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Impacts of Mileage Accumulation and Fast Charging on EV Range and Energy Use

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Executive Summary

The effects of mileage accumulation and charge rate on the performance of two 2015 battery electric vehicles (BEV) were investigated in Canadian climate between 2015 and 2021. One BEV was charged exclusively on 7 kW AC (ACL2), and the other on 50 kW DC fast charge (DCFC). During this time, they were tested on chassis dynamometers at intervals of 15,000 km. After 104,000 km of accumulation, the 25°C useable battery energies have decreased by 18% (DCFC) and 13% (ACL2). This study compares these and other findings to models and relevant benchmarks, and looks to the future of regulating battery durability.

1 Introduction

An unprecedented number of governments and OEMs have set ambitious targets for battery electric vehicle (BEV) market penetration as early as 2030 and 2040 [1], [2]. These targets are being set for several reasons, one of which is to reduce the carbon intensity of the transportation sector. Key to this objective is the battery electric vehicle's longevity. If a BEV's traction battery lasts only 5 years before it cannot provide enough energy for the daily requirements of the consumer, its benefits over a conventional internal combustion engine vehicle (ICEV) are not realized. Thus, battery durability continues to be an important subject, both from the perspective of the consumer, and from the perspective of regulators, who have widely allowed OEMs to set their own durability standards via warranties that specify mileage, calendar age and battery degradation. In 2021, California Air Resource Board (CARB) announced a new battery durability requirement for OEMs: at least 80% of the original usable battery energy (UBE) after 10 years or 150,000 miles (241,000 km) [3]. Additionally, the World Forum for Harmonization of Vehicle Regulations, with input from major Tier 1 OEMs, governments and industry representatives, has drafted a global technical regulation (GTR) that specifies less than 20% battery capacity be degraded after 5 years or 100,000 km and less than 30% after 8 years or 160,000 km [4], [5].

Part of the development of these regulations, and establishing expectations for the consumer, is determining what level of durability can be expected with today's, and tomorrow's technology, and how a durability test can be established for multiple architectures, drivetrains and battery technologies.

Battery durability is not a new subject; many studies have been conducted on various battery chemistries and usage patterns to estimate the battery performance throughout its life, and J. Guo et al. (2021) summarizes multiple review papers that describe these many studies in relation to one another, covering various battery technologies, aging mechanisms and usage patterns [6]. The majority of these studies have investigated battery durability at the cell level or through modelling, at the battery pack level [7-11]. Very few studies have been published that demonstrate a BEV's durability empirically [12-15]. These studies are resource intensive, last multiple years and are very costly, yet they are the foundation of validating all models that purport to estimate battery performance over its lifetime. The effects of combining multiple cells into modules and packs and the addition of packaging, thermal management controls and the interface between the pack and a vehicle may result in degradation profile differences between vehicle level testing and cell level studies.

This paper reports the final results of a joint six-year study between Environment and Climate Change Canada (ECCC) and Transport Canada (TC) that measured battery electric range and energy usage in two identical BEVs while they were tested on a chassis dynamometer using the Canadian Environmental Protection Act 1999 (CEPA1999) procedures (equivalent to the U.S. Environmental Protection Agency (EPA) Code of Federal Regulations (CFR) Title 40 Part 86, which references the SAE J1634 recommended practice) [16-18]. The study began in 2015 and concluded in 2021, after eight rounds of in-lab chassis dynamometer testing at approximately 15,000 km intervals, and 104,000 km of mileage accumulation.

2 Method

Three previous interim papers concerning this six-year study [13-15] detail the materials, instruments and procedures used throughout this test program. Some of the information is provided in this paper as well, with updates on the driving statistics, instrumentation and test matrix.

Transport Canada mileage accumulated two identical 2015 model year BEVs on-road in Ottawa, Ontario over two prescribed city routes (both with similar drive characteristics) to 104,000 km between 2015 and 2021, throughout all seasons of the year. Figure 1 presents the on-board diagnostic average measured ambient temperatures, and battery temperatures throughout this study. The daily measured average ambient temperatures reached highs of over 30°C and lows of close to -20°C. The gaps in data represent the time periods for which the vehicles were being tested in-lab.

