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Impact of Ambient Temperature and Battery Activity on Internal Battery Temperatures of Electric Vehicles

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Summary

The longevity of Electric Vehicle (EV) batteries strongly depends on their internal temperatures, which are directly affected by ambient conditions and by the operation of the battery thermal management system. Natural Resources Canada and Environment and Climate Change Canada investigated the internal battery temperatures of a 2015 Kia Soul EV, a 2016 Chevrolet Volt, and a 2016 Tesla Model S 70D, tested on-road in Ottawa, Ontario, Canada, under various ambient conditions and for different types of driving.

Results were analyzed and correlations were determined between the temperature change of the EV battery and ambient temperature and battery activity.

Keywords: BEV, PHEV, battery, thermal management, BMS

1 Introduction

Electric vehicles (EVs) can provide significant environmental benefits. However, detailed information on the longevity of EV batteries is necessary to convince the general public to switch to electric driving. Three EVs were tested on-road in Ottawa, Canada between January 2017 and March 2018 in a joint project between Natural Resources Canada and Environment and Climate Change Canada. The project focussed on collecting information on the operation of the battery thermal management system (TMS) and on in-use EV battery temperatures under different ambient conditions and types of driving. The collected data will support EV battery life modelling activities and will inform emerging recommended test procedures.

2 Method

2.1 Test Vehicles

The three test vehicles were a 2015 Kia Soul EV, a 2016 Chevrolet Volt, and a 2016 Tesla Model S 70D. The Soul EV and the Model S are Battery Electric Vehicles (BEVs) with battery sizes of 28 kWh and 70 kWh, respectively. The Volt is a Plug-in Hybrid Electric Vehicle (PHEV), which combines a conventional 1.5-liter gasoline engine with an electric drive train, including an 18 kWh propulsion battery (85 km all-electric range [1]).

2.2 Thermal Management Systems

All three EVs use an active TMS to maintain thermal stability in their battery packs using different technologies.

The Volt and the Model S have advanced battery conditioning systems, which employ capillary-like coolant lines within the battery pack structure to maintain safe battery cell temperatures; the coolant is electrically heated and cooled as needed. The Soul EV uses electric heating and air-cooling instead for battery pack thermal management [2].

The internal temperatures of the batteries of these EVs are controlled using a feedback system that relies, in part, on temperature sensors located within the battery packs. Figure 1 provides a side-by-side comparison of the various locations of each temperature sensor inside the battery packs of the three test vehicles. Although the type of sensors used were not explicitly determined, in general, electric vehicles rely on thermistor technology to monitor temperatures at multiple points within a battery pack. This technology provides excellent accuracy and stability within a small temperature band, which happens to be ideal for Li-ion battery packs [3 and 4]. Typical accuracy ratings for thermistors applicable for use in EVs fall in the range of ±0.2°C [4]. However, for the purposes of the feedback system, the temperature sensor of a given EV may report the temperature as a whole number as opposed to a decimal number.

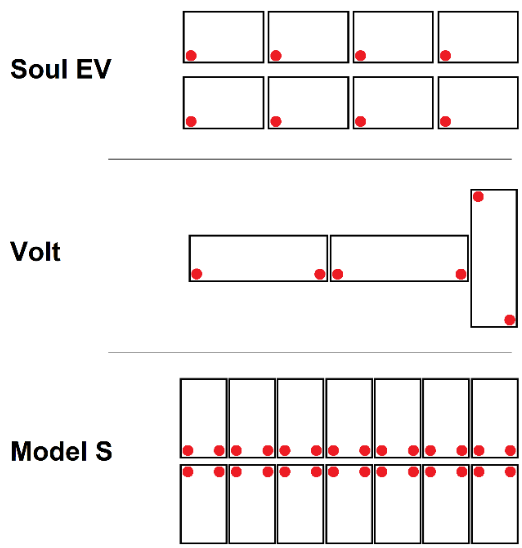


Fig. 1: Schematic of thermistor locations in the battery packs of the Soul EV, Volt and Model S [5, 6, 7]

The Soul EV uses forced air convection to transfer cool air into the battery pack. The eight battery thermistors provide the TMS with the battery temperature, and another thermistor provides the TMS with the inlet air temperature into the battery pack. The TMS then decides if the battery pack requires cooling air to maintain proper operating conditions and a 9-speed fan provides the desired airflow into the battery pack. This cooling air is drawn from the vehicle cabin through two air ducts at the front of the battery pack and is exhausted out the back of the pack. When heating, a battery-dedicated electric positive temperature coefficient (PTC) heater system, composed of 16 heaters (one on each side of each battery module) is activated. Two thermistors on two different heater blocks report the heater temperature to the TMS, and the eight battery thermistors report the battery temperature. [5]

The Model S moderates its battery pack temperature by actively pumping a glycol-water coolant through a ribbon tube that 'snakes' its way through the battery pack in a configuration that allows for contact with every battery cell in the pack [8]. This coolant is routed through the traction battery (heat source), main radiator (heat sink), a 12V pump, different adjustable redirection valves, the drive electronics and components (heat source), on-board charger (heat source), and an electric air conditioner heat exchanger (heat sink) when battery cooling is required [9]. When the battery requires heating, a battery-dedicated PTC heater actively heats the coolant before it enters the battery pack [10].

