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Separating the Effects of Calendar Ageing and Mileage Accumulation on Battery Degradation from a Pair of Light-Duty BEVs

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Executive Summary

In 2023, Environment and Climate Change Canada (ECCC) tested two identical make and model battery electric vehicles (BEVs) on a chassis dynamometer to quantify their respective battery degradations after almost 8 years of calendar ageing (low mileage vehicle – LMV), and separately, 8 years of calendar aging and 176,000 km of mileage accumulation (high mileage vehicle - HMV). The vehicles were tested at -7°C, 25°C and 35°C ambient temperatures using multiple transient drive cycles to characterize their performances over a broad range of usage cases. The capacity fade of the LMV over 7.7 years was measured to be 8% at 25°C, whereas the capacity fade of the HMV over 7.9 years was 19.9% at 25°C. Missing historical data on the vehicles' usages and storage makes conclusive statements impossible. But, assuming similar usages between the vehicles, the aging mechanisms associated with mileage accumulation affect capacity fade more than those of calendar aging.

1 Introduction

Degradation studies of battery electric vehicles (BEV) operated on-road, as a function of calendar aging and mileage accumulation are very rare. Yet, this data is precisely the information that consumers need to make informed vehicle purchases, especially with regard to the used car market. Likewise, governing bodies need this data to inform, validate and update regulations for BEV durability. In 2022, the United Nations Economic Commission for Europe (UNECE) published the Global Technical Regulation No. 22 (GTR22), "United Nations Global Technical Regulation on In-vehicle Battery Durability for Electrified Light Duty Vehicles." This regulation requires that after 8 years or 100,000 km of driving, a new BEV must retain at least 80% of its original useable battery energy (UBE) [1]. The United States of America Environmental Protection Agency (US EPA) and the European Union are adopting UN GTR 22 in their respective regulations as part of a global regulatory harmonization approach, and incorporating their requirements into their respective latest passenger automobile and light-truck regulations (US EPA Final Rule: Multi-Pollutant Emissions Standards for Model Years 2027 and Later Light-Duty and Medium Duty Vehicles, Euro 7) [2, 3]. These regulations and requirements are being written based on years of scientific investigations, technical collaborations, consultations and high-level discussions, but ultimately, they require primary test data that confirms the durability requirements will be fair for consumers and attainable using present-day technologies.

In 2022 and 2023, the authors presented studies of BEVs that were mileage accumulated on public roads and tested at intervals on chassis dynamometers at the Emissions Research and Measurement Section (ERMS) of Environment and Climate Change Canada (ECCC) [4, 5]. These studies evaluated the combined effects of calendar ageing and mileage accumulation on battery energy and range degradation, in addition to different charging/use strategies. The current study is similar to these previous studies in that the BEVs were subjected to chassis dynamometer tests in the new condition, and then again after years of mileage accumulation. However, as far as the authors are aware, at the time of submission, this current study is the only one published that investigates the battery degradation effects of mileage accumulation separately from those of calendar aging for a light duty BEV using primary test data (i.e. not modelling). In addition, this study adds to the small set of published data from laboratory-conducted BEV performance testing as a function of time and mileage.

2 Method

In 2023 and 2024, two BEVs of identical make and model, and manufactured only 7 months apart, underwent chassis dynamometer testing in environmentally controlled test chambers at the ERMS of ECCC. One BEV, hereafter referred to as the low-mileage vehicle (LMV) started the test program with 13,903 km on its odometer, while the other BEV, hereafter referred to as the high-mileage vehicle (HMV), started the test program with 176,200 km on its odometer, despite both vehicles being approximately 8 years old. Each BEV was tested at ambient temperatures of 35°C, 25°C and -7°C with cabin conditioning used in the hot and cold tests, and all tests were started at full charge and ended when the vehicle could no longer maintain the drive cycle trace-speed within 3.2 km/h/s.

2.1 Test Specimens

The two test BEVs (LMV and HMV) used in this study are identical models and trims and are equipped with electric air conditioning and positive temperature coefficient (PTC) cabin heaters, as well as a liquid-based battery thermal management system. Some general vehicle specifications are listed in Table 1.

Table 1: Test specimen vehicle specifications

Metric	LMV		HMV
Test Date	2017	2023	2023
Test Start Odometer [km]	4455	13,903	176,200
Test End Odometer [km]	8620	21,553	184,386
Manufacture Date	March 2016		October 2015
Model Year	2016		2015
Nominal Battery Capacity [kWh]	70		
ETW [kg]	2268		
Operating Voltage [V]	250-400		
Battery Chemistry	NMC		
Battery Geometry	Cylindrical		

The LMV was purchased in 2016, brand new, mileage accumulated to 1,600 km and was then used to conduct various research programs, one of which was a performance evaluation study during which it was subjected to SAE J1634-based full depletion testing at -7°C, 25°C and 35°C [6]. It was tested again in 2023, for this study, using the updated SAE J1634 test sequences, again at -7°C, 25°C and 35°C. The HMV was purchased by ECCC in 2023 to conduct this comparative study. It was tested in its as-purchased condition, after being serviced to ensure it had updated software and properly operating components and systems. While it is the same make, model and trim as the LMV, the HMV was manufactured 7 months earlier than the LMV. The history of both vehicles, which includes their energy throughput, while normally available to the registered owner, was not retrievable to the authors at the time of publication.