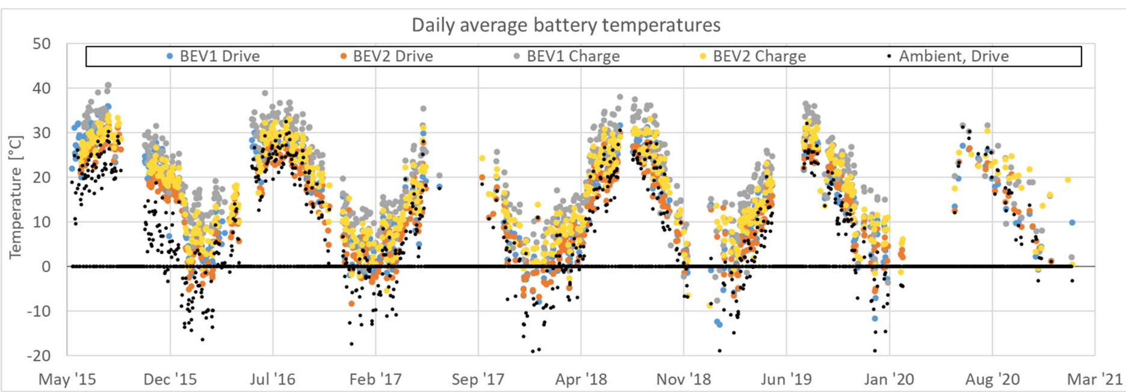


Figure 1: Daily average battery and ambient temperatures between 2015 and 2021 for both BEVs during on-road accumulation

At intervals of approximately 15,000 km, both vehicles were concurrently tested on chassis dynamometers at the Emissions Research and Measurement Section (ERMS) of Environment and Climate Change Canada (ECCC). One of the BEVs (BEV1) was charged exclusively on DC Level 3 charging (DCFC – 50kW) during mileage accumulation, and the other BEV (BEV2) was charged exclusively on SAE J1772 AC Level 2 (ACL2 – 6kW) during mileage accumulation. Both BEVs were charged at ACL2 while in-lab for chassis dynamometer testing.

On-Road Mileage Accumulation

Transport Canada contracted drivers to mileage accumulate both BEVs concurrently in order to expose them to identical environmental conditions. During the summer months, the BEVs were driven over a 35.3 km route, starting and ending at the Transport Canada depot. In the winter months, the two BEVS were driven over an abbreviated route of 23.2 km. Both routes were designed so that (a) the BEVs could easily complete two loops within one charge, (b) they exposed the BEVs to the driving characteristics one might expect in Canada, and (c) the extraneous variables one encounters on-road would be limited (i.e. traffic lights, traffic density, pedestrians). During all six years of mileage accumulation, drivers were rotated between vehicles, and tires were switched from summer to winter and back again in November and April, respectively. The vehicles' cabin environments were set to 22°C and automatic fan for the majority of mileage accumulation. During particularly hot or cold days, drivers were permitted to adjust the cabin environment to maintain safe driving conditions for the occupant.

Instrumentation and Data Acquisition

The battery temperatures, states-of-charge (SOC) and energy consumption rates (ECdc) of both BEVs were monitored during mileage accumulation with the use of an on-board diagnostic (OBD) tool. Additionally, a GPS on the OBD logger was used to accurately characterize the driving route. The full list of signals measured during on-road accumulation (and during in lab testing) is presented in Table 1. Using this data, the metrics presented in Table 2 were calculated.

Table 1: On-board diagnostic signals collected during on-road accumulation and in-lab testing

Signal	Units	Signal	Units	Signal	Units
Battery Module Temp 1	°C	PTC Power	kW	Charge Level	#
Battery Module Temp 2	°C	Dash Odometer	km	Motor Speed	rpm
Battery Module Temp 4	°C	Main Battery Current	Ampere	Motor Torque	Nm
Board Temp	°C	Main Battery Voltage	Volts	GPS Latitude	#
Outside Air Temp	°C	Main Battery SOC	%	GPS Longitude	#
Vehicle Speed	km/h	Air Conditioning Power	kW	GPS Altitude	m
Minimum Cell Voltage	Volts	Maximum Cell Voltage	Volts	Time	ms

Table 2: Calculated metrics from measured OBD signals

Metric	Units	Metric	Units
Distance Travelled	Km	Max Deceleration	km/h/s
Time Spent idling	S	Current Throughput	Ah
Event Duration	S	Min / Max Battery Current	A
Min Battery Temp	°C	Min Ambient Temp	°C
Ave Battery Temp	°C	Ave Ambient Temp	°C
Max Battery Temp	°C	Max Ambient Temp	°C
Max PTC power	kW	AC Power	kW
PTC Energy	kWh	AC Energy	kWh
Average Speed	km/h	Battery Discharge / Charge / Regen Energy	kWh
Max Acceleration	km/h/s		

