

Practical Impacts of Ambient Temperature and Aging Combined on Maximum Travel Range of the Nissan Leaf

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Abstract

For electric vehicles, operating under variable climate conditions is an important consideration. In northern regions, including Canada, Northern U.S. states, and Scandinavian countries, for example, it is crucial to understand the practical impacts of cold weather operation during winter, in particular how maximum travel range, using a single full-charge, may be affected. At the same time, electric vehicles, which have been now commercially available for several years, are beginning to age. This paper explores the impacts of vehicle aging and ambient temperature effects, as can occur simultaneously, on vehicle range in order to understand their aggregate effect and their interaction for the Nissan Leaf, a commercial-available electric vehicle.

1 Introduction

Battery electric vehicles (BEV) rely entirely on stored electricity to provide their motive energy, and also to run their other on-board vehicle systems, including, in particular, cabin heating, ventilation and air-conditioning (HVAC) systems. Possessing no other source of energy, such as a gasoline-powered back-up engine, their overall operation depends critically on the performance characteristics of their batteries. Two obvious and significant variables affecting travel range are: (i) variations with respect to changing ambient temperature; and (ii) vehicle and battery aging. The objective of this paper is to present updated travel range data and analysis by the Electric Vehicle Technology & Education Centre (EVTEC) dealing with combined effects of these two variables, specifically for the all-electric Nissan Leaf, which has been commercially-available as a BEV for roughly five years.

2 Literature

The maximum travel range of a BEV on a single charge as a function of ambient temperature has been found overall to show the shape of a logistic curve. This type of curve is encountered for studies in such diverse areas as population growth and adoption of new technologies, with the value of the function starting at a lower asymptote, increasing rapidly to a maximum slope, and then tapering back toward an upper asymptote, literally forming the shape of an “s” [1]. This function, however, is mathematically complex, and provides little in the way of underlying explanation beyond the expediency of fitting data to a curve.

A much simpler, but potentially more useful, representation of BEV travel range as a function of ambient temperature has been developed, dubbed the “EVTEC” model. Outlined initially by Delos Reyes et al. (2014) [2], a fuller explanation of this model has been provided [1]. The model itself consists of three linear segments: (i) flat range plateau at warm temperatures above around +20°C, where no heating or AC is employed, showing the highest range value; (ii) flat range plateau at cold temperature below around -15°C, showing the lowest range value; and (iii) linearly-varying segment in the middle, showing a steady decline of range as the ambient temperature reduces.

The structure of the EVTEC model intuitively makes sense. A BEV possesses limited battery capacity, and can thus only travel a finite maximum distance on a single charge. The upper range plateau of the model represents the maximum possible vehicle travel without heating or AC engaged, which is no different from a conventional vehicle. The energy content of both air and the vehicle construction materials vary linearly with temperature, such that vehicle heating load varies linearly with declining ambient temperature. This is consistent with the linear decline of travel range outlined in the middle segment of the model. Lastly, for cold conditions, a BEV possesses 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, which is again no different from a conventional vehicle.

At the same time, the energy capacity of lithium-based batteries is understood to also vary linearly with temperature. An effectively flat range plateau at cold conditions still makes sense as long as the reduction in travel range due to battery energy capacity decline, firstly, is relatively small compared to the effects of cabin heating, and, secondly, is not as significant compared to other random variations.

A key need identified in earlier work was to gather additional data in order to confirm the validity of the model, in particular to confirm the presence of an effectively flat range plateau at cold temperatures. Recently published data for the Chevrolet Volt plug-in hybrid electric vehicle (PHEV) has now shown in that case all-electric range at lower temperatures is not a function of ambient temperature [3]. This is consistent with the model.

The effects of aging on lithium ion batteries within electric vehicles have been recently discussed by Danzer et al. (2015) [4]. Their work includes details of aging mechanisms and impacts on voltage and capacity characteristics of batteries. From the practical perspective of a driver, however, what is most important is the progressive effect on vehicle range. Although Danzer et al. do not present any explicit model for this, example data presented by them suggests that travel range declines with age in a mathematical form that is relatively hyperbolic in character, but close to linear. Their example data further suggests that the reduction in maximum travel range after two years of aging is about 8%. At the same time, the combined effects of ambient temperature and battery aging on vehicle electric range, whether for a BEV or PHEV, have remained completely unknown.

