Winter Happens: The Effect of Ambient Temperature on the Travel Range of Electric Vehicles

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***Abstract*—The operation of electric vehicles in cold weather is a concern, but there is not a lot of literature available regarding the precise nature of impacts on travel range. Two types of commercial battery electric vehicles, namely, the Nissan Leaf and the Mitsubishi i-MiEV, were driven to depletion across a broad range of temperatures that occur naturally in Winnipeg, MB, Canada, due to its climate. Analysis of data showed that the travel range can be reasonably interpreted as a function of ambient temperature using a series of simple linear segments: an upper plateau above about +20 °C, a lower plateau below about −15 °C, and a linearly varying segment in the middle. Both the Leaf and i-MiEV appeared to follow this model, with a good correlation of data for the middle (linearly varying) segment. Impacts of air conditioning on the travel range were also separately tested. This paper provides guidance for more rigorous assessments of electric-vehicle range performance into the future.**

***Index Terms*—Battery, battery electric vehicles (BEVs), cold weather, electric vehicle, Mitsubishi i-MiEV, Nissan Leaf, travel range, winter.**

Nomenclature

AC	Air conditioning.
BEV	Battery electric vehicle.
EVTEC	Electric Vehicle Technology and Education Center.
HVAC	Heating ventilation and air conditioning.
PHEV	Plug-in hybrid electric vehicle.
SOC	State of charge.
WADT	Winter average daily temperature.

I. Introduction

FOR electric vehicles, operating under variable climate conditions is an important consideration. Understanding the effects of winter operation is critical within Canada, Scandinavia, the Northern U.S. states, and other northern regions, where ambient temperatures can plunge to relatively low levels for a significant portion of the year. Despite the importance of ambient temperature effects on electric vehicle range, there is still little published literature available. Discussions on this topic have tended to be anecdotal in nature or provided via blogs or other popular media without any peer-review process, or based on commercial sources of information where data are not made fully available for further scrutiny.

The objective of this paper is to present a compendium of travel range data as complied by the Electric Vehicle Technology and Education Center (EVTEC) for two all-electric vehicles: the Nissan Leaf and the Mitsubishi i-MiEV. Both are classified as BEVs, and both have been commercially available for several years. Data cover a range of temperature conditions, including through the winter of 2013–2014. Additional data were also collected at the same time regarding vehicle energy consumption, but the latter is not presented in this paper for brevity.

EVTEC was established in 2011, with further background as provided by Hoemsen [1]. Its mandate has focused on three primary areas: applied research, public outreach, and education. This virtual organization has three key attributes that provide unique capabilities relevant to the assessment of electric vehicle performance. First, EVTEC was set up as part of Red River College, which is more of a polytechnic institute rather than a university. As such, the orientation has been not on fundamental research but toward applications and practical implementation. Second, EVTEC was established in part to address a growing perceived need among consumers for realistic information about electric vehicle performance to permit informed purchase decisions. In this regard, EVTEC since 2011 has been publishing a variety of annual experience reports for different electric vehicles [2]–[7].

The third important attribute is Manitoba's weather itself. Located in the dead-center overall of North America, Manitoba has a climate characterized as continental in nature. Ambient temperatures readily vary from less than −35 °C during the winter to more than +35 °C during the summer. As such, it is possible to investigate varying temperatures for vehicle operation relying solely on ambient conditions.

Manitoba is well known for its cold winters, and the paper by Gregor and Parsons represents the beginning of significant work on electric vehicle cold-weather assessment and adaption at Red River College [8], this just prior to the formal creation of EVTEC. Specifically, their paper concerned cold-weather modifications made to Toyota Prius hybrids that had been earlier converted into plug-in hybrid electric vehicles (PHEVs). Their work is unique in being one of the first of its kind in this field.

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II. Literature Review

The environmental advantages of electric vehicles have been well recognized for some time. As such, they were recently highlighted by the United Nations as a key technology for addressing climate change issues [9]. At the same time, concerns about winter operation have also been long recognized, as outlined by Adams and Song [10].