In-Lab Testing

In total, almost 1400 individual tests were conducted on the two BEVs between 2015 and 2021 on chassis dynamometers at the Emissions Research and Measurement Section (ERMS) of Environment and Climate Change Canada (ECCC). Due to the duration and the number of tests required for each round of testing, multiple drivers participated in undertaking the testing over the course of this project, which added to the variability in results (discussed in section 3). Over the duration of the study, in-lab testing consisted of -7°C US06 Multi-Cycle Tests (MCTs) and NYCC Single-Cycle Tests (SCTs) in Rounds 1 and 8, and 25°C testing of those same test sequences and 35°C testing of the SC03 SCT during all 8 rounds of testing. In general, the aim was to conduct three repeats of the US06 MCT and two repeats each of the NYCC and SC03 SCT during each round of testing. The individual duty-cycles in each of the test sequences are described in [13-15]. The complete test matrix for this study is presented in Table 3. Generally, each test sequence is comprised of 10 individual duty cycles.

Table 3: Number of test sequence repeats for each vehicle, temperature and testing round, for the entire study

Round	Vehicle	-7°C		25°C		35°C
		US06 MCT	NYCC SCT	US06 MCT	NYCC SCT	SC03 SCT
1	BEV1	5	1	4	1	2
	BEV2	5		4	1	1
2	BEV1			3	1	2
	BEV2	1		3	1	3
3	BEV1			3	2	2
	BEV2			3	2	2
4	BEV1			3	2	2
	BEV2			3	2	2
5	BEV1			3	2	2
	BEV2			3	1	3
6	BEV1			2	2	1
	BEV2			2	2	2
7	BEV1			3	2	2
	BEV2			3	2	2
8	BEV1	3	3	3	3	3
	BEV2	3	3	4	2	5

Instrumentation and Data Acquisition

During these tests, the same metrics that were monitored on-road were monitored in-lab, along with the current and voltage measurements shown in Figure 2. The specifications for the sensors/instruments used for in-lab testing are presented in Table 4. From the data collected by these instruments, the DC energy consumption (ECdc), useable battery energy (UBE), full-recharge energy (FRE), DC full-recharge energy (FRE_{DC}), range, propulsion energy, regenerative braking energy, motor energy and theoretical wheel energy were calculated. Additionally, specific cycle metrics were calculated to investigate discrepancies in ECdc calculations, discussed more in section 3. The calculation methods and practices are outlined in [13-15], and are reflective of the practices recommended in SAE J1634 [18].

Table 4: Instrument and sensor specifications for in-lab testing

Metric	**Units**	**Accuracy**	**Instrument**	**Brand / Model**
Current	Amp	0.5% reading	Clamp-on Amp Probe	HIOKI CT6843
Voltage	Volt	N/A	Voltage leads	HIOKI PW6001-6
Energy	Wh	0.6% reading	Power Analyser	HIOKI PW6001-6
Dynamometer Roller Speed	m/s	15 arcsec	Position sensors & encoder	Gurley Series 835S
Dynamometer Loading	Newton	0.03% FS	Load cell	Interface Force 1110F0P-5K
Temperature	Celsius	1 °C	T-type thermocouple	Omega Type T

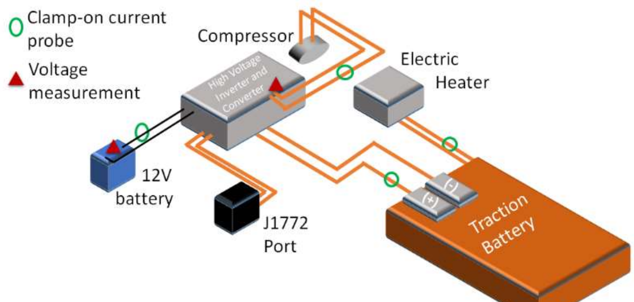


Figure 2: 2015 BEV powertrain measurement locations

3 Results

At the inception of this study (2015), when both vehicles had approximately 1500 km accumulation each, BEV1 started with a median 25°C UBE and range of 2.4% higher and 2.6% higher than BEV2's, respectively. At 104,000 km (2021), BEV1 had a median 25°C UBE and range of 3.4% and 2.2% lower than those of BEV2, respectively, indicating that BEV1's battery had degraded more quickly than BEV2's. This degradation, when simply integrated between the first and last rounds of testing, equates to a range loss of approximately 2.4 km per 10,000 km accumulation for BEV 1 and 1.7 km per 10,000 km accumulation for BEV2. These results indicate that DCFC, for this 2015 BEV model, does in fact accelerate battery degradation, compared to ACL2 charging. The Real Use versus Model Battery Degradation section provides a detailed examination of the UBE degradation at the different stages of this study and is based on several vehicle properties and metrics.