The Volt similarly employs coolant to moderate its battery temperature, but uses aluminum wafer plates with five capillary-like coolant lines interspersed within each plate in parallel [11]. Each cell is divided from the next by a wafer coolant plate [11]. This coolant passes through a 12V battery pack coolant pump, a heat exchanger, an electric A/C compressor motor control module, and the A/C compressor [6]. Similar to the Model S, the Volt uses a PTC heater to actively heat its coolant before it enters the battery pack [6]. The engine does not participate in heating the battery pack.

2.3 Instrumentation

2.3.1 Power and Energy

All vehicles were instrumented with heated clamp-on current probes on similarly selected components, and voltage leads on the high voltage and two of the 12Vdc systems (see Figure 2). All current and voltage measurements were processed using a high accuracy HIOKI power analyser.

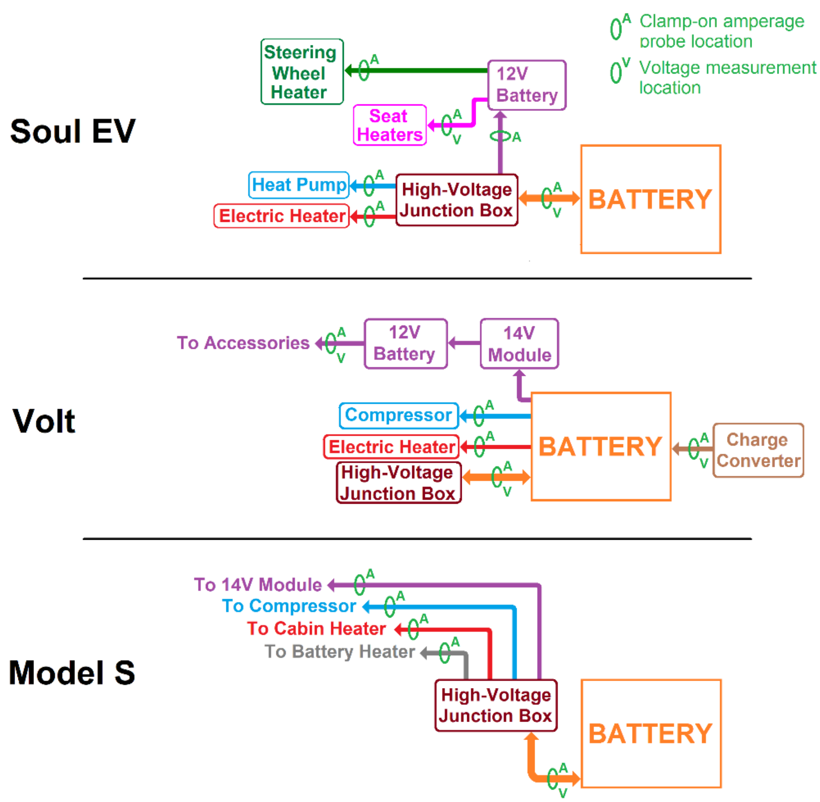


Fig. 2 Schematic of current probe and voltage lead locations on the Soul EV, Volt and Model S drive trains

2.3.2 On-Board Measurements

Select CANbus signals were monitored for all three vehicles. In the case of the Volt, a HEM Inc. OBD logger was used. The Soul EV and the Model S CAN signals were logged with the use of FleetCarma Inc. OBD loggers. These CAN signals include motor torque, battery amperage and voltage, battery state of charge, vehicle speed, ambient and cabin temperatures, and battery temperatures.

2.4 Test Route

All three test vehicles were driven over a 43 km test loop in Ottawa, Canada for all test days. This loop, named the ‘COMBO’ test route, circles through the City of Ottawa and consists of five distinct segments (S1-S5): Arterial-1, City, Congested city, Expressway, and Arterial-2 [12]. The characteristics of each mode of this on-road route, which were averaged over multiple loops and measured using a GPS system, are provided in Table 2. The COMBO route was driven twice in succession *(if time and conditions permitted)* with a 10-minute key-off soak between these repeats (S1-S5, S6-S10). In the remainder of this paper, the term ‘Highway’ will be used instead of ‘Expressway’.

Table 1: On-Road COMBO Route Characteristics by Section

Segment	Drive Cycle	Average Non-Zero Speed (m/s)	Max Speed (m/s)	Average Accel (m/s^2)	Max Accel (m/s^2)	Average Decel (m/s^2)	Max Decel (m/s^2)	Kinetic Intensity	Idle Time (s)	% Idling	No. of Idle Periods	Distance (m)	Time (s)
1	Artery-1	12 ± 6.8	23	0.64 ± 0.49	2.3	-0.70 ± 0.57	-2.8	0.64	144	21	6	6680	681
2	City	11 ± 5.2	19	0.67 ± 0.46	2.4	-0.74 ± 0.56	-2.7	1.04	168	26	7	5008	635
3	Congested	8 ± 3.9	15	0.61 ± 0.40	2.0	-0.60 ± 0.43	-2.4	2.04	98	21	6	2634	448
4	Expressway	20 ± 9.0	31	0.59 ± 0.42	2.2	-0.64 ± 0.51	-2.9	0.24	116	13	6	15643	920
5	Artery-2	14 ± 7.2	25	0.64 ± 0.52	2.9	-0.66 ± 0.56	-3.1	0.50	173	16	9	12894	1070

3 Results

3.1 EV Battery Temperatures

All three vehicles were driven over the test route in winter on multiple days, while the Volt and Model S were additionally tested in summer. Details on the test program are presented in Table 3. Figure 4 displays the average battery temperature, and the difference between the average battery temperature and the ambient temperature, as measured during the winter tests. Figure 5 shows similar results for tests in summer.