3 Methods

The testing methods involved essentially a replication of what had been earlier undertaken using the same vehicle [1]. A 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 [5]. Earlier tests were undertaken over the time period from June 2013 through March 2014, while the Leaf was approximately 1.2 to 2.0 years old. The second, more recent, tests were undertaken over the time period from September 2015 through February 2016, while the Leaf was approximately 3.5 to 3.9 years old. Hence, there was roughly a two-year difference in vehicle age between the two sets of tests undertaken.

Testing involved driving-to-depletion, literally, as implied by the name, driving the vehicle in a controlled manner from a full state-of-charge (SOC) until depleted, with all driving undertaken in the urban vicinity of Winnipeg, Canada. The associated travel distance was determined by recording odometer differences between the beginning and end of each test run. The distance traveled after zero-battery indication was recorded separately in each case, but also included in the total travel distance.

A generally similar travel route was employed, this in the form of a large circle-of-eight as outlined in Figure 1. Travel routes, however, could not be absolutely identical, given changes in available range with temperature. The travel route included sections with speed limits of 50, 60, 70 and 80 km per hour. Odometer readings were logged manually at approximately 1 h intervals during trials, as possible. Based on this, travel, including all stoppages, was maintained in the range of 35 to 40 km within 1 h (i.e., 22 to 25 miles within 1 h).

Testing was undertaken only on selected days in order to ensure differential increments of about 5°C to 10°C across the full ambient range covering approximately -25°C to +26°C. The Leaf’s climate control was maintained at +21°C in all cases. Ambient temperatures were referenced in all cases to official hourly readings from Environment Canada at Winnipeg’s 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.

The same driver operated the vehicle in all cases. Tests were done solely in normal drive mode, which for the Leaf is denoted as D-mode, with travel done around mid-day to avoid congestion. In all tests head lights and windshield wipers were not used. After testing, recharging of the vehicle was undertaken out of doors under ambient conditions solely using Level 1. Statistical analyses for data, in particular t-tests, were undertaken manually for data as required, using methods as outlined and critical data values from a standard text [6].



Figure 1: Approximate travel route for drive-to-depletion tests in Winnipeg

4 Results

During the earlier set of tests from June 2013 through March 2014, a total of eight relevant drives-to-depletion were completed, excluding those involving AC. During the more recent set of tests from September 2015 through February 2016, a total of fourteen drives-to-depletion were completed, almost double the number in the earlier campaign. These latter tests covered the temperature range from -25°C to $+26^{\circ}\text{C}$. This included four tests at temperatures higher than $+20^{\circ}\text{C}$ and four tests at temperatures lower than -20°C . Plots of data from both sets of tests are presented in Figure 2, with projections of results based on the EVTEC model. Overall, aging appeared to cause the curves to essentially “pivot,” which had not been initially anticipated.

It is clear from the data that the Leaf continued to perform consistent with the expectations of the model, but with some obvious changes occurring. It is also clear from the data, that the effects of aging on the Leaf cannot be represented in terms of a simple, single parameter, e.g., single range degradation factor. The effects are obviously more complex, and are discussed in the following subsections regarding different defined aspects of the model and of BEV performance.

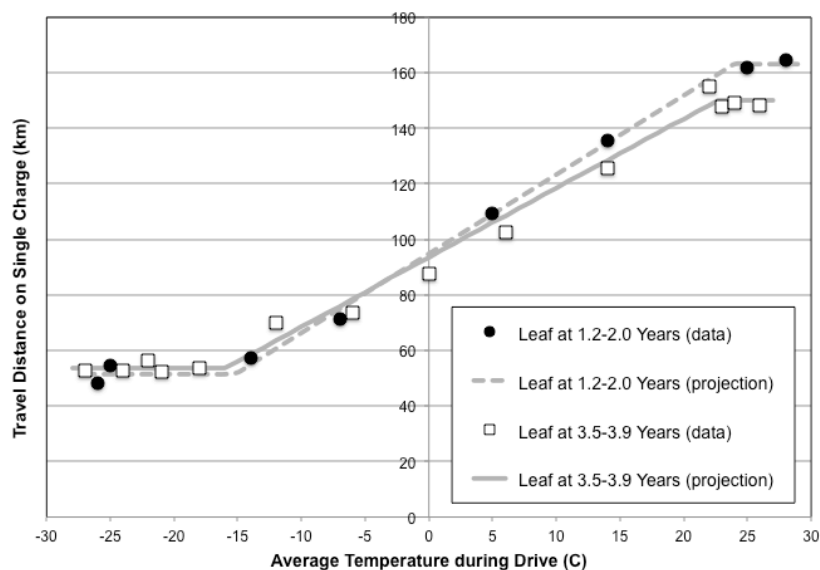


Figure 2: Plot of Leaf Travel Distance as Function of Ambient Temperature for All Data