Figure 3 presents the averaged UBE, FRE_{DC} and FRE metrics for all rounds of in-lab testing and both BEVs at 25°C. During Round 7, BEV2's radiator fan operated at all times during charge events, which lasted 12 hours; this was found to be due to a malfunctioning coolant temperature sensor, adjacent to the radiator. The continuous operation of the fan resulted in an unusually high amount of grid energy (FRE) being required to fully charge the BEV2 battery. This issue was resolved by having a local dealership replace the coolant temperature sensor. Aside from that malfunction, between 1500 km and 104,000 km, the energy transfer efficiency between the grid and the battery packs was minimally diminished: 2% for BEV1 and 1% for BEV2. Similarly, the energy transfer efficiency between charge energy into the battery pack and discharge energy out of the battery decreased by 1% for BEV1 and was unchanged for BEV 2 between 1500 km and 104,000 km. However, between 1500km and 104,000km, the 25°C UBE decreased by 17.5% and 13.5% for BEV1 and BEV2, respectively. The -7°C and 35°C UBEs decreased by similar percentages, and are presented in Table 5. The differences between the 25°C UBEs and the -7°C and 35°C UBEs in Rounds 1 and 8 for both BEVs varies between 1.5 kWh less (for -7°C) and 0.4 kWh more (for 35°C), and were not affected by the BEV or the accumulated mileage.

Table 5: Decrease in UBE between Round 1 and Round 8 for both BEVs, expressed as percentage

Vehicle	Decrease in UBE between Round 1 and Round 8 [%]		
	-7°C	25°C	35°C
BEV1	16.6	17.5	17.9
BEV2	13.9	13.5	13.1

The long-held criterion for end-of-life of a battery being below 80% its nominal battery capacity (introduced by the U.S. Advanced Battery Consortium (USABC) in 1996 [19]) continues to be a metric used in the industry. However, this convention is being challenged with assertions that even below 80% nominal capacity a traction battery will meet the requirements of many daily trips for commuters [20]. Around the inception of this study, many OEMs were offering warranties on their electric vehicles and battery packs of 160,000 km, or 8 years, before the battery would reach 70% to 80% nominal capacity, depending on the brand [21]. Using a Wh/1000 km metric similar to the km/10000 km metric above, a simplistic estimation of the 25°C battery capacity at 160,000 km can be extrapolated: 73% for BEV1 and 79% for BEV2; which matches the assertions of OEMs very closely.

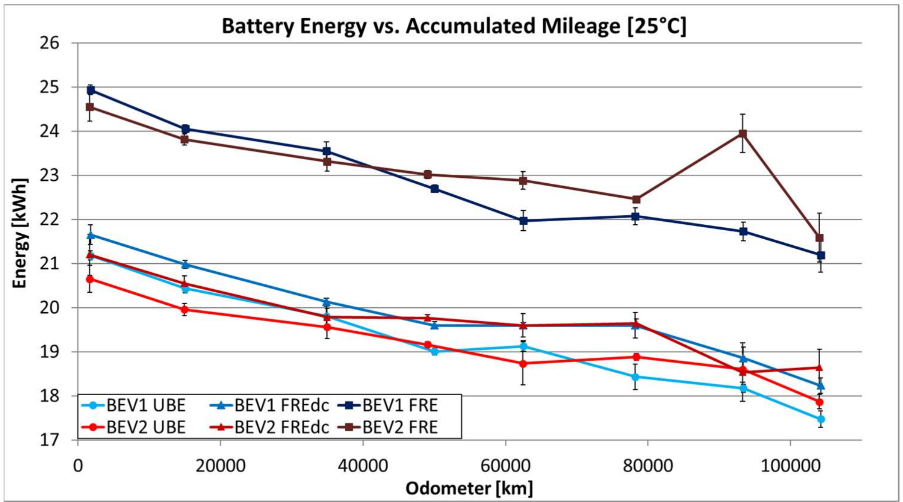


Figure 3: Measured battery energy capacities at 25°C over the duration of the project for BEV1 and BEV2