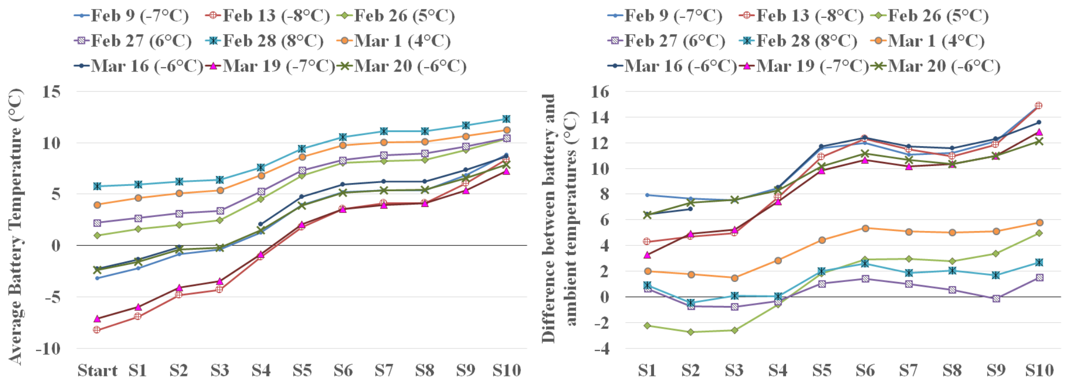
Table 3: Number of test days and average ambient temperature during the test for all vehicles and seasons

	Winter		Summer	
Test Vehicle	Test Days	Temperature (°C)	Test Days	Temperature (°C)
Soul EV	9	-8 to +8		
Volt	7	-11 to +3	5	20 to 27
Model S	12	-21 to +2	12	12 to 21

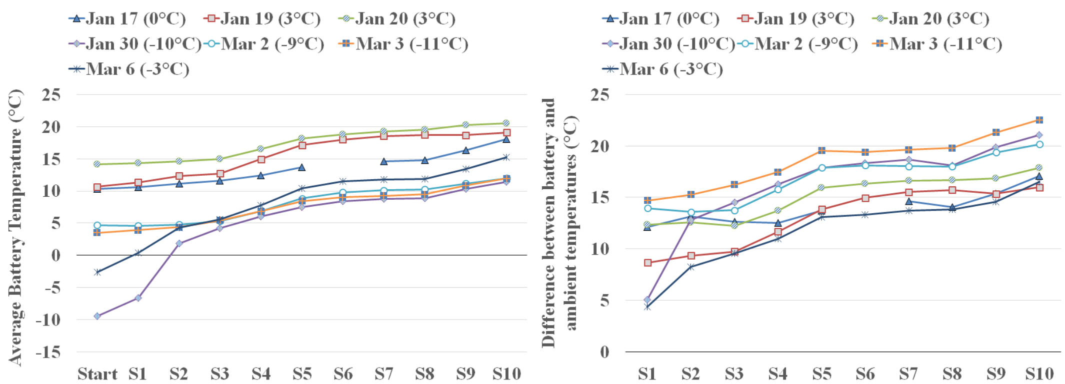
Close examination of battery temperature in winter reveals the actions of the thermal management systems of the Volt and the Model S. The TMS of the Volt actively heats the battery when its temperature is below 1.5 °C, while the Model S TMS engages its heater for battery temperatures under 10 °C. There was no evidence of the Soul EV using its battery heater during any of its winter tests. Anecdotally, Soul EV users have reported that the battery TMS is not activated, even as battery temperatures reach as low as -21 °C [13].

Unfortunately, none of the summer tests of the Volt or the Model S registered any battery cooling, which could provide an insight into the temperature thresholds for the TMS to activate the battery cooling system. The test results for the Volt on July 11 show a large increase in the difference between the battery and the ambient temperatures over the test. This difference, however, was not caused by an exceptional increase in battery temperature, but due to a sudden drop in ambient temperature. On September 12 and 13, the large battery of the Model S needed significant time to warm up after having been parked outside during a much cooler night.