Earlier electric vehicles, relying on lead acid batteries, were found to experience severe reductions in range under cold conditions [11]. The initial priority concern, as described by Dhameja, had been battery pack capacity [12]. At cold temperatures, effective battery pack energy was diminished due to increased internal resistance. Internal resistance is inversely proportional to temperature change and depends on cell chemistry [13].

Additional effects on vehicle range associated with cabin heating, ventilating, and air-conditioning (HVAC) systems, although important, appeared to be treated initially as secondary. Relative impacts depend on specific conditions. As outlined by Dhameja for lead acid batteries, reductions in travel range at cold temperatures were of comparable magnitude for internal resistance affecting battery capacity versus increased HVAC load, i.e., range reduced at -18 °C to only about 40% that at nominal conditions of $+21$ °C due to either effect separately and reduced to only about 20% of that at nominal conditions for the two effects combined [12].

The focus now is on lithium battery technologies [14], which offer significant advantages in terms of high specific energy, high efficiency, and long life. Lithium batteries, including a variety of chemistry options, dominate consideration by vehicle manufacturers. Indeed, lithium-based traction batteries are incorporated in all commercial electric vehicles today, including BEVs, such as the Leaf or i-MiEV that are the primary subject of this paper, and PHEVs, such as the Chevrolet Volt that also incorporates conventional engine technology for range extension.

For lithium batteries, the same general concerns for cold-weather operation continue to be emphasized, but with differences [15]. At low temperatures, energy capacity is reduced, but not to the same extent as lead acid batteries. Aggregated data from Bandhauer *et al.* for lithium battery energy capacity metrics at colder temperatures show that as the temperature is reduced from $+20$ °C down to -20 °C, energy capacity drops in a reasonably linear fashion but is still not excessively impaired, i.e., still around 80% capacity. Only at much lower temperatures, i.e., around -40 °C, has aggregated data shown battery capacity to be dramatically reduced, i.e., to only 30% or less [16].

It also becomes important at low temperatures for lithium batteries to limit maximum charge current to prevent adverse impacts [15]. The latter concern was reiterated by Kamachi and Hosokawa [17], their work involving cold-weather testing (i.e., at -30 °C) of the Mitsubishi i-MiEV at a North American site. They showed that while battery discharge current is not constrained at lower temperatures, the upper limit for battery charging current drops as the ambient temperature reduces below certain limits, leading practically to a slower overall recharging rate for the vehicle. Their overall assessment at low temperatures was good, based on parameters of acceleration, driving feel, and vehicle stability. Only recharging time appeared to be impacted but was still deemed acceptable.

Cold weather impacts on the range of actual operating electric vehicles are known but, unfortunately, are not systematically understood. Testing has been more snapshot oriented, in part due to data limitations, costly testing methods and associated equipment, e.g., environmental cold chambers, and ambient temperature uncertainties.

Testing by Transport Canada of BEV performance under cold conditions (i.e., at -7 °C and -18 °C/-20 °C) was recently reported [18], using defined dynamometer drive-cycle operations. Their work was limited in that the specific electric vehicles tested could not be disclosed, with only relative range impacts reported. It was shown that at -18 °C/-20 °C, range was reduced to 40% to 45% compared with baseline conditions (i.e., $+20$ °C operation with no heating or AC employed). Hydro Quebec, as part of their larger pilot project involving i-MiEV BEVs, reported on an aggregate basis that maximum range was reduced to about 60% during the winter (i.e., < 0 °C) compared with summer (i.e., $> +15$ °C) but with no further details [19].

A wide variety of cold weather experience and insights have been presented on the Internet. These have been mostly fragmentary, with some notable exceptions. FleetCarma, which is a vehicle data-logging and analytics firm based in Waterloo, Canada, has been actively involved with electric vehicles for many years and has made summary data on electric vehicle winter performance publicly available. Recent data for the Leaf, as presented by Allen [20], were based on more than 5400 data points and showed available travel range to vary in a relatively linear manner at lower temperatures. The available range at 0 °C was indicated to be about 85 km (i.e., intercept) and the change in range to be about 1.1 km/°C (i.e., slope). At the coldest temperature recorded, i.e., around -24 °C, an available range of about 59 km was indicated. Only aggregate data trends were presented, which limits utility. Their data also implicitly included both battery capacity and HVAC system impacts.