2.2 Instrumentation

During each test, chassis dynamometer drive metrics, including roll speed, roll force, distance, simulated mass and coastdown coefficients, among other dynamometer related metrics, were recorded. A HIOKI PW6001-16 analyser was used in conjunction with HIOKI clamp-on current probes to measure each vehicle's battery terminal current, DC-DC converter current, battery heater current, electric air conditioner (eAC) current and PTC heater current (see Figure 1). Additionally, the current and voltage coming from the grid to charge the BEVs were measured. Like most BEVs, this model uses a common nominal voltage for all high-voltage systems, and the battery voltage was taken at the battery terminals and then used in conjunction with the other components' currents to integrate current and energy and to calculate power over each test.

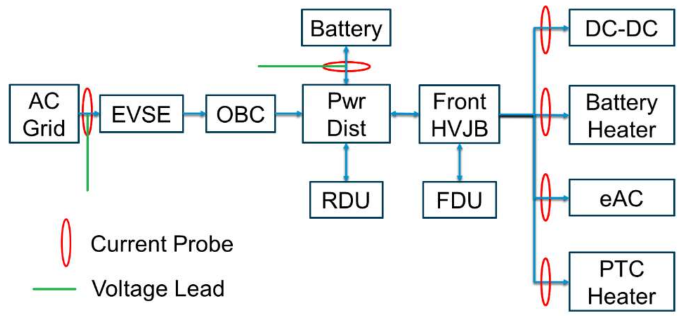

Figure 1: Powertrain schematic of the LMV and HMV, where Pwr Dist = Power Distribution Unit; RDU = Rear Drive Unit; FDU = Front Drive Unit; eAC = Electric Air Conditioner; OBC = On-Board Charger; EVSE = Electric Vehicle Supply Equipment and HVJB = High Voltage Junction Box.

During testing, the ERMS was able to acquire an OBDLink MX+ CANlogger and a standard tablet to log controller area network bus (CANbus) signals. Given that this device and the software were not created or owned by the BEV original equipment manufacturer (OEM), it did not log data with ideal fidelity, but it was the only available solution at the time. Some tests, and even a few entire test days, were not recorded. Additionally, during charge events, only three files successfully logged. The CAN data provided information that is otherwise difficult to measure using third-party equipment, including the following signals in Table 2. Unfortunately, the equipment did not arrive in time to collect these signals on the HMV, but most of the LMV tests were successfully logged. Note that the accuracy of the measured CANbus metrics is unknown.

Table 2: CANbus signals that were logged for LMV tests

Vehicle speed	State of charge
Mechanical combined power	Battery cell temperatures
DC-DC power	Odometer and distance
Battery current and voltage	HVAC related settings
Cell imbalances	Cabin and outside temperature

2.3 Test Setup

The test procedure for this study was adapted from the recommended procedures for testing electric vehicles found in SAE J1634 [6]. The BEVs were tested on a 4-wheel chassis dynamometer that simulated its road losses by using the standard technique of applying a load curve (set coefficients) to the dynamometer controller that is based on track coastdowns (target coastdowns) of the test BEV. Additionally, for the tests conducted at ambient temperatures of -7°C, the target coastdown coefficients were increased by 10% before determining the set coefficients at -7°C to account for increased vehicle power losses at cold temperatures.

Both BEVs were tested over three different types of full depletion tests (FDTs); the US06 Multi-Cycle Test (MCT), the SC03 FDT and a New York City Cycle (NYCC) FDT, at ambient temperatures of -7°C, 25°C and 35°C. During the cold and hot tests, the cabin was set to 22°C with an automatic fan. During the 25°C tests, the cabin thermal conditioning system was turned off completely. The test matrix for this study is provided in Table 3. Depending on the set of conditions (i.e. ambient temperature, vehicle, and driving sequence), the tests were repeated between 2 and 5 times. The full recharge matrix is provided in Table 4 for all ambient temperatures and both sets of the LMV and HMV 2023 tests, and also includes full recharge events that followed preconditioning tests.

During testing, all advanced driver assistance features were disabled on the vehicles, and augmented braking was disabled on the chassis dynamometer to allow the vehicles to recuperate energy through regenerative braking energy from the dynamometer's inertia.