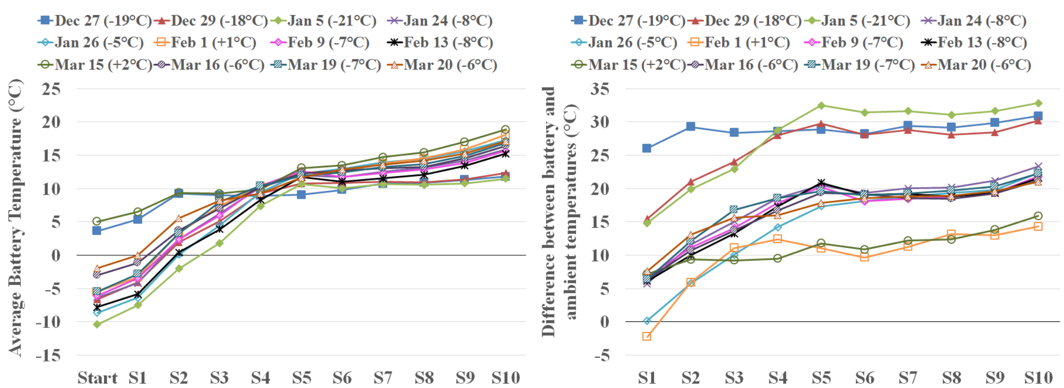
The battery temperature measurements indicate that most of the tests were conducted in conditions under which the TMS of the three vehicles would not activate cooling or heating to influence the battery temperature. The remainder of the paper will therefore focus on vehicle operation that was not influenced by the activity of the TMS.



a) Soul EV (The test on March 16 has no data for Segment 3)



b) Volt (The test on January 17 is missing data for Segment 6)

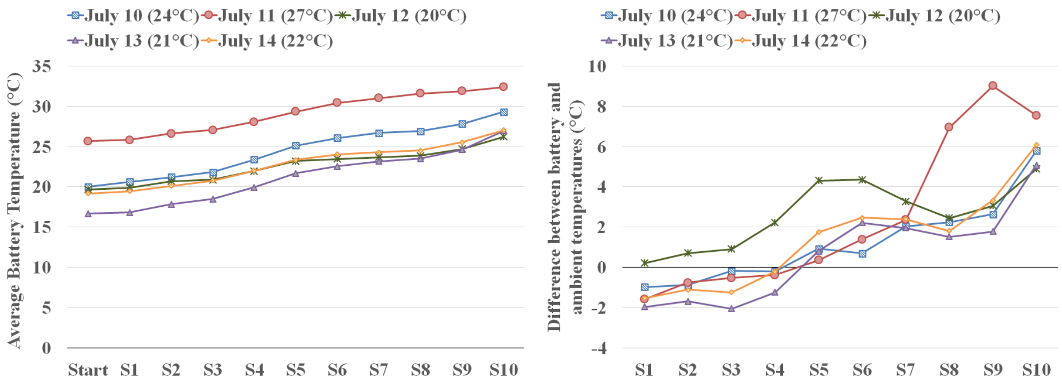


c) Model S

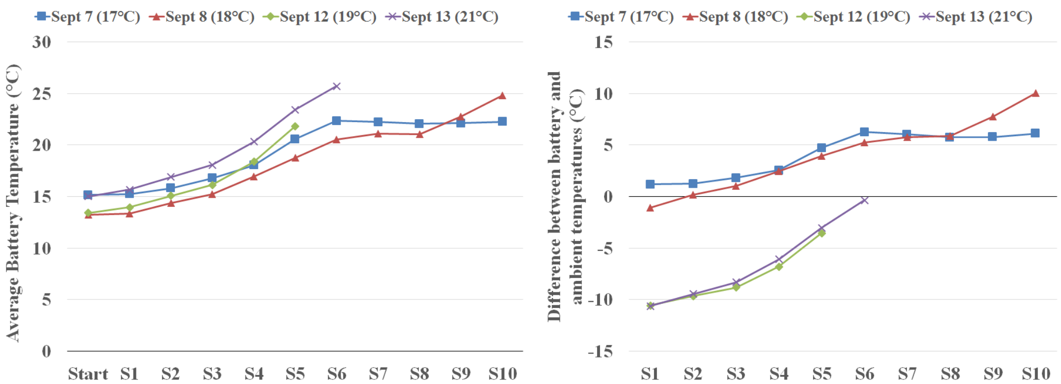
Fig. 4 Evolution of average battery temperature over the driving segments (left) and temperature difference between average battery temperature and ambient temperature over the winter testing period (right)

3.2 Correlations between Battery Temperature and Ambient Temperature & Battery Activity

The temperature of an EV battery is constantly changing due to heat generation from charging or discharging, active battery heating or cooling, or passive battery cooling through heat transfer with the environment. In this analysis, only the internal heat generation and heat transfer with the environment are considered because the on-road tests did not produce sufficient data during active battery heating or cooling for all test vehicles. Any test segments in winter for which active battery heating was observed were excluded from the analysis.



a) Volt



b) Model S (On some days, testing concluded before the COMBO route was fully completed)

Fig. 5 Evolution of average battery temperature over the driving segments (left) and temperature difference between average battery temperature and ambient temperature over the summer testing period (right)

Under normal conditions, EV battery temperatures increase due to ohmic losses (I^2R). For each driving segment, the change in battery temperature and average value of battery activity expressed as current squared (I^2) over a segment are shown in Figure 6 for the Soul EV winter tests. The graphs reveal a clear correlation between these parameters, but also show a smaller increase in battery temperature during the second iteration of the test route (S6-S10), due to increased heat transfer to the environment from a warmer battery. Similar results were found for the other two vehicles.

