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Impacts of Further Aging on Maximum Travel Distance for the Nissan Leaf over a Range of Ambient Temperatures

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Vehicle Technology International Conference

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Victoria Inn and Convention Centre

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Objective of ongoing vehicle testing work

- RRC has had interest in and applied research ongoing regarding the effects of both ambient temperature and battery aging on electric vehicles (in particular battery electric vehicles or BEV)

- BEV rely solely on stored electrical energy in batteries for motive operation, as well as for cabin conditioning, including heating, air conditioning, etc.

- RRC has had a unique opportunity to undertake ongoing testing with a 2012 Nissan Leaf over its life to assess changes over time

- This sort work is entirely unique, and has not been undertaken or published anywhere else in the world so far

EVTEC Model for Electric Vehicle Range

- Model emerged from earlier work by RRC on cold weather performance. Was developed under RRC's previous Electric Vehicle Technology & Education Centre initiative, hence name

- Winnipeg's continental climate involves a range of temperature conditions, literally from -30° C to +30° C, so why not take advantage of this to inexpensively test vehicles by driving-to-depletion across a range of temperatures?

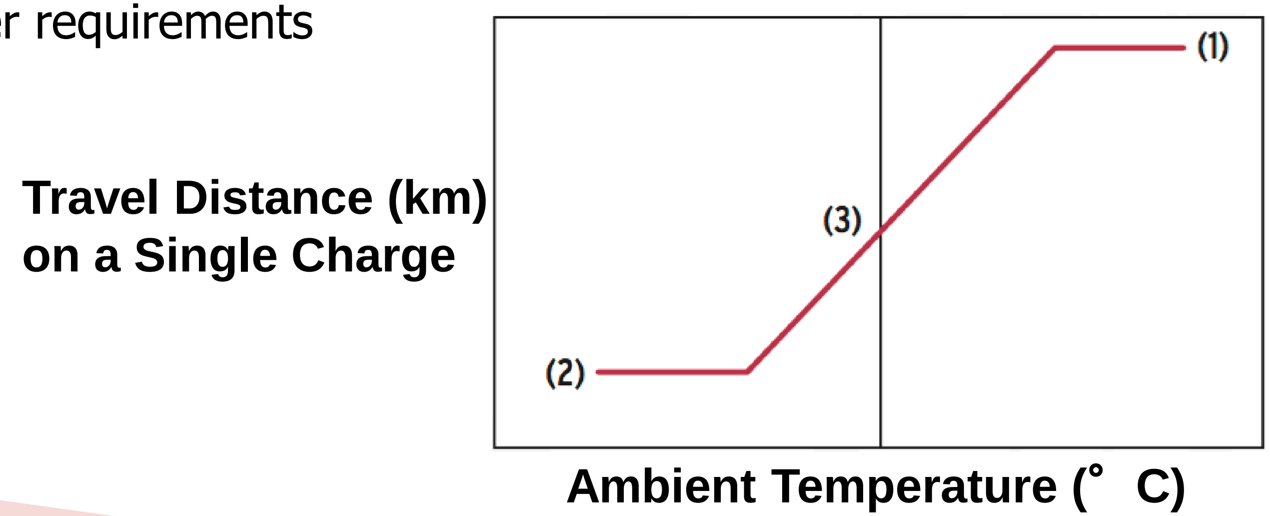
- Nature of travel distance versus ambient temperature curve follows a logistical or "S" shape, but mathematically complex

- Can be easily approximated using three linear lines. Simple and intuitive model was confirmed with three types of vehicles: Mitsubishi iMiEV, Nissan Leaf and Chevrolet Volt (PHEV)

EVTEC Model for Electric Vehicle Range

- Model first mentioned in Delos Reyes et al. (2014) and more fully described in Delos Reyes et al. (2016a and 2016b)