Table 3: Test Matrix

Test Vehicle	**Start Odometer [km]**	**End Odometer [km]**	**-7°C**		**25°C**		**35°C**
			US06 MCT	**NYCC FDT**	**US06 MCT**	**NYCC FDT**	**SC03 FDT**
LMV (2023)	13,903	21,553	3	3	3	3	3
HMV (2023)	176,200	184,386	3	3	5	2	4

Table 4: Full charge repeats

Test Vehicle	-7°C	25°C	35°C
LMV (2023)	10	9	4
HMV (2023)	10	13	5

3 Calculations

3.1 State of Charge versus Energy

The state-of-charge (SOC) of the traction battery was recorded for the LMV using a CANlogger. The quantity of energy consumed per 1% SOC was calculated from the CANlogger data to determine (1) if the metric was consistent across temperatures and test conditions and (2) if it could be used to extrapolate a good estimate of the UBE. For each individual drive cycle where the SOC was recorded, the CANbus-determined battery energy was used to determine the amount of kWh associated with 1% SOC. This analysis revealed that 1% SOC is equivalent to 1.59 kWh with a coefficient of variation of 2.1%. The metric was steady across all LMV tests for which it was possible to calculate.

3.2 Energies

Each of the energy metrics presented in Section 4 are derived from the HIOKI-measured and integrated current and voltage readings. The useable battery energy (UBE) was calculated from the sum of all propulsion and non-propulsion discharging activities that the vehicle underwent in a single test day, from fully charged to fully depleted. The full-recharge energy (FRE) was similarly calculated as the total energy drawn from the AC grid to the electric vehicle supply equipment (EVSE) to charge the vehicle after each test. The FRE_{DC} is a metric the represents the total charge energy rectified by the on-board charger (OBC) for charging the battery and/or concurrently powering on-board auxiliaries. The BAT_{IN} metric is the sum of all charge energy entering the battery during a charge event. Depending on the battery heater, DC-DC, eAC and PTC heater use during charge events, the difference between the FRE and BAT_{IN} can be significant. Separately, the difference in energy between the BAT_{IN} and UBE represents the inherent hysterysis of the battery pack [7]. In any BEV, the relationship between the above variables is as shown below:

$$FRE > FRE_{DC} > BAT_{IN} > UBE$$

The above metrics are located along the powertrain of the test BEVs in Figure 2 and their differences and losses for both the LMV and HMV are discussed in Section 4.

While dynamometer metrics were logged in order to cross-check test data and verify correct loading, it was also used to attempt an estimation of total roll energy (i.e. the energy from the drivetrain that reaches the surface of the tires). However, this metric was determined to be inaccurate because the resolution of the data captured was 1 Hz, which is too sparse to accurately estimate drive metrics. SAE J2951 specifies an optimal resolution of 10Hz [8]. The ECCC dynamometers are capable of this data logging resolution and in subsequent work, this requirement has been integrated into test program designs.

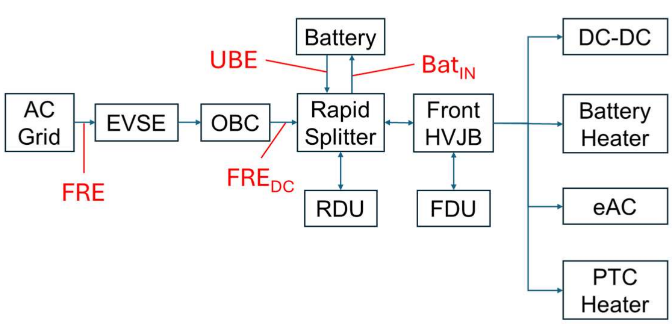

Figure 2: Locations along powertrain associated with energy metrics.

4 **Results**

4.1 Energy Differences between LMV and HMV

Figure 3 presents the average UBE's for the LMV tested in 2017 and 2023, and the HMV tested in 2023, at -7°C, 25°C and 35°C. The error bars represent one standard deviation from the associated average. In general, the -7°C energies are the least repeatable, which is likely due to the variable auxiliary loads (including DC-DC, cabin heater, electric A/C and battery heater). Out of the three vehicle test campaigns, the 2023 HMV tests have the highest energy variability. This variability can be at least partially attributed to its 'full-charge' state-of-charge (SOC). Despite consistently setting the maximum charge level to 100% SOC via the vehicle's dashboard screen, and the vehicle consistently being plugged into a Level 2 AC charger (ACL2) for more than 12 hours (after each test, overnight), the HMV 'full-charge' SOC at -7°C varies between 84% and 98% (median = 92%). In contrast, the LMV starting SOC for its -7°C tests varies between 92% and 97% (median = 96%). While the varying 'full-charge' SOC is an indication of why the HMV's energies were not as consistent from test-to-test, the reason for this variation in SOC remains unknown. Unfortunately, the vehicle's CANbus signals were not logged for the HMV, and its history is not accessible to the authors at the time of publication. These two sources of information would likely provide some valuable insight into the logic of the HMV's battery management system (BMS).