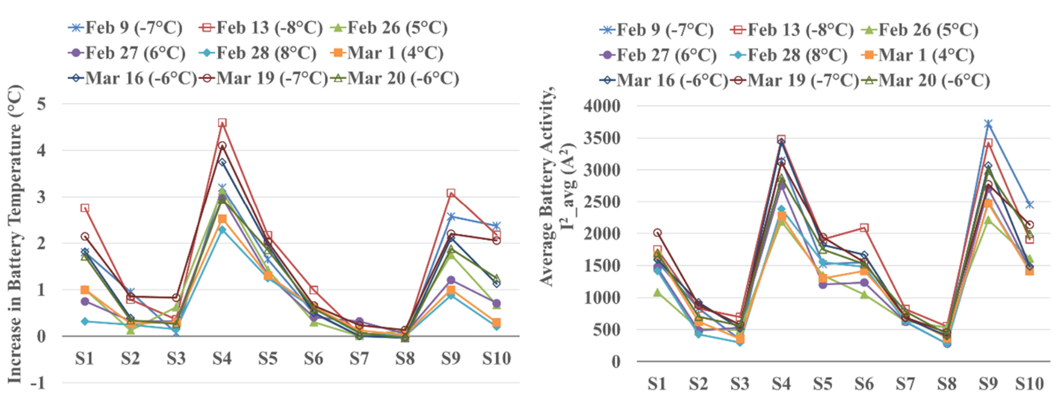


Fig. 6 Battery temperature increase over the winter driving segments (left) and average I^2 per driving segment (right) for the Soul EV

To develop correlations between the EV battery temperatures, and both the difference between battery and ambient temperature and battery activity for different types of driving, the change in battery temperature per segment was converted to a rate of temperature change per second. Figure 7 presents results for the Model S in winter, reflecting the rate of battery temperature change relative to the internal heat generation (left), and relative to the temperature difference with the ambient (right).

The leftmost graph of Figure 7 shows a group of data points for Segments S1, S2, and S3 in the top-left part of the graph, which correspond to test segments with an increased temperature change from active battery heating. When these data points are excluded from the analysis, the remaining data points show a loose correlation between an increase in change of battery temperature and an increase in the squared battery current. A similar correlation can be observed in the rightmost graph, but for a decreasing change in battery temperature with an increase in the temperature difference with the ambient.

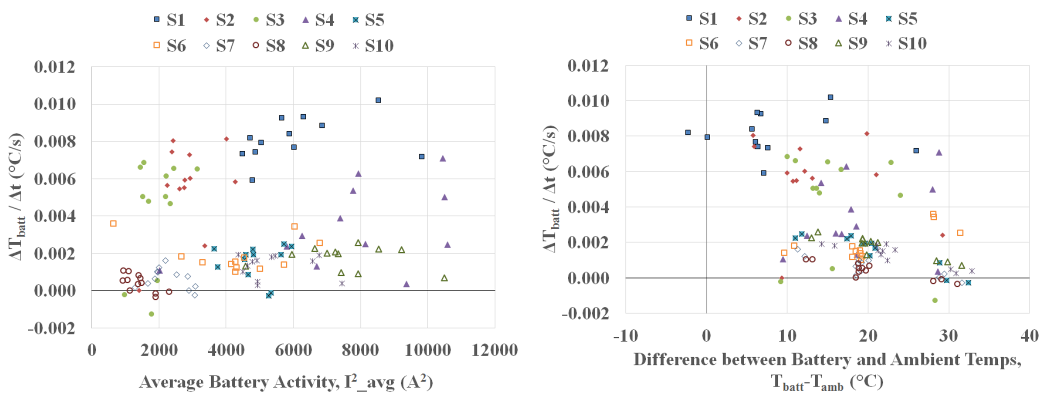


Figure 7: Rate of change of battery temperature vs. average battery activity represented as the time-averaged square of the traction battery current (left) and difference between battery and ambient temperatures (right), grouped by drive segment for the Model S in winter

For each drive segment, correlations between the rate of change of the EV battery temperature (T_{batt}) and the temperature difference between battery and ambient (T_{batt} - T_{amb}) and battery activity (Equation 1) were derived from the collected data using a least squares method. Heat transfer to the environment was assumed to be convective with a heat transfer coefficient h, which varies with the vehicle speed (in m/s, Equation 2).

$$\frac{\Delta T_{batt}}{\Delta t} = w\, I^2 + y * h * \ (T_{batt} - T_{amb}) * \left(\frac{\Delta t_{mov}}{\Delta t}\right) \qquad (1)$$

$$h = 10.45 - v + 10v^{1/2} \qquad (2)$$

Tables 3, 4 and 5 present the values for coefficients *w* and *y* for the Soul EV, Volt and Model S, respectively, under winter and summer conditions. Additionally, the tables show the relative contribution of the heat generation term ($w\, I^2$) and heat transfer to ambient ($y*h*(T_{batt} - T_{amb})*(\Delta t_{mov}/\Delta t)$) to the overall change in battery temperature in Equation 1. The results vary significantly between the vehicles, with clearly higher heat transfer during winter tests. The results for the City test segment require further investigation, as increased heat transfer to the ambient environment was not expected during this low speed drive segment.