Recent objective testing of electric vehicle range under different temperature conditions was undertaken by the Southern California Research Center of the American Automobile Association. Unfortunately, this was only discussed as a news release [21], without any detailed report or data. They indicated at an operating temperature of -7 °C that vehicle range was reduced to about 41% (i.e., 69 km) compared with maximum vehicle range at nominal conditions of $+24$ °C (i.e., 169 km, with no AC). This reduction also implicitly included both battery capacity and HVAC system impacts.

An unfortunate trend that has begun to emerge is apparent ambivalence toward the operation of electric vehicles in cold weather. This attitude suggests that cold weather operation is too problematic, and such markets are simply too small to be worthwhile. Such sentiments have appeared in popular media and have begun to be evident in academic literature and business-oriented discussions.

Bullis, in a blog-only commentary associated with Technology Review, implied this line of thinking [22]. Two key observations were noted, which were consistent with the literature. First, cold temperatures adversely affect battery performance, and second, cabin-heating requirements can quickly drain a vehicle's battery. However, it was further noted that practical solutions to these issues appear to remain distant in the future, with little prospect of a near-term resolution.

Zubaryeva *et al.* investigated market deployment scenarios within Europe for electric vehicles, significantly based on expert opinion [23]. Although not strongly highlighted, climate was included as a factor, specifically winter average daily temperature (WADT). It was suggested that until 2020, preferred geographic areas for electric vehicles would have WADT values only as low as the range of $+1$ to -13 °C, and by 2030, preferred areas could have WADT values as low as the range of -8 to -13 °C, reflecting technology improvements. These are not particularly cold temperatures and reflect perceptions as to the apparent difficulty of operating in cold weather. Importantly, Norway has begun to emerge as a top-selling location for electric vehicles, not just in Europe but in the world as a whole. This has occurred for a variety of reasons, but it is also important to note that Norway has a cold climate.

A recent strategic study by the Boston Consulting Group, regarding batteries and the electric vehicle industry, contains a number of indirect comments, presenting cold weather operation of electric vehicles as a conundrum [24]. They suggested any intent to operate electric vehicles uniformly across a range of climate conditions involved significant technical challenges and was likely not practical. They recommended tailoring or at least rating battery systems for specific climates.

The case for considering electric vehicles in cold weather is best made by the experience with conventional internal combustion engine vehicles. Conventional vehicles too experience significant issues in cold weather, but these are not perceived as problems because of established adaptations. The electric block heater, for example, is a standard feature of conventional vehicles in cold climates. Rather than being factory installed, allowance is typically now made in the design of vehicles to permit installation as required, often at the dealership level. For electric vehicles, understanding their operability in cold weather, including both advantages and disadvantages, is important to identify potential practical adaptations. This necessitates systematic testing and review, hence the mandate of EVTEC and the research discussed in this paper.

III. Methods

Two types of BEVs were involved in testing. A single 2012 model-year Nissan Leaf, normally operated by the Energy Division of the Manitoba Government, was made available for testing. This Leaf incorporated a "winter package," including electric-heated front seats, electric-heated steering wheel, and on-board warming system for the battery pack [25]. Two 2012 model-year, North American version Mitsubishi i-MiEVs were also made available for testing, the first i-MiEV being normally operated by the Energy Division of the Manitoba Government, which incorporated the premium package including navigation screen, and the second being normally operated by EVTEC itself. In terms of winterization, the i-MiEVs incorporated an electric-heated driver seat and an on-board warming system used during cold weather charging of the battery pack [26]. Both types of vehicles employ lithium batteries, with 24-kWh energy capacity for the Leaf and 16-kWh energy capacity for the i-MiEVs. Both types of vehicles incorporated active thermal management systems for their battery packs. The presence of deliberate battery warming in both cases reflected the need to address cold-weather battery concerns previously outlined. In both vehicles, the main cabin heater systems employed electrical resistive heating, rather than a heat-pump approach. Both vehicles also incorporated 3.3-kW on-board charging systems.