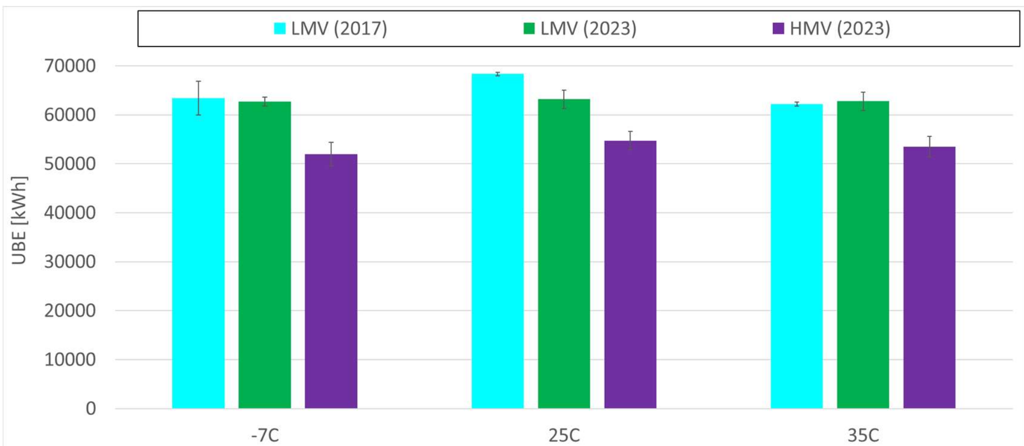

Figure 3: Useable battery energy of LMV in 2017 and 2023, and HMV in 2023 at -7°C, 25°C and 35°C.

The UBEs presented in Figure 3 illustrate the maximum available energy of the 2016 BEV model in its 'new' condition (LMV (2017)), tested in 2023 with low mileage (LMV (2023)) and tested in 2023 with high mileage (HMV (2023)); with the caveat that the HMV (2023) tests were conducted on a different vehicle. With a nominal rated battery energy of 70 kWh, this BEV has an as-new 25°C UBE of 68 kWh, indicating an absolute depth of discharge (DoD) of 97%; if so, the BMS strategy allows battery discharge and charge at extreme SOC levels that accelerate battery degradation. It is possible, however, that the vehicle is rated at 70 kWh, but equipped with a larger battery pack, with some energy held in reserve, as is the practice of several electric vehicle manufacturers [9]. In this scenario, as the battery capacity decreases, the BMS will open more battery capacity for the user to access, thus reducing the higher loss in range that would otherwise be observed by the BEV owner.

The LMV 25°C UBE, after 7.7 years and 13,903 km, decreased by 8%; the same UBE comparisons at -7°C and 35°C are non-statistically significant ($\rho = 0.05$). The HMV (2023) UBEs at -7°C, 25°C and 35°C are 18%, 20% and 14% less than the LMV (2017) UBEs ($\rho = 0.05$), respectively. The temptation is to attribute the difference between the LMV (2023) and HMV (2023) losses, 20% versus 8% at 25°C, to the difference in mileage between the two vehicles (176,200 km versus 13,903 km), since they close to the same age. In this case, 8% capacity loss would be associated with calendar aging and 12% (8% subtracted from 20%) capacity loss would be associated with the difference in mileage accumulation between the two BEVs (162,187 km). Calendar aging and mileage accumulation, while part of the cause of battery capacity degradation, cannot be used on their own to predict capacity fade. Whether a BEV is left unused (static ageing) or it is being driven (discharging), or it is being charged, it will undergo physical, electrical and chemical processes that age a lithium battery [10]. The factors affecting the rates of these processes are the battery temperature, discharge or charge rate (C-rate), depth of discharge (DoD), cut-off voltage and static state-of-charge [10-11]. While this study provides comparisons between battery capacity fade, mileage accumulation and calendar ageing, it does not include the history of the vehicles' C-rates, DoDs (which can be user-defined), temperature exposures (particularly salient in Canada) and their static SOCs. These metrics, had they been controlled and measured over the almost eight years spanning the vehicles' lives, would contextualize the LMV's and HMV's capacity fades beyond the simple metrics of calendar ageing and mileage accumulation. It is important to note, however, that while calendar ageing and mileage accumulation cannot be used to accurately predict capacity fade on their own, they are often referenced when discussing battery life because they are so easy to measure and track, and because they are widely used as determinants of vehicle warranties and national BEV durability regulations [1, 12]. As such, comparisons of mileage accumulation and calendar age to capacity fade continue to be useful to regulators, automotive groups and consumers.

Another perspective of electric vehicle aging is to look at the deterioration of non-battery components. Figure 4 presents the average battery energies required to propel the 2016 BEV over the CSC, HWFCT, LA4, NYCC and US06 drive cycles, at 25°C. It excludes the recuperation of energy during the tests through regenerative braking. While only the 25°C results are shown below, they are representative of the -7°C and 35°C comparisons as well. Both the low- and high-mileage vehicles have nearly identical tractive efforts, indicating that despite being driven over 160,000 km more than the LMV, the HMV drivetrain has not degraded any more than the LMV's. While it is expected that electric vehicle components degrade much more slowly than internal combustion engine vehicle (ICEV) components because they are exposed to much less friction, movement and temperature extremes, this comparison illustrates just how little BEV components can degrade even after extensive driving.