Using the coefficients from Tables 3, 4 and 5 in Equation 1, covariance plots were made for the test results of the Soul EV (Fig. 8), the Volt (Fig. 9), and the Model S (Fig. 10). In a covariance plot, the calculated change in battery temperature during a specific test segment is graphed against the measured value for that drive segment. When the calculated value equals the measured value, the data point will fall on the line of perfect agreement, which is shown in each of the graphs. The covariance plots show a reasonable general agreement between the values obtained from evaluating Equation 1 with the calculated coefficients and the measured values. However, for each vehicle there is also significant variation in the level of agreement. This variation is due to many factors, including:

- Natural variability in traffic flow and the number of red or green traffic lights: Every full stop increases the energy demand for the driving segment.

- Variability in weather conditions at the same ambient temperature: Higher wind speeds require more propulsion power, sunny days result in a lower need for cabin heating.
- Driving behaviour: Some drivers brake and accelerate harder than others. Intense braking and fast acceleration increase energy losses.
- Resolution of reported battery temperatures: Some battery temperature sensors reported temperature in whole degrees, resulting in smallest changes in average battery temperatures of 0.125 °C for the Soul EV and 0.167 °C for the Volt. Many drive segments showed an increase in battery temperature of 0.5 °C or less, which is relatively small compared to the smallest change in average battery temperature.

Table 3: Calculated coefficients for Equation 1 for the Soul EV in winter

		w (°C$A^{-2}s^{-1}$)	*y* (s^{-1})
Coefficients	Highway	1.10E-06	-1.76E-06
	Artery	1.18E-06	-1.62E-06
	City	1.09E-06	-1.79E-06
	Congested	1.88E-06	-3.68E-06
		Heat generation (°Cs^{-1})	Heat transfer (°Cs^{-1})
Term Evaluated (relative to total)	Highway	0.0032 (109%)	-0.0003 (-9%)
	Artery	0.0019 (116%)	-0.0003 (-16%)
	City	0.0008 (133%)	-0.0002 (-33%)
	Congested	0.0008 (183%)	-0.0004 (-83%)

Table 4: Calculated coefficients for Equation 1 for the Volt in winter and summer

		Winter		*Summer*	
		w (°C$A^{-2}s^{-1}$)	*y* (s^{-1})	*w* (°C$A^{-2}s^{-1}$)	*y* (s^{-1})
Coefficients	Highway	7.84E-07	-6.03E-07	6.57E-07	-2.13E-06
	Artery	5.13E-07	1.45E-08	7.05E-07	-2.60E-06
	City	1.10E-06	-3.25E-06	6.87E-07	-3.79E-06
	Congested	5.00E-08	2.79E-06	1.24E-06	-5.14E-06
		Heat Generation (°Cs^{-1})	Heat Transfer (°Cs^{-1})	Heat Generation (°Cs^{-1})	Heat Transfer (°Cs^{-1})
Term Evaluated (relative to total)	Highway	0.0026 (111%)	-0.0003 (-11%)	0.0019 (107%)	-0.0001 (-7%)
	Artery	0.0009 (99%)	0.0000 (1%)	0.0011 (111%)	-0.0001 (-11%)
	City	0.0014 (315%)	-0.0009 (-215%)	0.0006 (112%)	-0.0001 (-12%)
	Congested	0.0000 (4%)	0.0008 (96%)	0.0007 (117%)	-0.0001 (-17%)

Table 5: Calculated coefficients for Equation 1 for the Model S in winter and summer

		Winter		*Summer*	
		w (°C$A^{-2}s^{-1}$)	*y* (s^{-1})	*w* (°C$A^{-2}s^{-1}$)	*y* (s^{-1})
Coefficients	Highway	5.63E-07	-3.53E-06	4.29E-07	-1.43E-07
	Artery	5.08E-07	-2.06E-06	4.81E-07	-1.90E-06
	City	8.74E-07	-3.56E-06	6.60E-07	-4.81E-06
	Congested	3.69E-07	-6.40E-07	7.85E-07	-4.40E-06
		Heat Generation (°Cs^{-1})	Heat Transfer (°Cs^{-1})	Heat Generation (°Cs^{-1})	Heat Transfer (°Cs^{-1})
Term Evaluated (relative to total)	Highway	0.0045 (170%)	-0.0019 (-70%)	0.0025 (100%)	0.0000 (0%)
	Artery	0.0025 (174%)	-0.0011 (-74%)	0.0015 (103%)	0.0000 (-3%)
	City	0.0020 (354%)	-0.0014 (-254%)	0.0009 (88%)	0.0001 (12%)
	Congested	0.0005 (191%)	-0.0002 (-91%)	0.0007 (92%)	0.0001 (8%)