The SAE J1634 standard outlines the approach for measuring both the range and the energy consumption of electric vehicles [27]. This involves a dynamometer system operated within a controlled-environmental chamber, to ensure consistency irrespective of test location, using multiple- rather than single-defined drive cycles, to reduce resources required for testing. However, such an approach when applied to investigating performance across a broad range of temperatures is impractical, being both technically challenging and expensive, particularly for operation at colder temperatures.

A different tactic was employed to gain at least a preliminary understanding of the nature of vehicle performance at reasonable cost. The vehicles were tested via actual driving in the urban vicinity of Winnipeg, Canada. This used Winnipeg as a live test-bed across a range of temperature conditions, with testing undertaken within the period from June 2013 through March 2014.

Drive-to-depletion testing involved literally driving individual vehicles from a full state-of-charge (SOC) until depleted. Travel distance was simply obtained by recording odometer differences in each case. Testing was undertaken only on selected days to ensure differential increments of about 10 °C across the full ambient range covering approximately -25 °C to $+25$ °C. Data points were thus relatively well spaced across the range of temperatures, although not perfectly so given dependence on naturally occurring conditions. The travel endpoint was Red River College's Notre Dame Campus in Winnipeg, where both Level 1 and Level 2 recharging capabilities are available. In the case of both the Leaf and i-MiEVs, each vehicle was driven until full battery depletion was indicated on the display and then driven further within the confines of the campus. The distance traveled after zero-battery indication was separately recorded in each case but was included in the total travel distance as well.

The same driver operated the vehicle in all cases. All of the vehicles were operated solely in normal drive mode, which, in both cases, was denoted as D-mode. Travel was done around mid-day to avoid congestion. In all tests, head lights and windshield wipers were not used. Travel was entirely within the Winnipeg urban area, with a generally similar travel route employed, this in the form of a large circle-of-eight as outlined in Fig. 1. Travel routes, however, could not be absolutely identical, given differences in available range with temperature. The travel route included sections with speed limits of 50, 60, 70, and 80 km/h. Odometer readings were manually logged at approximately 1-h intervals during trials. Based on this, travel, including all stoppages, was maintained in the range of 35–40 km within 1 h (i.e., 22–25 mi within 1 h).

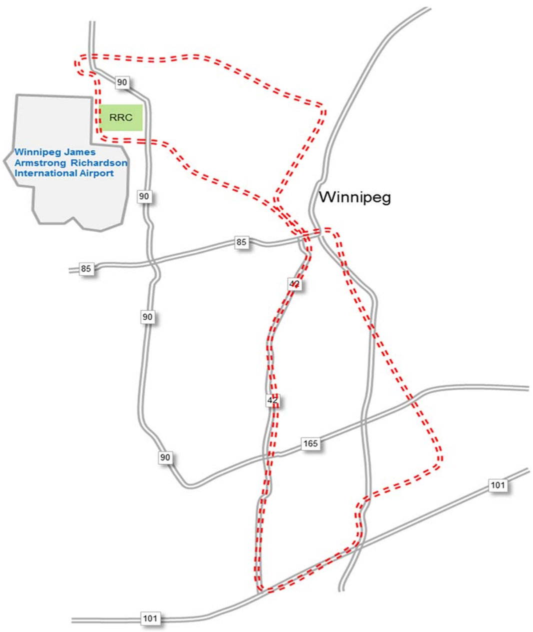

Fig. 1. Approximate travel route for drive-to-depletion tests in Winnipeg.