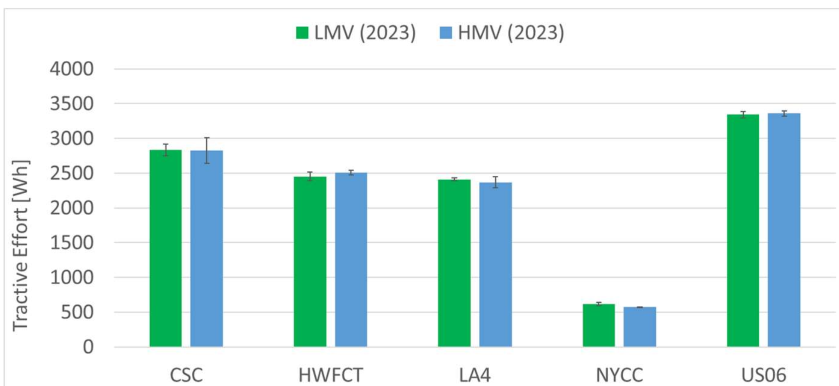

Figure 4: Battery discharge energy required to propel the 2016 BEV during transient drive cycles at 25°C.

4.2 Charge Energy Losses – Comparison between LMV and HMV

The average percentage of energy losses between the AC grid (FRE) and the battery charge (FRE_{DC}), the battery energy received (BAT_{IN}) and the UBE, and the overall losses between the AC Grid and the UBE, are summarized in Table 5 for all test conditions. The errors presented are one standard deviation from the associated average. Charge events consisted of battery charging, followed by a period known as 'conditioning', where the charger remained connected to the BEV, but only drawing electricity from the grid occasionally and on demand by the BEVs' power electronics and auxiliary systems, such as the battery heater. The analysis below excludes the vehicle conditioning energy, but includes the energy consumed by the power electronics and auxiliary energy during active charging.

Table 5: Average energy transfer losses during charging and discharging (standard deviations are gray font to facilitate interpreting the numbers in the table).

Vehicle	Ambient Temp. [°C]	Energy Loss [%]			
		FRE → FRE_{DC}	FRE_{DC} → BAT_{IN}	BAT_{IN} → UBE	FRE → UBE
HMV (2023)	-7	6.3 ± 0.8	5.4 ± 4.8	7.6 ± 2.8	18.1 ± 4.4
LMV (2023)		6.9 ± 0.4	6.6 ± 8.0	5.6 ± 1.7	18.1 ± 6.9
LMV (2017)		7.5 ± 0.9	3.2 ± 1.2	6.3 ± 2.2	16.1 ± 0.5
HMV (2023)	25	6.9 ± 1.2	4.2 ± 2.4	6.3 ± 2.0	15.9 ± 2.8
LMV (2023)		6.9 ± 0.2	3.1 ± 0.2	6.4 ± 0.7	15.5 ± 0.9
LMV (2017)		7.6 ± 1.3	2.3 ± 1.8	5.9 ± 1.2	15.0 ± 1.4
HMV (2023)	35	3.5 ± 0.1	4.7 ± 0.2	6.8 ± 1.0	17.3 ± 1.5
LMV (2023)		7.0 ± 0.0	4.0 ± 0.3	7.8 ± 2.8	17.7 ± 2.5
LMV (2017)		8.1 ± 0.3	2.2 ± 0.1	4.6 ± 1.0	14.2 ± 1.3

4.2.1 Loss of Energy between the FRE to FRE_{DC}

The energy losses that occur between the grid and the battery during charging are due to heat dissipation in the EVSE (which essentially acts as a large switch), the EVSE cable, the BEV's internal cabling, and the OBC. Most of the energy transmission losses between these two points occur in the OBC, which includes an electromagnetic interference filter, power factor converter, transformer, rectifier and DC filter [13]. The FRE to FRE_{DC} comparison includes all the energy sent from the grid to the point just after the charge power exits the OBC and thus includes energy concurrently sent to the battery and to the power electronics and low-voltage auxiliaries – see Figure 2). The FRE→FRE_{DC} losses between the 2017 LMV, 2023 LMV and 2023 HMV charge events are not statistically significantly different ($\rho = 0.05$), except for a few of the -7°C and 35°C charge events. This indicates that the OBCs of both BEVs did not degrade over almost eight years and more than 170,000 km of driving (for the HMV). Interestingly, in a test campaign evaluating the OBCs of multiple BEV models, it was found that the average charging efficiency for 2022 model BEVs averaged approximately 90% [14]. Shahed et al. (2024) states that depending on the technology used, the maximum rectifier efficiencies vary from 82.1% to 99.84%, with each variety of rectifier having its own inherent weaknesses and strengths [15]. In this study, the 2016 model BEV charger averaged 93% efficiency, regardless of ambient temperature, age of the vehicle or its mileage. This particular model of BEV not only has a durable and robust OBC, but it is also efficient for its vintage.