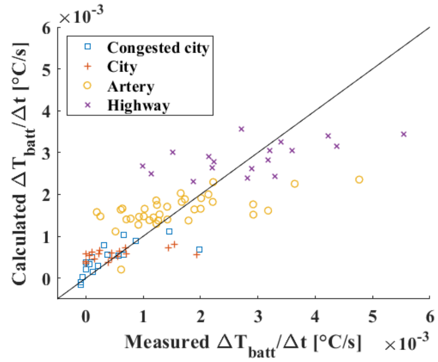


Figure 8: Soul EV (winter) covariance

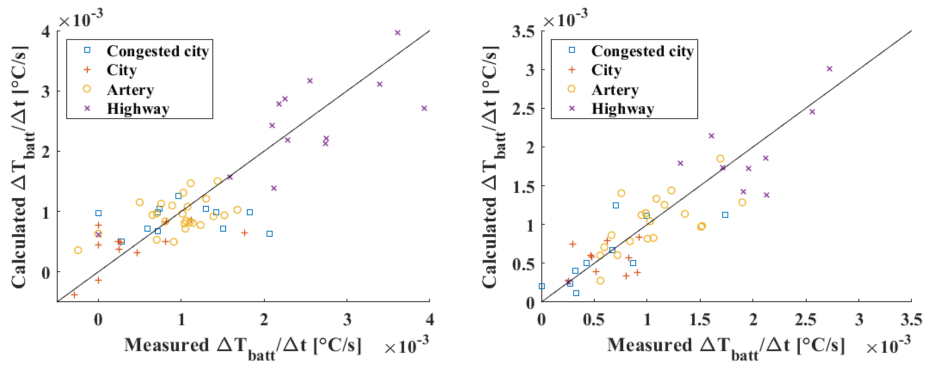


Figure 9: Volt covariance in winter (left) and summer (right)

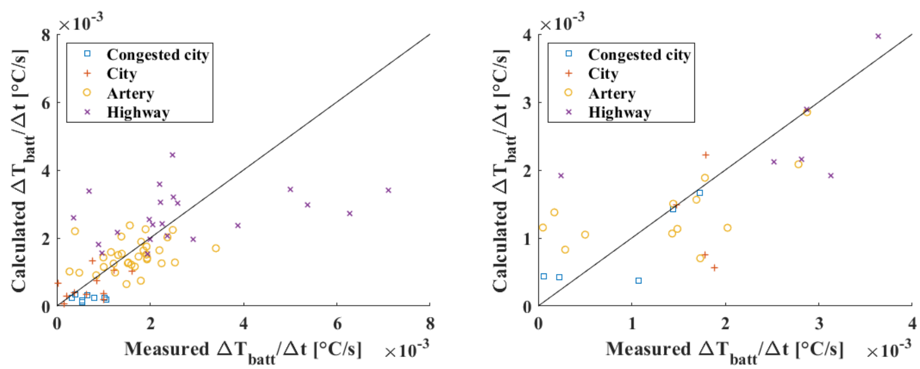


Figure 10: Model S covariance in winter (left) and summer (right)

Table 6 presents a few examples of the variation in results from tests of the same driving segments on different days for the Model S in winter. In this table, I^2 is the battery activity and h is the heat transfer coefficient to the ambient, as defined in Equation 2; these two parameters are calculated for each data point, and then averaged over the segment. *Measured* $\Delta T_{batt}/\Delta t$ is the overall rate of change in battery temperature throughout a given test segment, and t_{mov} and t_{stat} are the times spent moving or stationary, respectively All other metrics in Table 6 are averaged over the segment. The examples for Segment 4 and 7 show that tests conducted under similar conditions resulted in quite different values for the change in battery temperature. Examples for Segment 6 and 8 display differences in battery activity that are much larger than would be expected from the difference in cabin conditioning under the ambient conditions experienced during the test. Figure 11 illustrates the impact of differences in traffic flow and driver behaviour on the battery activity for the example of segment S6.

Table 6: Examples of variation in test results (Model S in winter)

Segment type	Date	I^2 [A^2]	T_{batt} [ºC]	T_{amb} [ºC]	Speed [km/hr]	Measured $\Delta T_{batt}/\Delta t$ [ºC/s]	t_{mov} [s]	t_{stat} [s]	h [-]
Highway	Dec 27, 2017	9364	8.9	-19.7	66.0	**0.0004**	745	115	30.79
(S4)	Jan 5, 2018	10462	7.4	-21.4	56.5	**0.0071**	841	168	29.34
Artery	Jan 5, 2018	**6799**	10.0	-21.4	39.3	0.0025	590	0	33.52
(S6)	Mar 15, 2018	**2675**	13.5	2.6	40.5	0.0018	524	45	29.76
City	Dec 27, 2017	3087	10.7	-18.7	30.0	**0.0002**	507	93	27.11
(S7)	Jan 5, 2018	3058	10.7	-21.0	28.9	**-0.0003**	510	130	26.89
Congested	Dec 29, 2017	**1903**	11.0	-17.1	18.3	-0.0002	406	123	24.26
City (S8)	Feb 1, 2018	**1104**	14.5	1.4	17.8	0.0010	429	118	23.71

