statistically significant. Assuming a linear relation between mileage accumulation and BEV range, the range degradation corresponds to approximately 2.3% per 10,000 km for BEV1, and 1.5% per 10,000 km for BEV2. Other studies have reported values close to 2.2% [8].

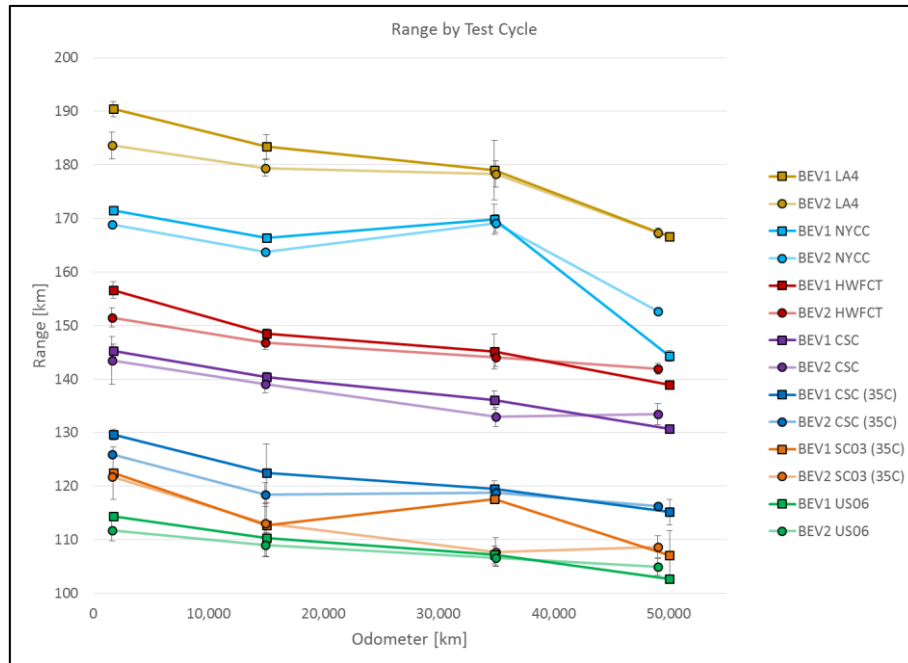


Figure 8. Evolution of available range for different test cycles for each vehicle.

Table 8. Reduction in vehicle range from round 1 (1,600 km) to round 4 (50,000 km).

	25°C					35°C		Legend
	LA4	HWFCT	US06	CSC	NYCC	CSC	SC03	
BEV1 – DCFC	12.5%	11.3%	10.3%	10.1%	15.9%	11.2%	12.5%	Significant (0.01 < p <= 0.05)
BEV2 – ACL2	8.9%	6.3%	6.1%	7.0%	9.6%	7.7%	10.7%	Significant (p <= 0.01)

It is worth noting the initial offset in performance between BEV1 and BEV2 when comparing the baseline ranges between the two BEVs; specifically, for every baseline (1,600 km) test cycle, BEV1 had a greater range than BEV2.

4 Conclusion

This paper describes the first four rounds and interim results of a multi-year, 8-round study to investigate the impact of mileage accumulation and fast-charging in Canadian seasonal climates on driving range and the battery energies of two 2015 BEVs of the same make and model. As of July 2017, the vehicles achieved 65,000 km and round 5 testing is currently underway.

On-board CAN bus data was collected during mileage accumulation and chassis dynamometer testing, which was performed at 15,000 km intervals to determine the UBEs, ECdc rates, and ranges.

During mileage accumulation, the vehicles were subjected to temperatures as low as -22°C. The battery temperatures were generally higher for the fast-charging BEV1, by about 2.7°C during driving and charging events. The maximum battery temperature reached by BEV1 during charging was 49°C, while the maximum battery temperature for BEV2 was only 38°C.

In-lab chassis dynamometer testing indicated an initial performance offset between the two BEVs, where BEV1 achieved generally greater range and usable battery energy than BEV2. After 50,000 km of accumulated mileage, driving range decreased by between 6.1% and 12.5%, depending on the test cycle applied, and UBE decreased by 6.8% to 10.0%. BEV1 exhibited up to 5% greater degradation in range than BEV2.

The study will continue until the vehicles reach 105,000 km. Supplemental analysis is scheduled, including an analysis of on-road charging parameters, top of charge voltage, and thermal performance.

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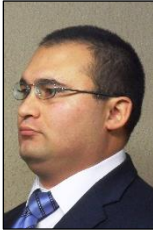
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