4.2.2 Loss of Energy between the FRE_{DC} and the Battery Received Charge

Figure 5 presents the minimum and maximum non-battery energy draws from the energy supplied post-OBC (FRE_{DC}) for all ambient temperatures and both the LMV and HMV during 2023 tests. Note that the scale of the chart is logarithmic. For all charge conditions, the power electronics and auxiliaries drew inconsistent quantities of energy for powering the battery heater, cabin heater, electric air compressor and 12V accessories, regardless of the test vehicle or temperature. Strikingly, the electric air conditioner and cabin heater consumed significant energy during charge events, despite the vehicles being turned off after each test, before charging commenced. The reasons for these energy consumptions could not be discerned from the available data, but the overall impact is that the energy received by the batteries (BAT_{IN}) was between 100 and 23,000 Wh less than the output of the FRE_{DC}, resulting in the energy 'losses' shown in Figure 5. The variability in the accessory usage during charging resulted in the LMV (2023) and HMV (2023) FRE_{DC}→BAT_{IN} losses not being statistically significantly different from one another, despite the HMV having driven 162,187 km more than the LMV.

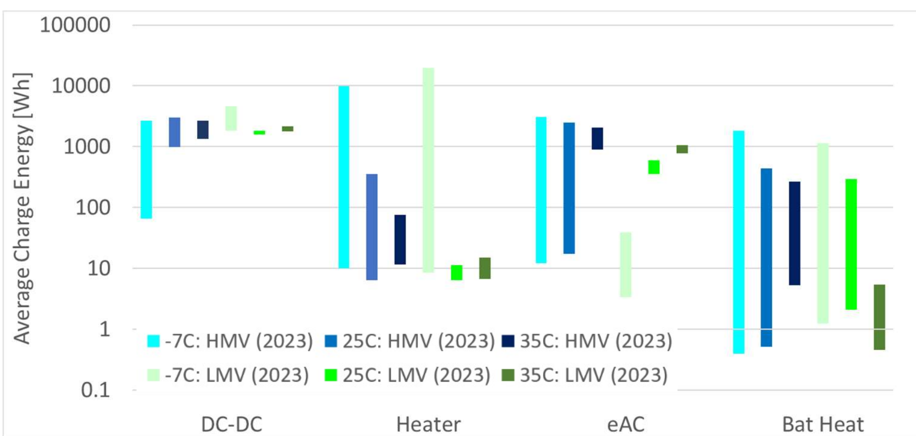

Figure 5: Minimum and maximum spectrum of energies consumed by the DC-DC converter, cabin heater, electric air conditioner and battery heater of the LMV and HMV during charge events at -7°C, 25°C and 35°C.

4.2.3 Loss of Energy between the BAT_{IN} and UBE

A lithium-ion battery's SOC versus open circuit voltage curve follows a hysteresis type loop, which illustrates its characteristic and inherent inability to discharge the same quantity of energy that is used to charge it [7]. Researchers continue to explore this hysteresis phenomenon in lithium batteries to determine its causes, but it is at least in part associated with mechanical stresses on the surfaces of the active material, thermodynamic effects, and the effects of reaction paths within a battery [16-19]. The outcome of this phenomenon is that more energy is required to charge a battery than can be discharged. The values in the BAT_{IN} → UBE column in Table 5 represent the effects of the internal resistances in the LMV and HMV. At each ambient temperature, comparisons between the LMV (2017), LMV (2023) and HMV (2023) BAT_{IN} → UBE losses resulted in no discernible differences ($\rho = 0.05$) between one another. A full charge on this 2016 model year BEV provides approximately 380 km of driving range. Extrapolating this to the odometer difference between the LMV and HMV, the HMV battery may be estimated to have cycled at least 500 times more than the LMV's battery, assuming similar charging habits. And yet, the ability of the HMV's battery to transport lithium ions and exchange electrons did not deteriorate more than the LMV's. This indicates that the HMV's higher loss in UBE than the LMV's is not caused by differences between the vehicles' battery hystereses.

The overall losses of energy from the AC grid charge energy supplied to the battery energy being used during driving are shown in the last column of Table 5. While the 2017 LMV tests clearly resulted in the lowest overall losses, the comparisons to the 2023 LMV and 2023 HMV tests resulted in non-statistically significant differences; this is due to the overall high standard deviations arising from the accessory usages during charging events (Figure 5).

4.3 Comparison of Results to Public Data

Because the historical information of the 2016 BEVs tested in this study are unavailable, its empirically determined capacity fade data cannot be compared to the estimates from existing rigorous models, such as Paffumi et al. (2024) [20]. Similarly, while numerous lithium battery cell ageing studies have been conducted (Medium (2020), Luh M. & Blank T. (2024)), and comparison to the results of this study are possible, it is outside the scope of this paper to attempt [21 and 22]. However, several companies offer automotive analytics solutions and have compiled immense datasets of thousands of BEVs driving on-road, and published their findings for public use. Individual BEV owners have also created crowdsourced datasets of specific BEV brands' ranges and battery capacity retentions, such as *Teslanomics* [23].

