

Cold Weather Issues for Electric Vehicles (EVs) in Alaska



Photo courtesy of Kirk Martakis



ACEP
Alaska Center for Energy and Power

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Executive Summary

An informal statewide survey distributed by the Alaska Center for Energy and Power (ACEP) at the University of Alaska Fairbanks (UAF) in November of 2019 showed there is substantial interest in electric vehicle (EV) adoption in Alaska, though concerns related to cold weather issues remain. To address these concerns, this review of literature and existing information on EVs in Alaska finds that the current generation EVs typically perform well in cold weather, with similar or better handling compared to morphologically similar internal combustion engine (ICE) vehicles. The most concerning cold weather issues are large range decreases, slower charging times, lower power availability in extreme cold, and the need to keep a vehicle plugged in or in a heated space especially during extended periods with ambient temperatures below about -20°C (-4°F). Figure ES-1 characterizes some of these operational concerns with respect to their corresponding temperature ranges.

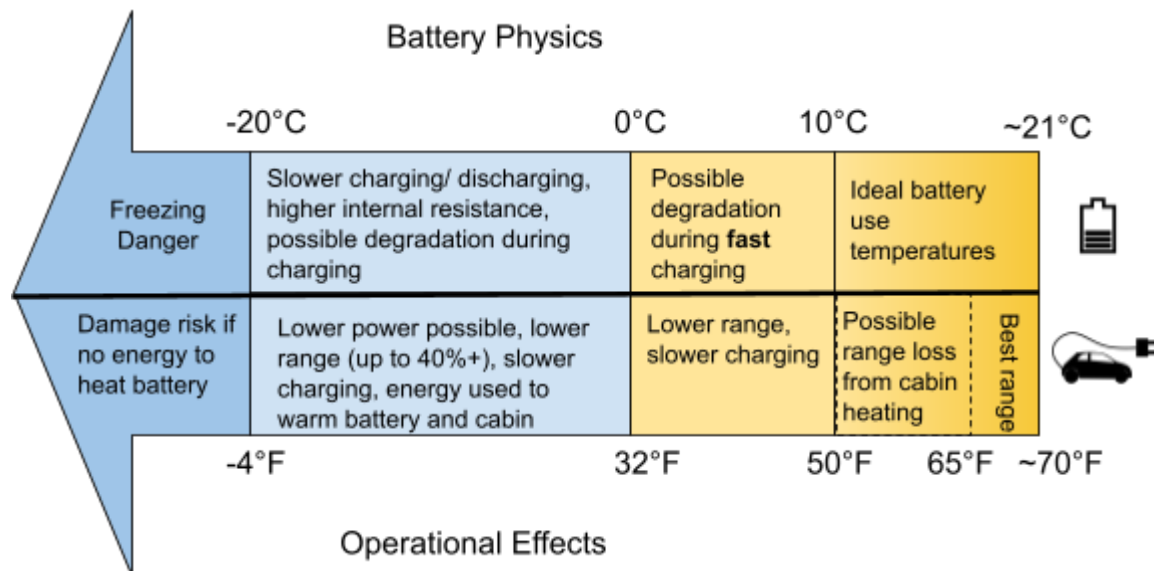


Figure ES-1. Low temperature regimes for EVs: The top half shows effects of cold temperatures on batteries due to their physics. Most of these effects are prevented through battery management and thermal management systems (e.g., heating the battery or charging it more slowly). The bottom half shows common operational effects, up to the possibility of battery damage if stored for extended periods at temperatures below -20°C (-4°F) without access to adequate power to run the battery heater. Source: Compiled by Michelle Wilber.

Much of Alaska’s population lives in areas where winter temperatures are commonly below -20°C (-4°F), with even colder temperatures in Interior Alaska. More research is needed to understand the charging patterns that enable regular use of EVs in colder climates, such as plugging in at work and the resultant energy use for stationary battery protection. Owner’s manuals recommend plugging in or parking in warmer spaces during cold weather (the recommendation varies based on make or model but can be as high as 0°C (32°F)). Based on

the literature review and anecdotal evidence from individual Alaska drivers, EV ranges during the winter are about half of summer, or nominal, ranges.

ACEP worked with the University of Washington DIRECT program to create an online EV Temperature Map (Figure ES-2) that shows three metrics related to temperature effects on performance.¹ One metric is a normalized EV score based on the average daily range loss for any location on land, calculated from a fit of driving range loss vs. temperature, using 10 years of NASA temperature data. The second metric is the Maximum Expected Range Loss based on the coldest temperature reached in the last 10 years. The third metric is “Must-Plug-in-Days” or MPID, which is the maximum number of consecutive days in the 10 year temperature record in which the average temperature does not exceed -20°C (-4°F), as this is the approximate temperature at which an unplugged EV may be permanently damaged.