As shown in Figure 4, the BEVs' 25°C ranges for all drive cycles (LA4, HWFCT, NYCC, CSC and US06) decreased between Round 1 and Round 8, as expected. BEV1 started the test program with a higher energy capacity (1-3% higher at 25°C) and range (1-4% higher at 25°C) than BEV2. However, over a 6 year period and 104,000 km of accumulation, the 25°C ranges decreased by between 15-17% and 10-14% for BEV1 and BEV2, respectively. Interestingly, the calculated ranges sometimes increase between rounds of testing. The calculated motor energies for each drive cycle, vehicle and temperature (rpm and torque from OBD logger) do not vary greatly from test round to test round; however, battery energy discharge rates (ECdc) do vary across testing rounds. Figure 5 presents the averaged battery ECdc for all drive cycles and test rounds, and both BEVs tested at 25°C. The averaged drive cycle ECdc rates generally exhibit the same increases and decreases between rounds. Positive kinetic energy (PKE), relative positive acceleration (RPA) and the sum of the positive speed changes per km (SPS), along with 31 other more conventional drive metrics, were calculated for all tests. These metrics were selected based on the findings of A. Braun and W. Rid (2017), who calculated the correlation coefficients of 45 driving pattern metrics on BEV energy consumption and found the strongest individual correlations (>0.3) for PKE, RPA and SPS [22]. From the analysis of these drive metrics and energy consumption rates, no trends of significance (correlation coefficient > 0.3) were established between drivers and test rounds and nor was there a correlation between these metrics and the test rounds or drivers that matched the trends of the ECdc curves in Figure 5. Additionally, all tests were conducted using Title 40 Code of Federal Regulations Part 86, which includes a speed tolerance of 2 mph/s deviation limit [23]. Particularly for the 25°C NYCC in Round 7 for BEV2, all 34 drive metrics calculated in this study are highly comparable to previous rounds of testing, and the motor and chassis dynamometer energies are also comparable, suggesting that the source of the erroneous ECdc rates can be attributed to the traction battery or a factor upstream to the battery. It is possible that before the coolant temperature sensor was replaced, the powertrain was negatively impacted by improper coolant circulation patterns, which affected vehicle performance; however, this hypothesis cannot be confirmed because coolant behavior and motor output were not independently measured during the study.

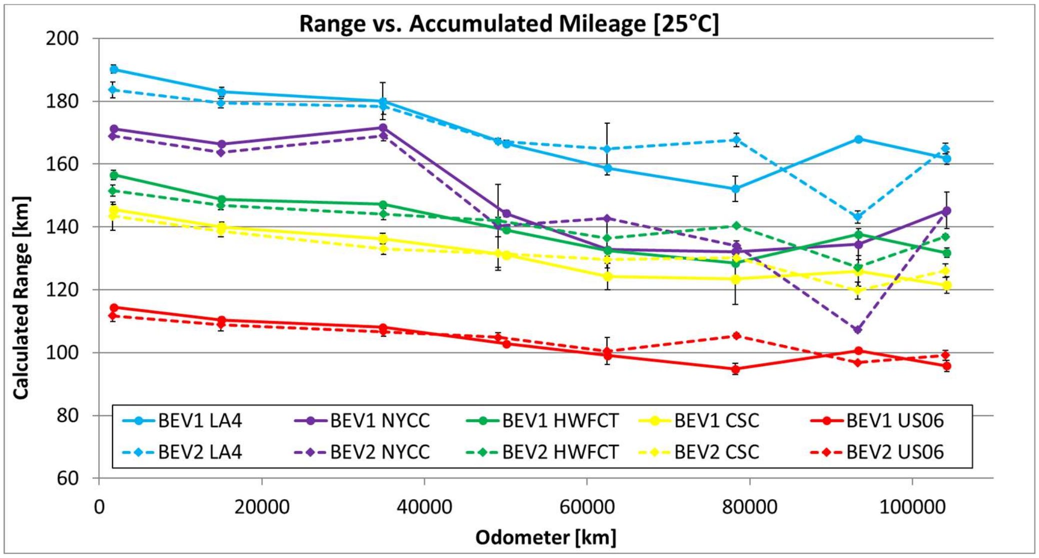


Figure 4: Calculated ranges for five chassis dynamometer drive cycles for both BEVs between 2015 and 2021 at 25°C