For instance, Geotab Inc. launched an EV battery degradation tool in 2019. At the time, their analysis indicated that EV batteries degraded at a rate of 2.3% per year [24]. In 2024, they updated their analysis to include more than 10,000 EVs and 1.5 million operating days and determined that, on average, EV batteries now degrade at a rate of 1.8% per year [25]. *Recurrent* publicly published their own long-term study that includes over 250 million miles of EV driving data from more than 15,000 BEVs and determined that for most BEVs, the battery degrades at a rate of 1-2% per year; assuming a linear regression [26]. A UK-based not-for-profit company, called *Which?*, conducted a car survey in the spring of 2024 that included more than 3,500 BEV owner submissions, in which the respondents self-reported the range of their BEVs compared to when they were new [27]. This survey found that the average range decrease was 7% over the first 7 years of owning a new BEV [27]. Similarly, an Australian company that purchases and sells used assets, *Pickles*, conducted an in-house study consisting of more than 250 tests of their used BEVs for sale in most major capital cities since October 2023 [28]. They found that even for BEVs having been driven more than 120,000 km, the 'average battery health' remained above 90% [28]. How they define battery health is not disclosed; the authors assume they refer to battery capacity retention for the purposes of this paper. All of these studies, published datasets and trends were extrapolated to compare their battery capacity loss rates to those determined in this study for both the LMV and HMV. The capacity fade rates estimated by the results from *Pickles* and *Teslanomics* for the LMV are significantly less than those from the other studies, including this one, because they related capacity fade solely to kilometers travelled, and thus their degradation metrics inherently assume a calendar aging (i.e. the time required to accumulate the mileages in their data); whereas the LMV has only 13,903 km odometer, but 7.7 years of calendar aging. Similarly, the other studies, and even the *Pickles* study using the percent capacity fade per annum metric, overestimated the battery capacity fade in the LMV; again, because those metrics from the other studies include vehicles that travelled an undisclosed mileage per annum, which is very likely more than the average 2,000 km/yr travelled by the LMV. The HMV, having been pre-owned by a private citizen, was driven approximately 25,000 km/year. All of the other studies' capacity fade rates resulted in lower overall capacity fade for the age and odometer of the HMV, compared to the capacity fade determined by this study. In particular, vehicle surveys by *Teslanomics* and *Which?* regarding capacity fade rates resulted in less than half of the overall capacity fade that this study measured for the HMV. Nonetheless, the comparisons shown in Table 6, are useful for estimating the spectrum of capacity fades one might expect for a given vintage and odometer reading of BEV, and at the very least illustrate that they are averages and do not account for atypical driving frequency.

Table 6: Comparison of the battery capacity losses determined in this study to the extrapolated losses determined in other available studies.

Source	% Loss in Battery Capacity		Data Source	Metric of comparison
	LMV	HMV		
This Study	7.6	19.9	Chassis dynamometer	N/A
Recurrent	7.8-15.6	8.0-15.9	CANbus	1-2%/year
Geotab (2019)	17.9	18.3	CANbus	2.3%/year
Geotab (2023)	14.0	14.3	CANbus	1.8%/year
Teslanomics	1.2	9.4	User survey of ranges	Trendline of range vs odometer
Which? Car Survey	7.8	8	User survey of ranges	1%/year
Pickles	1.5	14.9	Undisclosed SOH metric	9.9%/120,000km
Pickles	12.8	13.2	Undisclosed SOH metric	6.3%/4years

4.4 Differences between Onboard Diagnostics and External HIOKI Analyzer

With the advent of new vehicle technologies, it is incumbent on individual nations to develop a means to evaluate these technologies in a manner that fits their regulatory framework. With regard to electric vehicles (hybrid electric, plug-in hybrid electric, full battery electric and fuel cell electric), stakeholders in this field have lobbied to allow CANbus signals to be utilized in the regulatory confirmation process; whereas historically the measurements of vehicle metrics used to evaluate compliance to national regulations were limited to instrumentation that (1) met stringent measurement accuracy, traceability and repeatability requirements and (2) were third-party sourced.

A tangent to the primary goal of this study is the opportunity to compare the CANbus signal measurements of the traction battery energy to those of the HIOKI PW6001-16 and its clamp-on current probes, which were calibrated using a Fluke 5730A High Performance Multifunction Calibrator. This comparison can be useful in evaluating the appropriateness of permitting the use of CANbus data for reporting battery electric vehicle current and voltage measurements in confirmatory tests. Figure 6 presents the percent differences in integrated energy measurements between the HIOKI current and voltage measurements, and the CANbus recorded current and voltage measurements for all LMV tests for which the CANbus was successfully logged. The percentage differences are distinguished by temperature, and then by drive cycle, to illustrate that ambient temperature does not influence the difference in energies between the two measurement sensors, whereas drive-cycle does. Specifically, positive kinetic energy of a drive-cycle linearly and positively correlated to percentage differences between HIOKI and CANbus energy measurements ($R^2 = 0.59$). The reason why this relationship exists is that the current draw from the traction battery is low during less aggressive drive-cycles compared to more aggressive or transient cycles. At low currents, sensors tend not to be as accurate or repeatable as they are in the middle of their operable ranges. The HIOKI power analyzer is fabricated, tested and certified with a temperature drift coefficient of 0.01% current reading/°C and 0.005% full scale voltage/°C for ambient temperatures below 0°C.