- Three linear lines (identified in plot) are as follows:
  1) **Upper temperature plateau** – maximum travel range of vehicle as determined by battery capacity (with no A/C used)
  2) **Lower temperature plateau** – limited heat output means only limited draw so as get colder range limited by driver tolerance
  3) **Linearly-varying section** – range declines in a way consistent with the linear nature of increasing heat transfer requirements

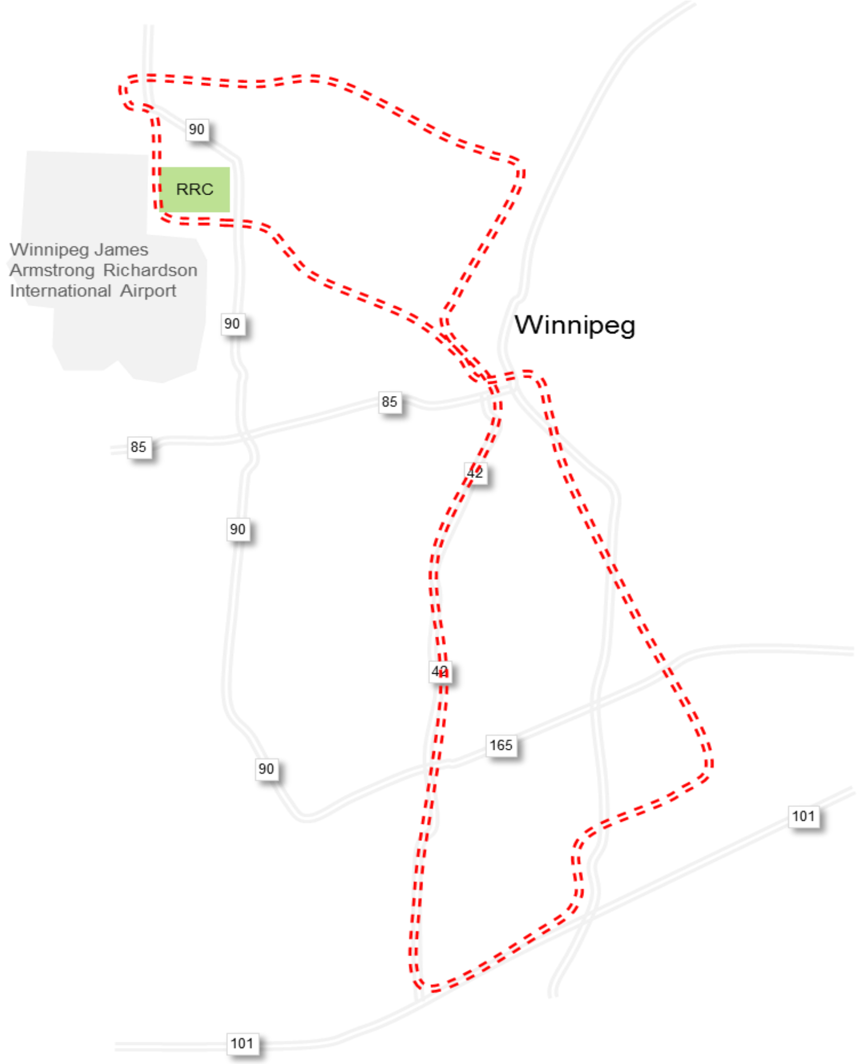


2012 Nissan Leaf as Used in Testing

- Nissan Leaf owned and managed by Vehicle and Equipment Management Agency (VEMA) of Manitoba Government
- Incorporates "winter" package included heated steering wheel and on-board battery self-warming system, but no Level 3 port. All charging using Level 1 (or Level 2)
- Vehicle used by several government departments over life, involving more than twenty different drivers

Operation During Testing Runs

- Generally similar travel route employed for testing, albeit with changes necessary due to reductions in travel distance during colder weather
- Same driver involved for vehicle in all test runs
- Regular (“D”) mode of operation at all times
- Climate system set to 21° C, with minimum wiper use, and headlights off



Three Test Campaigns so far using Vehicle

- Total of three testing campaigns have been undertaken so far using the 2012 Nissan Leaf:

  - **First Set** – undertaken from June 2013 through March 2014, when Leaf aged 1.2 to 2.0 years

  - **Second Set** – undertaken from September 2015 through February 2016, when Leaf aged 3.5 to 3.9 years

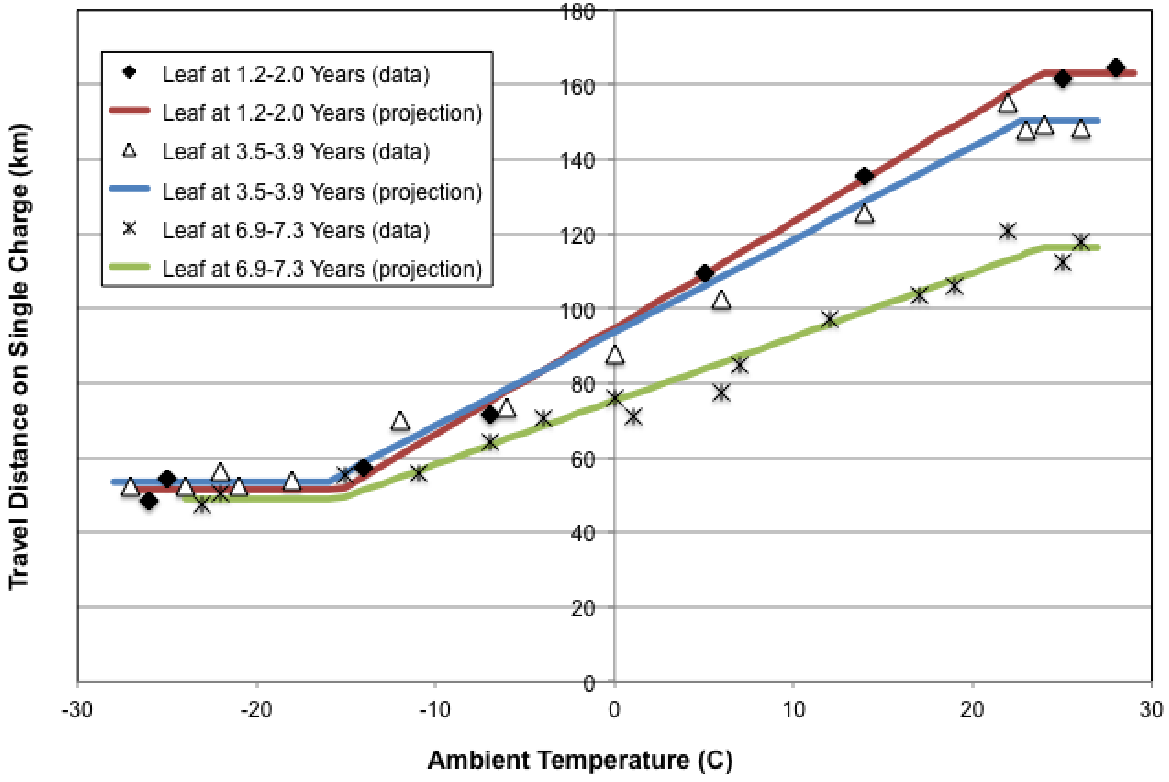
  - **Third Set** – (Most Recent) undertaken from from February 2019 through June 2019, when Leaf aged 6.9 to 7.3 years

- Selections of timings provides a useful distribution of data

- Total travel distance determined from odometer reading differences. Travel distance after reaching 0 Bars also recorded

Summary Data for Total Travel Distance

- Resulting data for travel distance as a function of ambient temperature summarized in the following figure:



Obviously different impacts on different parts of the EVTEC model

Aging Impacts on Upper Temperature Range

- Maximum vehicle range (at warmer temperatures but without A/C) continued to decline as the vehicle aged:

Vehicle Age	Travel Distance for Single Charge
1.2 - 2.0 Years	163.2 ± 2.1 km (1.3%), n = 2
3.5 - 3.9 Years	150.2 ± 3.3 km (2.2%), n = 4
6.9 - 7.3 Years	117.1 ± 4.4 km (3.7%), n = 3

- Decline found to be highly linear in nature relative to aging
- Decline translated to 4% to 5% annual reduction in range, consistent with suggested battery capacity reductions as outlined by Danzer et al. (2015)

Aging Impacts on Lower Temperature Range

- Vehicle range at cold temperatures showed relative constant values despite age:

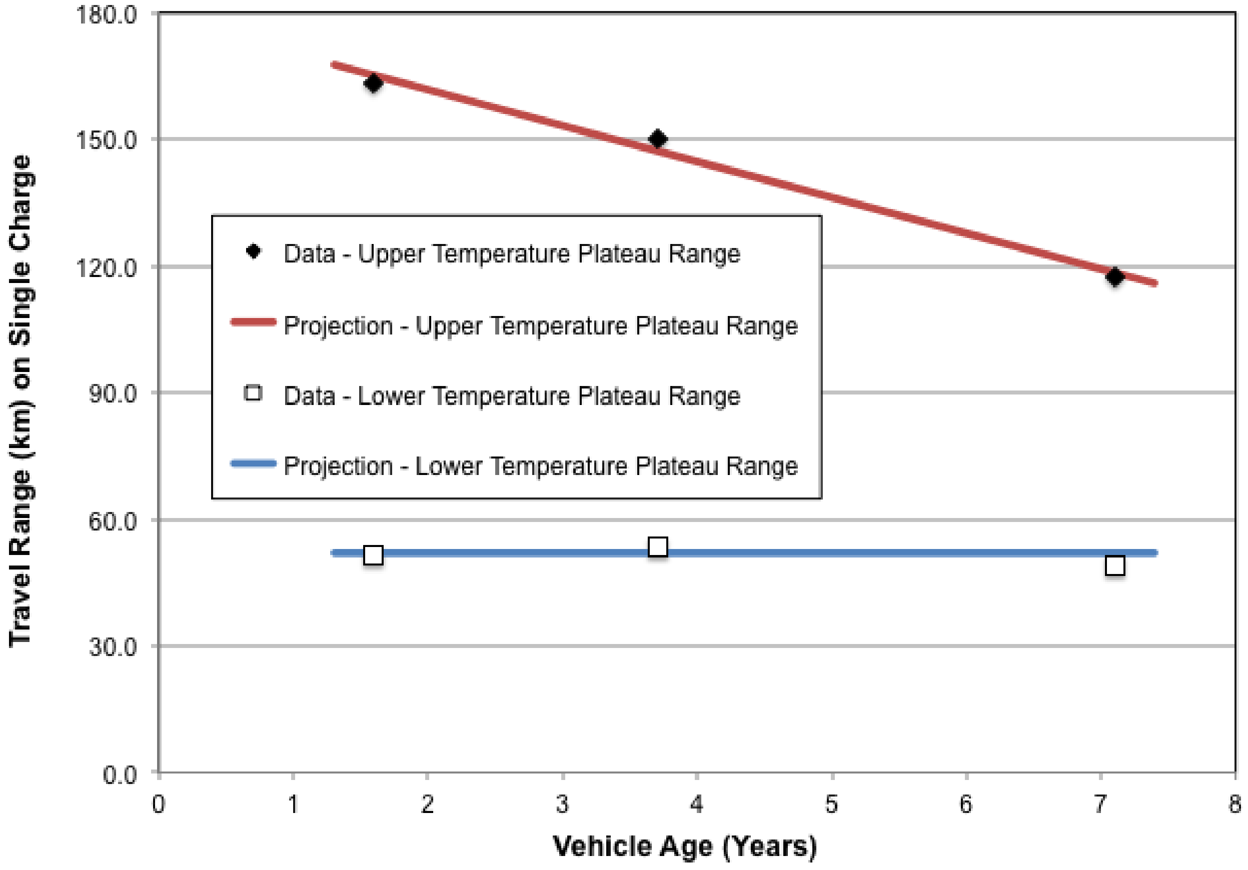
Vehicle Age	Travel Distance for Single Charge
1.2 - 2.0 Years	51.4 ± 4.3 km (8.3%), n = 2
3.5 - 3.9 Years	53.5 ± 1.7 km (3.1%), n = 5
6.9 - 7.3 Years	49.0 ± 2.3 km (4.8%), n = 2