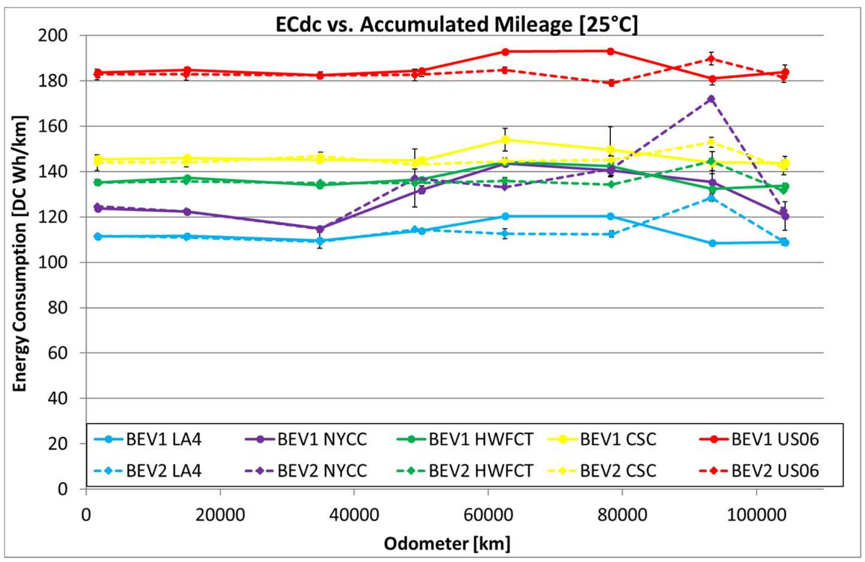


Figure 5: Calculated ECdc rates for five chassis dynamometer drive cycles for both BEVs between 2015 and 2021 at 25°C

Figure 6 presents the on-road measured ECdc rates for both BEVs from the inception of this study in 2015 (no mileage accumulation) up to 2021 (104,000 km). These values are juxtaposed against the spectrum of ECdc rates calculated for in-lab tests over all drive cycles, test rounds, temperatures and for both vehicles. As can be observed, the in-lab tests cover a large enough spectrum of driving conditions (temperatures and duty cycles) that only one real-world accumulation trip's ECdc rate exceeded the range of ECdc rates measured in-lab.

The cyclic trend of the ECdc rates over time reflects the seasonal changes, and in particular, the peaks in Figure 6 are the winter season ECdc rates, when the resistive cabin heater was being used. The spread in ECdc rates (ignoring seasonal trends) can be attributed to the numerous extraneous variables on-road, some of which are described in [15], including: pedestrians, time of day, weather conditions (diurnal heat loads, wind patterns, road conditions, temperature) and unpredictable traffic events (accidents, emergency repairs, heavy traffic). Generally, the ECdc rates from the on-road accumulation trips did not increase throughout the 6 years of this study; this matches the in-lab ECdc rates between Round 1 and Round 8.