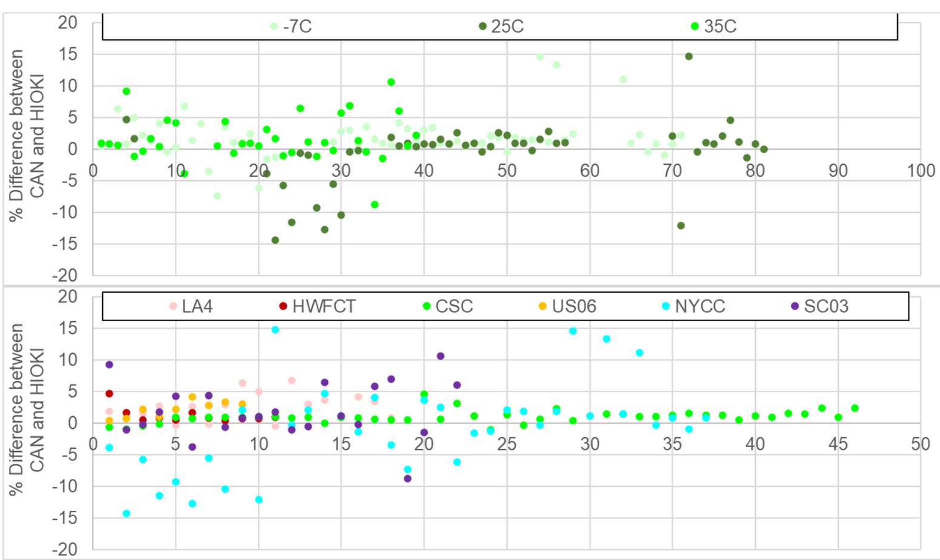

Figure 6: Percent differences between HIOKI and CANbus integrated energies for all individual tests of the LMV for which the CANbus was successfully logged: (a) separated by temperature and (b) separated by drive-cycle.

In contrast, the accuracy and effects of temperature on the CANbus recorded signals are not published or known at the time of publication. Of the 143 tests for which the HIOKI analyzer energy integration results were compared to those of the CANbus, 90 of the comparisons resulted in percentage differences being less than 2%, while four tests resulted in percentage differences of more than 12% (maximum was 15.2%). These results indicate that a discrepancy exists between the OEM CANbus signal outputs (using 2016 technology) and third-party high-fidelity instrumentation.

5 Conclusions

In 2023, the Emissions Research and Measurement Section (ERMS) of Environment and Climate Change Canada (ECCC) conducted a total of 50 full depletion tests of a low mileage BEV (LMV: model year 2016) and a high mileage BEV (HMV: model year 2015) of the same model and trim. This amounted to 399 individual transient and steady state drive-cycles being driven on a 4-wheel chassis dynamometer. Additionally, the ERMS conducted similar testing of the same LMV six years prior, in 2017. The results of all three test campaigns were analyzed to estimate the individual contributions of calendar aging and mileage accumulation to the vehicles' observed capacity fades by subtracting the effects of calendar aging (observed on the LMV) from the combined effects of calendar aging and mileage accumulation (observed on the HMV).

This study determined that the LMV, having accumulated only 13,903 km over 7.7 years (from date of manufacture) before initiating testing in November 2023, lost 8% battery capacity when tested at 25°C. In contrast, the HMV, having accumulated 176,200 km over 7.9 years (from date of manufacture) before initiating testing in August 2023, lost 20% battery capacity when tested at 25°C. Without knowing the history of the BEVs' static SOCs, their DoDs when driven, the temperatures to which they were exposed and their driving and charging patterns (C-rates), it cannot be conclusively stated that the difference between 20% and 8% capacity loss is solely attributable to mileage accumulation. The comparisons made to other public datasets of BEV capacity/range loss in this paper illustrate the effects of considering only mileage accumulation or only calendar aging when observing capacity fade, as neither alone can provide an accurate perspective of this complex metric. In an effort to tease out other variables that could affect the battery capacity fade, this paper examined the total energy throughout to drive over the transient and steady state test cycles and found that between the two BEVs, despite more than 160,000 km difference in odometer, there was no discernable difference in the energy required to drive any of the test cycles. Additionally, this paper analyzed the energy transfer losses between the AC Grid, the OBC, and the battery. It was determined that the OBCs and batteries of the LMV and HMV are not any more or less efficient than one another, indicating that the capacity fades observed in this study for the HMV are not more than the LMV because of energy transfer efficiency. Finally, although not directly related to capacity fade, the measurements of CANbus and third-party high-accuracy instrumentation were compared to provide policy makers with primary data in the hopes of informing their discussions on accepting CANbus data in place of the current stringent instrumentation accuracy, repeatability and traceability required for regulatory confirmatory testing in North America.

The ERMS has already initiated the next phase of this study by conducting similar testing on two 2022 light-duty all-electric trucks, one with 14,000 km and the other with 69,000 km. The results of this next test program will be compared to those of this study in a subsequent paper.

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