4.1 Impact of Aging on Upper Range Plateau

For the older set of tests, only two data points were available at warmer temperatures, such that it had not been possible to confirm absolutely whether or not a plateau existed. This was possible, however, with the new set of tests, involving four data points above +20°C. For these latter data, the correlation coefficient (r^2) value was approximately 0.50, and was insufficient to conclude that a linear relationship existed between travel range and ambient temperature. A lack of any linear relationship, thus, effectively confirmed a flat plateau for these conditions. The mean value for the upper range plateau from the new data was 150.2 km $\pm$ 3.3 km ($n = 4$). This was much lower than the mean value from the older set of tests at comparable warm temperatures, which was 163.2 km $\pm$ 2.1 km ($n = 2$). A statistical t-test confirmed the difference in mean values to be significant, based on a calculated t-statistic of about 5.9 compared to a critical t-statistic of about 3.1 in this case for a 95% confidence level. These results meant that over roughly a two-year period, the upper (maximum possible) range of the Leaf BEV at warmer temperature, without heating or AC, declined about 8%, or roughly a reduction of 4% per year. This was highly consistent with the sample data presented by Danzer et al. [4].

4.2 Impact of Aging on Lower Range Plateau

Again for the older set of tests, only two data points were available at cold temperatures below about -15°C, such that it had not been possible to confirm absolutely whether or not a plateau existed. This was possible, however, with the new set of tests. There were four data points below -20°C, but as noted in Figure 1, the plateau appeared to extend to higher temperatures, so that a fifth data point at -17°C was added for analysis. These five data points showed a correlation coefficient (r^2) value of only approximately 0.16, confirming that no linear relationship existed between travel range and ambient temperature at those conditions. The results conclusively confirmed the presence of a flat range plateau at cold temperatures for the Leaf BEV, lower than about -17°C and at least down to about -25°C.

The mean value for the lower range plateau from the new data was 53.5 km $\pm$ 1.7 km ($n = 5$). This was not very different from the mean value from the older set of tests at comparable colder temperatures, which was 51.5 km $\pm$ 4.3 km ($n = 2$). A statistical t-test confirmed the mean values were not significantly different, based on a calculated t-statistic of only about 0.6 compared to a critical t-statistic of about 12 in this case for a 95% confidence level. These results meant that while the upper temperature range of the Leaf BEV declined with age, the lower temperature range did not. Such a finding has never been previously reported.

4.3 Impact of Aging on Middle Linear Model Segment

The third major portion of the EVTEC model is the middle, linearly-varying segment. An important feature of the model has been the finding of strongly linear relationships between travel range and ambient temperature at intermediate temperature values for BEV from about -15°C up to about +20°C. This strong linear relationship was again confirmed with the newer set of tests. There were, however, changes evident with the summary results, as presented in Table 1.

Table 1: Comparative Results for Linear Model Segment

	Slope (km/C)	Intercept (km)	r^2	n
Older tests	2.9	94.9	0.99	4
Newer tests	2.5	93.5	0.98	7
Change	- 14%	- 1%		

The most significant change, as indicated, was a reduction in the slope, declining roughly 14%. The intercept value, on the other hand, remained relatively similar. Such a net change is consistent with the findings noted above that the upper temperature travel range declined, but the lower temperature travel range did not. An additional implication of the finding of a significant change in slope was that a statistical analysis of covariance was not appropriate. A key assumption for analysis of covariance is homogeneity of regression slopes, a condition obviously not satisfied in this case.

4.4 Impact of Aging on Travel Range After Reaching Zero-Battery Indication

An important aspect of travel range for BEV involves the distance traveled after the vehicle display indicates zero-battery energy has been reached. Consistently it has been observed that all BEV possess some additional reserve after reaching zero-battery indication, such that drivers are not immediately stranded. For the older set of tests with the Leaf, this was found to be 4.1 km $\pm$ 1.0 km (n = 8), and did not show variation with ambient temperature. For the newer set of tests, the result was almost the same, being 4.5 km $\pm$ 0.6 km (n = 14), again not related to ambient temperature. A statistical t-test confirmed the mean values were not different, based on a calculated t-statistic of only about 1.0 compared to a critical t-statistic of about 2.3 in this case for a 95% confidence level. The results showed that travel distance after reaching zero-battery indication was unaffected by either ambient temperature or aging of the vehicle.