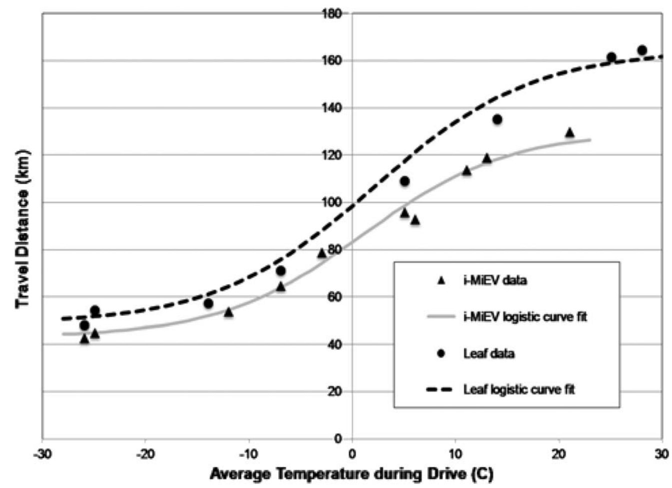

Fig. 2. Travel distance as a function of ambient temperature for Leaf and i-MiEV, including logistic curve fits for data.

Sufficient heating was used to maintain comfort for the i-MiEVs, given they have no preset temperature control setting. In the case of the Leaf, the climate control was set to +21 °C. No AC was employed, except in deliberate tests, in which cases, the AC was set to maximum. Ambient temperatures in all cases were referenced to official hourly readings from Environment Canada at Winnipeg James Armstrong Richardson International Airport, which is located adjacent to Red River College's Notre Dame Campus. Ambient temperature was averaged for the actual period of each individual drive. Recharging of all the vehicles was undertaken out of doors under ambient conditions as they occurred.

IV. Results

A total of 21 drive-to-depletion tests were completed across temperature conditions ranging from +28 °C down to −26 °C. Twelve tests involved one or other of the two i-MiEVs, and nine involved the Leaf. The highest travel distance achieved was in the range of 162–165 km for the Leaf and around 130 km for the i-MiEV. These values are consistent with maximum distances outlined by the manufacturers. The lowest travel distances, during cold winter weather, ranged from 48 to 55 km for the Leaf and from 43 to 45 km for the i-MiEV. These represent reductions in travel distance for a single charge down to only 30%–35% compared with what could be achieved at nominal conditions. Such significant travel range reductions at low temperatures had been previously suggested. As noted earlier, Transport Canada indicated a relative reduction in range down to 40%–45%, compared with baseline [18], and in the data outlined by Allen [20], a Leaf travel distance of approximately 59 km at −24 °C was inferred, similar to the results obtained.

Moreover, separately recorded for both types of vehicles were distances traveled once zero battery energy was indicated on the displays. Average values were 4.1 ± 1.0 km $(n = 8)$ for the Leaf and 3.3 ± 0.5 km $(n = 12)$ for the i-MiEVs. Both types of vehicles thus retained some reserve even after reaching the indication of zero available energy. This means drivers are not immediately or suddenly stranded and still have some limited ability to get off major roads and potentially plug-in. An important distinction in this regard is that once zero-energy indication is reached, HVAC systems on the i-MiEVs, whether heater or AC, immediately turned off, whereas in the case of the Leaf, they did not, leaving that option to the discretion of the driver. Note for consistency, during testing of the Leaf, the driver turned off HVAC systems at zero-energy indication.

The travel distance data for both types of vehicles are summarized in Fig. 2, with travel distance as a function of the ambient temperature. Three test runs undertaken with AC fully on were excluded in this case. It was immediately apparent that the data for both vehicles tended to approximate the form of a logistic or sigmoid curve, which is commonly used in population or new technology market adoption studies.