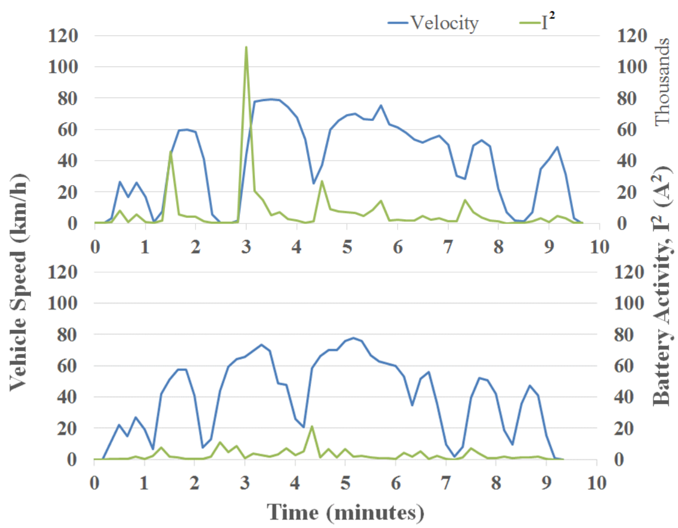


Figure 11: Drive charts for Segment 6 for Model S in winter on January 5 (top) and March 15 (bottom)

4 Conclusions and Recommendations

A 2015 Kia Soul EV, a 2016 Chevrolet Volt, and a 2016 Tesla Model S were tested on-road in Ottawa, Ontario, Canada under winter and summer driving conditions. Operational data from the vehicles was logged for different types of driving (city, artery, congested and highway). The collected data was processed to investigate the operation of the thermal management systems of the propulsion batteries and to determine correlation coefficients between the change in battery temperature and heat generation from battery use and heat loss to the environment.

Winter test results show that at battery temperatures below 1.5 °C, the TMS of the Volt actively heated the battery. The battery heater of the Model S was activated for battery temperatures lower than 10 °C. No active heating of the battery of the Soul EV was evident during winter testing at ambient temperatures as low as -8 °C. The Volt and the Model S were also tested in summer. However, no active battery cooling was measured during these tests, likely because the test were conducted on days with moderate ambient temperatures (up to 27 °C for the Volt and up to 21 °C for the Tesla).

Measured data of battery usage and of internal battery temperatures was used to develop correlations between the rate of change in battery temperature, the battery current and the temperature difference with the ambient. Predicted changes in battery temperature using the developed correlations were compared to the actual measured change in battery temperatures. Some tests resulted in a good match between predicted and measured values. Other test showed significant differences. These differences were attributed to differences in traffic flow, in driver behaviour, and in weather conditions, as well as due to relatively insensitive temperature measurements for the Soul EV and the Volt.

Additional testing of EVs on-road and in the lab is recommended to collect higher resolution data for more accurate battery temperature correlations. These tests should especially be conducted on days with extreme temperatures to fully characterize the operation of the battery thermal management system.

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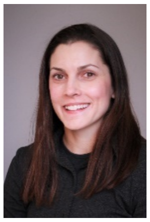
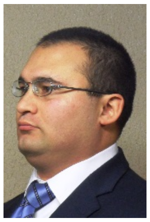
Authors

Hajo Ribberink has a M.A.Sc. degree in Applied Physics from Delft University in the Netherlands. He has over 25 years of experience in using modelling and simulation to assess new and innovative technologies in the energy field. At Natural Resources Canada, he leads CanmetENERGY's research on transportation electrification.



Kathleen Lombardi has a M.A.Sc. degree in Mechanical Engineering from Dalhousie University. She develops simulation models to predict performance, greenhouse gas reduction potential, and economic benefit of renewable and hybrid energy systems. She has a strong background in experimental research, both in laboratory and real-world settings, that provides a grounded perspective for data analysis and simulation modelling.

Kieran Humphries completed a Master's thesis in mechanical engineering at McGill University in 2015 on the topic of multi-speed transmission use in electric and hybrid delivery vehicles. His project work at ERMS has included studies on battery electric and hybrid vehicle efficiency in the Canadian climate, the electrification of public transit, and performance measurement for hybrid vehicles.



Aaron Loiselle-Lapointe has 10 years of experience testing electric mobility technologies, both on the road and on chassis dynamometers. Previous to this, Aaron conducted 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.

Nadia Stefopulos is a Systems Design Engineering student at the University of Waterloo. She is expected to complete her degree in April of 2020. Nadia has completed four 4-month work terms in positions working with electric vehicle data, including a term at Natural Resources Canada. She plans to continue to work in the electric vehicle field after completing her degree.

Sharon Ann Varghese is a student at the University of Waterloo who is currently pursuing her Bachelor's Degree in Mechanical Engineering. Her past work experiences in the manufacturing quality assurance, software quality assurance and research fields have provided her with a diverse set of skills and outlook. She is presently working as an Automation Engineer in process industries. She is a member of the University of Waterloo Alternative Fuels Team. Sharon is passionate about developing creative solutions to solve real-world problems.

Natalie Pundsack is a Chemical Engineering student at the University of Waterloo. She intends to graduate in 2021. Her previous work experience includes a variety of research environments that have provided her with a broad understanding of model development and data processing methods. She is presently completing a four-month work term at Natural Resources Canada.