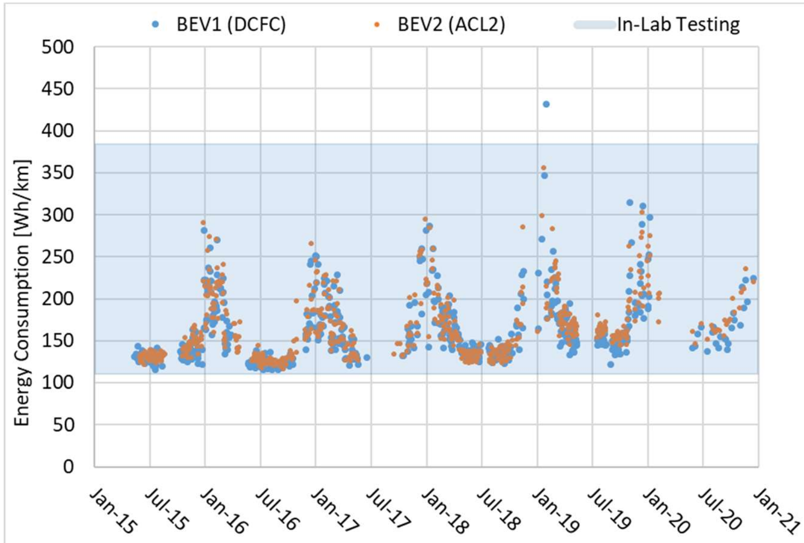
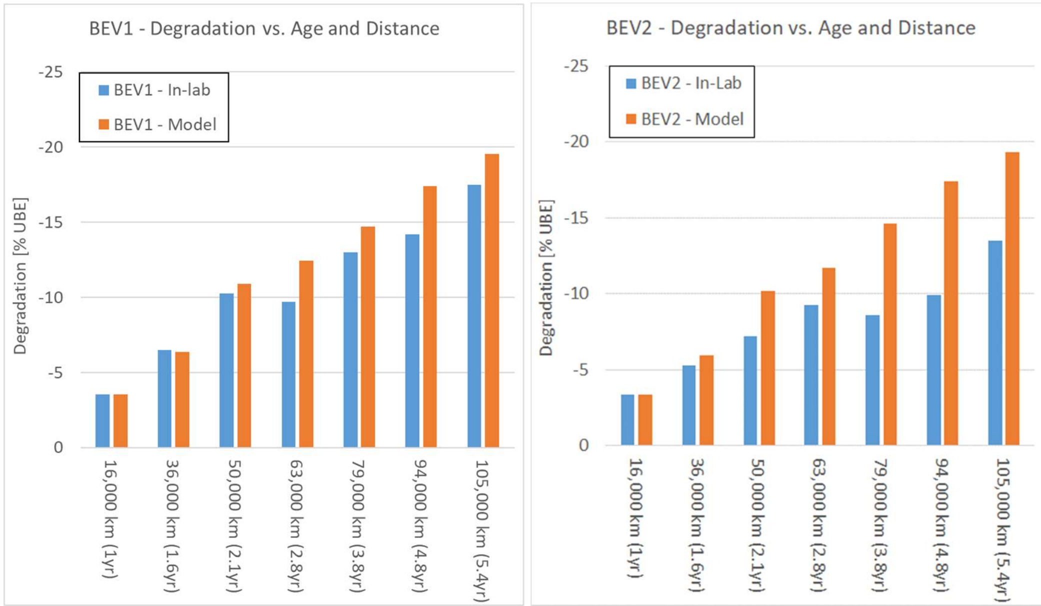


Figure 6: ECdc rates for both BEVs between 2015 and 2021 during on-road accumulation, and the range of in-lab ECdc rates for all drive cycles, test rounds, BEVs and temperatures

Real Use versus Model Battery Degradation

The model comparisons to empirical results made in Loiselle-Lapointe et al. (2018) were repeated for these final test results [15]. The tested battery degradation values for both BEVs are compared in this section to predictions for NCM-LMO cells calculated by the Joint Research Centre (JRC) Transport Technology and Mobility Assessment (TEMA) platform [11]. JRC TEMA is a modular big data platform designed to reproduce mobility behaviors of vehicles from datasets of trips collected on conventional fuel vehicles in Europe by means of GPS and to support transport policy assessments [24].

The recorded on-road test data from the vehicles was used as an input to (i) the Wang et al. capacity fade model [25] for taking into account the calendar aging and to (ii) the Cordoba-Arenas et al. capacity fade model [26] for taking into account the cycle ageing. These two models are used in combination with the battery durability module of TEMA, assuming a reserve value of 10% of the nominal battery capacity. The recorded test data needed for the calculation include the average weighted battery temperature, the average air temperature, the battery Ah-throughput during active phases (driving and charging), the minimum SOC of the battery, the driven mileage between each checkpoint, the cumulative calendar time that the vehicle is inactive, as well as the average temperature during these inactive periods, and the age of the vehicle. For this comparison, the inactive battery temperature was assumed equal to the ambient air temperature, while the active battery temperature was assumed equal to the average temperature the battery experiences during driving and charging events. The comparison of the measured and calculated UBE degradation is reported in Figure 7.



(a) (b)

Figure 7: Model versus laboratory UBE degradation (percentage) for BEV1 (a) and BEV2 (b)

The calculations tend to overestimate the measured UBE degradation values. The higher the mileage, the higher the overestimation, with the largest difference exhibited at 63,000 km for BEV1 (9.7% from the test against 12.4% from the calculation) and at 94,000 km for BEV2 (9.9% from the test against 17.4% from the calculation). In both BEV1 and BEV2, an oscillation of the measured UBE degradation is observed. In fact, the capacity fade decreases between 50,000 km and 63,000 km for BEV1 and between 63,000 km and 79,000 km for BEV2. This drop might be generated by the intervention of the battery management system (BMS); specifically, it might be that the BMS rebalances the battery under specific environmental and/or use conditions, enlarging the UBE window when a set of constraints is met. In this respect, the fact that the capacity fade inversion appears in the vicinity of the 10% degradation of the UBE and that the drop is about 0.7% for both vehicles is highly suggestive of a BMS intervention. Further investigations are needed to clarify this aspect; however, the model can be adjusted to mimic this behaviour, improving the comparison as the mileage increases. It should be noted that the capacity fade drop in BEV2 was measured after 13,000 km and after 16,000 km for BEV1, highlighting the difference with the calculated values by the model for BEV2.