4.5 Impact of Aging and Temperature on Remaining-Range Indicator Estimates

In earlier testing of the Leaf, and other electric cars, it had been found that remaining-range indicators of all vehicles are relatively unreliable. Although the Leaf's indicator has not been necessarily any worse than any other such vehicle, the prominence of its positioning on the Leaf display just makes it more obvious. Using data from the newer set of tests, it was possible to more systematically evaluate the accuracy (or lack thereof) of this display. For each drive-to-depletion test, the ratio was calculated of the initially projected-range at the start of each drive divided by the actual range achieved for that test. This permitted the percentage over-estimate of the initial range projection to be calculated. In one test, the range was accurately projected, i.e., over-estimate of 0%, but in all other cases the projected range over-estimated actual travel, in one case by as much as 84%. Overall, for all tests, projected range was found to be an over-estimate of 33% $\pm$ 22% (n = 14) compared to actual. When the percentage over-estimate was considered relative to ambient temperature, the correlation coefficient (r^2) was found to be only 0.06. This confirmed that the over-estimate by on-board range projection was not related to ambient temperature. In earlier tests the range projection data was not collected in as systematic a manner, but appeared unrelated to ambient temperature. With age, the range projection appeared to remain inaccurate, but the extent to which it was more or less worse could not be determined. In short, reasonable projection of expected range for electric vehicles, including the Leaf, remains a problem.

5 Implications and Further Research Directions

The results of this work provided validation of the EVTEC model in describing the travel range behaviour of electric vehicles using a single charge. So far, the model has been applied to two BEV, the Nissan Leaf and Mitsubishi i-MiEV, and one PHEV, the Chevrolet Volt. It is desired to expand testing to include additional vehicles in order to confirm broader applicability.

The results of this work showed that the impacts of vehicle aging on BEV travel range are complex, but can be fully quantified using the EVTEC model, based on changes to four distinct parameters: (i) upper plateau range value; (ii) lower plateau range value; (iii) linear segment slope value; and (iv) linear segment intercept value. Further testing of different electric vehicles at increasing ages is desired to understand impacts with different vehicles, including identifying potential similarities or differences. So far, the Leaf has been tested most extensively, and it is desired to continue testing the same vehicle, if possible, on a further, longitudinal basis. This would include, in particular, testing in roughly two years (i.e., when vehicle is 5 to 6 years old), and in four years (i.e., when vehicle is 7 to 8 year old), in order to better understand aging impacts over the entire life of a vehicle.

A subtle but important implication of this work is that colder climate areas appear to be well-suited as locations for used electric vehicles. Although cold temperatures obviously reduce travel range significantly, the range reduction is not worsened through vehicle aging. As such, aging has less relative impacts on operation in a cold climate, which represents a potential benefit.

Obtaining more realistic estimates of the anticipated range for drivers of electric vehicles is important, but still a largely unmet goal. The EVTEC model provides a reasonable method to estimate travel range, in particular as a function of ambient temperature. As such, it is desirable to explore the EVTEC model as a basis for developing better methods to estimate electric vehicle travel range. One relatively near-term option is a simplified smart-phone app.

6 Conclusions

The results of this work validated the EVTEC model in the case of the Nissan Leaf, as a simple means to represent travel range as a function of ambient temperature. The results, in particular, confirmed the presence of range plateaus at both warmer and colder temperature conditions, and also showed that the impacts of electric vehicle aging are complex, i.e., cannot be represented by a single variable value. Using the EVTEC model does permit full quantification of aging impacts relative to variable temperature operations. Specifically for the Leaf, aging over two years resulted in: (i) reduced upper plateau range; (ii) unchanged lower plateau range; (iii) reduced linear segment slope; and (iv) largely unchanged linear segment intercept. The results of this work confirmed that even with aging, the Leaf retains some reserve energy after indication of zero-battery energy available, ensuring that drivers are not immediately stranded. The travel distance after zero-battery indication was consistently in the range of about 4 km to 5 km, and was not affected by either ambient temperature or aging. Lastly, results confirmed the relatively unreliable nature of range projection by the Leaf's on-board systems, suggesting better range projection methods are needed.

Acknowledgments

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