To practically fit a logistic curve, however, data for the travel distance variable as a function of temperature for each vehicle had to be first transformed. This involved a dimensionless travel distance ratio varying from 0 to 1, outlined in (1), with Range being the travel distance at each data point, $\text{Range}_{\min}$ being the minimum range achieved by the vehicle, and $\text{Range}_{\max}$ being the maximum range achieved by the vehicle, i.e.,

$$\text{Travel}_{\text{Ratio}} = \frac{\text{Range} - \text{Range}_{\min}}{\text{Range}_{\max} - \text{Range}_{\min}}. \tag{1}$$

Evaluating the correlation with ambient temperature (T in °C) for a logistic curve then involved the use of the "logit" function, to be able to undertake linear regressions, with a and b being slope and intercept constants, respectively, as outlined in (2), using the travel ratio value as previously defined, i.e.,

$$\ln\left(\frac{\text{Travel}_{\text{Ratio}}}{1 - \text{Travel}_{\text{Ratio}}}\right) = aT + b. \tag{2}$$

Fitted logistic curves for the two vehicles as a function of ambient temperature are included in Fig. 2. The logistic curves by

TABLE I
LINEARLY VARYING SEGMENT RESULTS FOR LEAF AND i-MiEV COMPARED WITH A LOGISTIC CURVE

Parameter	Vehicle	
	Leaf	i-MiEV
Middle (linearly-varying) segment		
Slope	2.9 km per °C	2.5 km per °C
Intercept	95 km	84 km
Correlation coefficient (r^2)	0.99	0.98
Data points	4	7
Logistic curve fit		
Correlation coefficient (r^2)	0.96	0.99
Data points	8	10

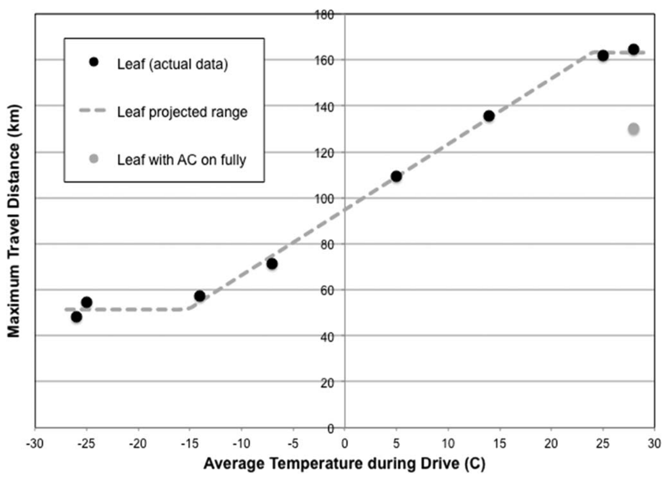

Fig. 3. Travel distance as a function of ambient temperature for Leaf based on interpretation as linear segments and including data with AC fully on.

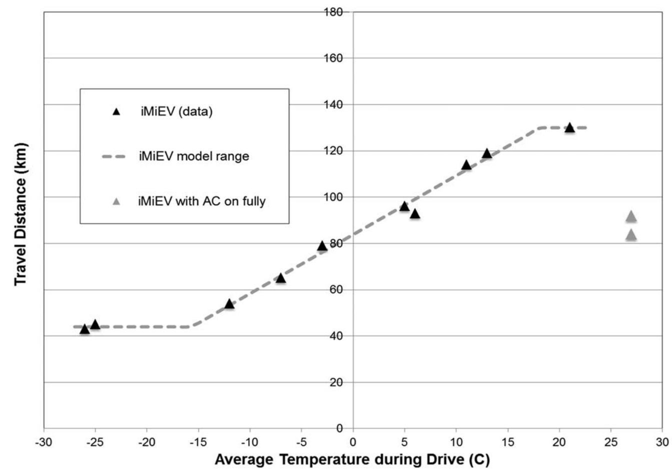

Fig. 4. Travel distance as a function of ambient temperature for i-MiEV based on interpretation as linear segments and including data with AC fully on.

nature provided good correlations of data, as outlined later on in Table I, but the functions are highly complex, as evidenced by the extensive explanation required here. Furthermore, beyond the expediency of fitting a curve to data, this approach provided little in the way of useful underlying explanation. As such, a simpler alternative approach was employed to interpret data, namely, a series of linear segments.