Battery Degradation Regulations

Understanding battery capacity degradation over time is important to accounting for the environmental performance of electrified vehicles. Degradation can reduce the electric driving range of BEVs and plug-in hybrid electric vehicles (PHEVs), potentially reducing their utility and thus reducing electric mileage travelled during their useful life. Because vehicle regulations commonly credit BEVs and PHEVs with a useful life similar to that of ICEVs, less electric mileage would lead to less environmental benefit than is credited. Degradation can also change the electric utilization of PHEVs and/or result in more cycling and usage of the engine, increasing emissions. The United Nations Economic Commission for Europe (UN ECE) has issued Global Technical Regulation (GTR) No. 22, which establishes some of the first specific requirements for light-duty BEV and PHEV battery durability in adopting countries [4]. The California Air Resource Board (CARB) is also introducing battery durability standards and warranty requirements as part of its Advanced Clean Cars II (ACC2) program [3]. The current study has informed these regulatory efforts by providing an empirical example of battery degradation in a production vehicle, and was used to help validate the results of a battery degradation model that played a role in informing the performance requirements established by GTR No. 22. Examples of actual degradation, such as those reported here, will continue to be essential to inform the necessity for modifications to such regulations as the BEV and PHEV market evolves.

As stated in the Introduction, the provisions of the new GTR 22 regarding in-vehicle battery durability for electrified vehicles will require manufacturers to certify that the batteries in their electric vehicles will lose less than 20% of their initial capacity over 5 years or 100,000 km and less than 30% over 8 years or 160,000 km [5]. The two tested vehicles in this study, BEV1 and BEV2 show less than 20% capacity fade after 6 years and 104,000 km, indicating that this standard is achievable for vehicles that are solely ACL2 charged, as well as DCFC charged.

Conclusions

In the last year, two new battery durability regulations have been announced. The California Air Resource Board (CARB) has indicated that it will tentatively require 2026 model year and later BEVs to retain not less than 80% of their original UDDS rated range after 15 years or 150,000 miles [3]. Similarly, the United Nations Economic Commission for Europe (UNECE) reporting to the Working Party on Pollution and Energy (WPPE) published a United Nations Global Technical Regulation No. 22 entitled "Regulation on In-vehicle Battery Durability for Electrified Vehicles". In this regulation, "from the start of life to 5 years or 100,000 km, whichever comes first" the battery energy available for use must be at least 80 % of its original new condition rated energy [5]. For "Vehicles more than 5 years or 100,000 km, and up to whichever comes first of 8 years or 160,000 km" the battery energy available for use must be at least 70 % of its original new condition rated energy [5]. In this study, it was found that after 104,000 km of mileage accumulation and 6 years of continuous and recorded on-road usage in Canadian winters (~ -20°C) and summers (~ 30°C), the 25°C useable battery energy (UBE) measured 86.5% of the original new condition (1500 km) UBE for the AC Level 2 charged BEV, and 82.5% of the original new condition (1500km) UBE for the DC fast charged BEV. The BEV model tested did not employ complex battery management systems, but was able to meet these requirements nonetheless, indicating that they are achievable standards. The interim results of this study were used to inform the GTR No. 22, and have been provided to a number of research institutions hoping to validate their thermal battery, grid, and battery durability models. In addition, the two vehicles are now in the possession of the National Research Council of Canada for further testing (exact testing not yet announced at time of publication).

As new battery technologies continue to emerge, it will be important for regulatory bodies to continue updating durability (and other) performance metric testing procedures and standards of battery electric vehicles. From that perspective, the effect of bi-directional charging on battery electric vehicle durability is a natural progression from this study, and one that requires further investigation, as it continues to be a subject moving through legislative and regulatory bodies of many nations and could have significant impacts for consumers and utility providers alike.

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Presenter Biography

Aaron Loiselle-Lapointe has more than 15 years of experience testing electric mobility technologies, both on the road and on chassis dynamometers. Aaron also spent several years of in-use emission and fuel consumption tests on marine and locomotive engines. Aaron has a Masters of Applied Science degree in Environmental Engineering and a Bachelor's of Engineering degree in Aerospace Engineering.