- One-way analysis of variance (ANOVA) clearly shows these values to be not statistically difference, given F = 2.6 only, whereas for df = 2, 6 the $F_{critical}$ = 5.1 (i.e. F less than critical)

- As such, overall average lower temperature plateau range = 52.0 ± 2.9 km (5.5%), n = 9

Visualization of Plateau Range Changes

- Changes with age for the upper and lower temperature plateau ranges are represented in the following plot:



Aging Impacts on Linearly-Varying Section

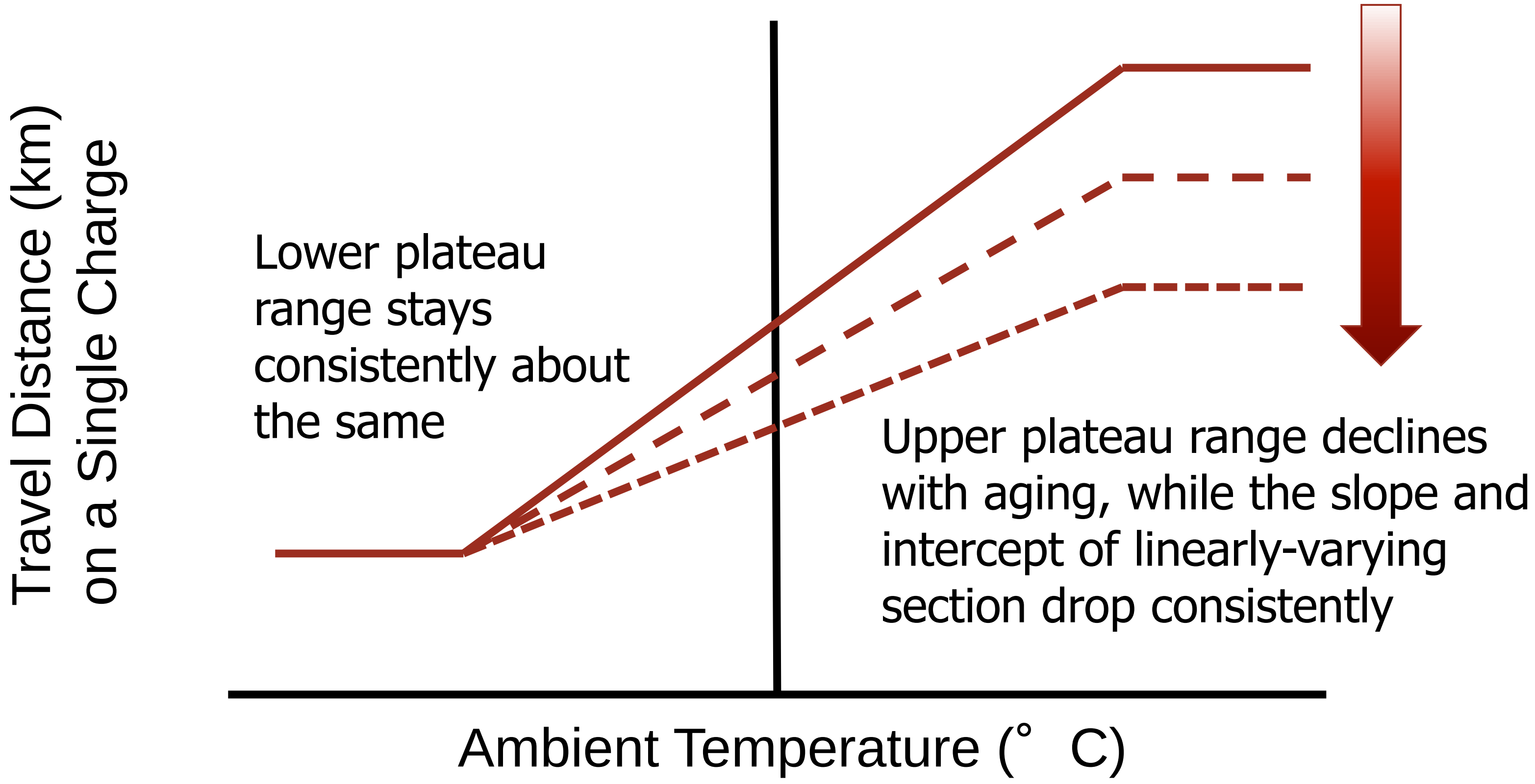
- Linearly-varying section parameters changed consistently:

Vehicle Age	Slope	Intercept	r^2	N
1.2 - 2.0 Years	2.9 km/°C	94.9 km	0.99	4
3.5 - 3.9 Years	2.5 km/°C	93.5 km	0.98	7
6.9 - 7.3 Years	1.7 km/°C	75.3 km	0.95	12

- As the vehicle aged, both the slope and intercept values for the linearly-varying section declined, all reducing in a relatively linear manner relative to the age of the vehicle

Resulting EVTEC Model Representation

- Analysis using the EVTEC Model suggests the following expected behaviour as a result of aging on vehicle travel distance based on a single charge:



Better Indication of Capacity Effects Needed

- Reductions in travel range due to aging were obviously due to reduced battery energy capacity over time, with range in the Third Set of testing reduced by about 28%
- Yet, Leaf display showed only 1 Bar drop in terms of capacity reduction. Improved display for the driver would be useful in order to give a more realistic indication

Problems with Remaining-Range Display

- The Leaf remaining-range display (see earlier slide) continued to indicate generally excessive (overly optimistic) values

Vehicle Age	Over-Estimate of Remaining Range
1.2 - 2.0 Years	No systematic data but consistent
3.5 - 3.9 Years	+33% ± 22%, n = 14
6.9 - 7.3 Years	+35% ± 26%, n = 16

- Important to note that Nissan is not uniquely at fault in this regard. All on-board systems projecting remaining-range have been found to be poor. The Leaf display is just more prominent and thus notable for the driver

Aging Impacts on Range after 0 Bars

- Travel range after vehicle reached 0 Bars was also tracked:

Vehicle Age	Range after 0 Bars Indication
1.2 - 2.0 Years	4.1 ± 1.0 km (25%), n = 8
3.5 - 3.9 Years	4.5 ± 0.6 km (14%), n = 14
6.9 - 7.3 Years	3.3 ± 0.9 km (28%), n = 16

- One-way analysis of variance (ANOVA) shows statistically significant differences to exist, given $F = 8.1$, while for $df = 2, 35$ the $F_{critical} = 2.9$ (i.e., F more than critical)
- However, earlier analysis had shown values for the first two test periods were not statistically different, such that the change occurred for the third test period. Range after 0 Bars declined but not as quickly nor as much as overall travel range

Conclusions and Future Directions

- This research work continued to validate the EVTEC model for electric vehicle range as a function of ambient temperature
- Upper temperature plateau range (maximum overall vehicle range) declined with age in a relatively linear manner. Despite reduction, the vehicle remains usable, even at advanced age, consistent with suggestions of Saxena et al. (2015)
- Lower temperature plateau range appears unaffected by aging. This suggests used electric vehicles are particularly suitable for colder climates, given performance is relatively less impacted
- Travel distance after reaching 0 Bar declined somewhat, but not as fast nor as much as overall travel distance
- Leaf remaining-range indicator is unreliable/overly optimistic

Thank you!

If you have any feedback or questions regarding this work, please contact the lead author:

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