Representations of travel distance as a function of ambient temperature for the Leaf and i-MiEV, interpreted as a series of linear segments, are presented in Figs. 3 and 4, respectively. In both cases, the data were interpreted as consisting of range plateaus at upper and lower temperatures, with a linearly varying segment in the middle. The data for tests employing AC fully on are also included, as indicated, on both plots.

The most evident segments of the respective model curves are the middle linearly varying portions, covering from around +20 °C (estimated as +23 °C for the Leaf and +19 °C for the i-MiEVs) down to around −15 °C (same for both vehicles). These were treated as simple linear regressions with respect to ambient temperature, involving four data points for the Leaf and seven data points for the two i-MiEVs. Linear correlation results are presented in Table I, along with correlations for the logistic curves in Fig. 2 for comparison. As illustrated, the linear correlation coefficient (r^2) values are at least comparable to the logistic curves and show strong relationships between range and ambient temperature. The data points for the i-MiEVs over this segment were split between the two vehicles, i.e., four for one and three for the other. Further statistical analysis (not presented) showed that the behaviors of the two vehicles were not different; hence, all data points for the i-MiEVs were therefore combined.

The linearly varying nature of the middle segments in both plots makes sense in terms of the two major effects that are related to ambient temperature, namely, battery energy capacity decline and cabin heating requirements. As previously noted, data from the work of Bandhauer *et al.* suggested that battery energy capacity linearly varies from +20 °C down to −20 °C [16]. In terms of cabin heating, as ambient temperature cools, more energy is required from the vehicle heating systems, with the energy content of air and of vehicle construction materials all varying linearly with temperature. Additional data presented by Allen indeed showed the auxiliary heating load for the Leaf to increase linearly as the temperature declined [28].

There were limited data points describing operation both above +20 °C without AC (i.e., two for the Leaf and one for the i-MiEVs) and below −15 °C (i.e., two each for the Leaf and the i-MiEVs). In terms of the proposed model, these were treated as flat plateaus in Figs. 3 and 4, rather than as the ends of logistic curves. The form of this model as it resulted was unknown when the experiments were first planned, with tests being spread out relatively evenly across the full temperature range. Given potential battery degradation effects with vehicle age, it was also not possible to simply go back and add more data points.

The suggestion of the flat plateaus in the proposed model could easily appear artificial, i.e., trying to make the data fit a predetermined model. This is particularly true at lower temperatures, where a continued reduction of range might be expected at lower temperatures due to further battery energy capacity declines. Ongoing experience, however, suggests the finding of relatively flat plateaus at cold temperatures to be legitimate. In recent work, Delos Reyes *et al.* directly found the Chevrolet Volt to exhibit a flat plateau for all-electric travel distance at lower temperatures, using the same testing methods outlined in this paper. Specifically, data for the travel distance achieved were not correlated to ambient temperature [29]. These included four data points in the range of -14 °C to -17 °C and three data points in the range of -25 °C to -26 °C.

Further data are obviously needed to confirm the travel range behavior of the Leaf and i-MiEV. It is particularly important to confirm the proposed upper and lower range plateaus. At the same time, logical interpretations emerged to describe the meanings of these plateaus.

Both types of BEVs have limited battery capacity and can thus only travel a finite maximum distance on a single charge. The upper plateaus appeared to represent maximum vehicle travel possible without any heating or AC engaged. This is no different than a conventional vehicle. As previously noted, the highest travel distances achieved were consistent with the maximum ranges suggested by the manufacturers. Moreover, the ratio of travel distance for the Leaf compared with the i-MiEVs was found to be about 125% (i.e., 163 km $\div$ 130 km). This was consistent with the Leaf having a larger battery pack capacity, yet also having a larger vehicle size and mass.

For cold conditions, the findings of flat-range plateaus can be explained using the hypothesis that temperature-related impacts of the HVAC systems are much more significant than impacts of battery capacity changes. Both types of vehicles have only limited maximum possible heating system output. Once reached, no more heat can be generated, and travel at any further reduced temperatures is more constrained by the tolerance of the driver and passengers. Again, this is as would be expected for a conventional vehicle. In the tests, at cold temperatures below -15 °C, all heating systems for all vehicles were noted to be at maximum levels. If reductions of travel range due to battery energy capacity decline were relatively small compared with both the effects of cabin heating and random variations, then the logical expectation would be for travel range to be not correlated to ambient temperature at colder conditions.

Travel ranges for the two cold-temperature data points for the i-MiEVs in Fig. 4 were almost identical and involved one test for each of the two vehicles. For the Leaf, however, as shown in Fig. 3, the two cold-temperature data points involved more significant differences. This reflected an important observation of behavior for the Leaf. The higher data point, i.e., around 55 km, corresponded to normal battery operation, whereby a full 100% SOC was available and used to drive the vehicle to depletion. The ratio of travel distance for the Leaf compared with the i-MiEVs in this case was about 125% (i.e., 55 km $\div$ 44 km), consistent with the ratio at warmer temperatures. The lower data point, i.e., around 48 km, reflected an apparent issue involving self-consumption of electricity to keep the battery sufficiently warm. It was intermittently observed at cold temperatures that the SOC for the Leaf might inexplicably drop somewhat overnight after fully charging although plugged in throughout. For the lower data point in Fig. 3, a reduction in SOC to only 75% was observed, even though it was plugged in. In this case, the ratio of travel distance for the Leaf compared with the i-MiEVs was only about 110% (i.e., 48 km $\div$ 44 km), which is a significant relative impairment. Such problems were not observed in the case of the i-MiEVs.

Finally, travel distances with AC turned fully on were also included in Figs. 3 and 4 but only shown as individual data points, given the relative few involved. Energy draw for AC in a vehicle relates back to the electrically powered refrigerant compressor and any associated pumps and fans. As with heating systems, these can only be operated to maximum limits. For the Leaf, the ratio of travel with AC fully on to maximum nominal travel without AC was approximately 80% (i.e., 130 km $\div$ 163 km). Travel range for the i-MiEVs on a proportionate basis appeared to be more highly impacted by AC than the Leaf. The ratio of travel with AC fully on to maximum nominal travel without AC was approximately 68% (i.e., 88 km $\div$ 130 km). The reason for this significant difference in effects on the two vehicles is not understood and will require further investigation.

V. Conclusion

It has been already well known that the operation of electric vehicles is affected by cold temperature conditions. The results of this work give a better understanding of these impacts, providing insights as to how and to what extent electric vehicles are affected as temperature changes. From the pragmatic perspective of a typical driver, this is crucial information.

Results showed that on a preliminary basis, BEV range performance could be reasonably explained relative to changing ambient temperatures using a series of simple linear segments. The resulting model involves plateaus for range both at warmer temperatures above around $+20$ °C, appearing to correspond to the maximum travel range of the vehicle without heating or AC, and at cold temperatures below around -15 °C, appearing to be determined primarily by heating system operation. At intermediate temperatures between the two plateaus, travel range was confirmed to vary in a highly linear fashion with ambient temperature.

VI. Future Research

The travel range experiments need to be replicated to validate the simplified model proposed in this paper for vehicle range as a function of ambient temperature. The results derived so far were also based only on tests involving simply driving at different ambient conditions in the vicinity of Winnipeg. Although done in an internally rigorous fashion, the nature of testing obviously limited repeatability compared with other locations. The test results did provide a preliminary indication of expected performance and, most importantly, guidance on how to best use more expensive resources in the future, i.e., dynamometer systems within controlled environmental chambers.

Five areas of priority focus were identified for future testing of electric vehicles. These involve 1) verifying the range plateau characteristics at higher and lower temperatures in the proposed model (e.g., range testing from -15 °C to -30 °C with maximum heating and from $+20$ °C to $+30$ °C with no heating or AC); 2) further confirming the linear variation of travel range with temperature in the middle section of the proposed model; 3) investigating the upper and lower break points, which are implied to correspond to where heating systems initiate operation and reach maximum levels, respectively; 4) exploring much lower and higher temperatures to determine where the practical limits of operation exist; and 5) evaluating the relationship between travel range and energy consumption.

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