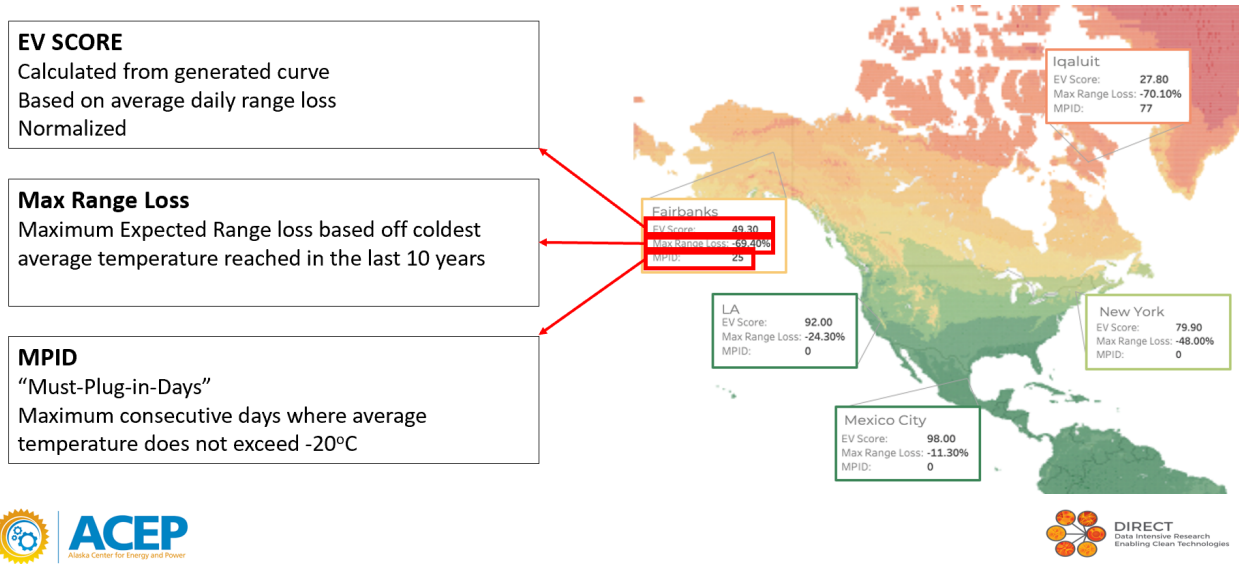


Figure ES-2. ACEP EV Map²

These metrics may be used to predict performance and efficiency or inform EV strategies in regions of the world. Looking at the EV score, much of China, Russia, Europe, Iceland, Greenland, Canada, the northern US, and mountainous regions of the world have scores overlapping with those found in Alaska.

¹ Kitt., M, Gu, D., Kau, Z. H., Suh, J., Wilber, M., Pike, C., Leach, T. (2020, June). ACEP EV Map. Retrieved January 8, 2021, from https://public.tableau.com/profile/michelle1506#!/vizhome/ACEPEVMAP_16061795177860/Home

² *Id.*

Opportunities for further research by ACEP, which could be conducted in a cold climate like Fairbanks, include the following:

- Test self-heating batteries.
- Collect and analyze data on power draw vs. temperature for different EV models while charging and while fully charged.
- Test Levels 1, 2, and 3 nominal charging speeds vs. temperature.
- Collect and analyze data on maximum range and energy use per mile vs. temperature for different EV models.
- Evaluate the change in maximum range over time (years) for several EV models parked outside in ambient air temperatures.
- Investigate effects of extreme cold on EVs parked in ambient air temperatures but not plugged in (e.g., minimum starting temperature, loss in battery state of charge with time, and battery recovery when brought back into a warm environment). Testing to the point of significant damage or failure (i.e., partial or total loss of battery capacity) would provide useful information, but would also incur substantial expenses.
- Develop a workable electric ATV and/or snow machine for rural Alaska using lithium titanate batteries for their superior cold performance.
- Investigate secondary/external/portable cabin heat sources that could alleviate the draw on the main battery for heating (e.g., heat packs).

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Glossary of Terms

Battery Degradation - permanent loss of storage capacity of the battery.

Battery Thermal Management System (BTMS) - The controls and infrastructure that allow the vehicle to cool or heat the battery automatically to enhance performance or battery health.

BEV - battery electric vehicle - an all-battery EV, without an internal combustion engine.

Cabin - the passenger compartment of the vehicle.

C-rate - the charge or discharge rate of a battery. A 1C discharge is complete discharge of the rated capacity of the battery in one hour, a 2C discharge rate is complete discharge in half an hour, and so on.

EV - electric vehicle - a vehicle that uses electric motor(s) for propulsion.

kW - kilowatt - a measure of electrical power.

kWh - kilowatt-hour - a measure of electrical energy and the unit of sale of electricity.

Level 1 Charging - Level 1 charging uses 120V AC, which is a standard household outlet. Charging power is generally around 1.4kW.

Level 2 Charging - Level 2 charging uses 240V AC, which is the same as a typical dryer outlet, and typically uses about 7kW of power.

Level 3 Charging - Level 3 charging is also known as DC Fast charging and generally is at power levels of 50kW or above.

PEV - plug in electric vehicle - any EV (PHEV or BEV) that can be plugged in to charge the battery.

PHEV - plugin hybrid electric vehicle - a vehicle with both electric motor(s) and an internal combustion engine.

Range - total number of miles that can be driven on a full charge of the vehicle battery pack; as displayed on an EV console, range is an estimate involving various assumptions.

Self-Discharge Rate - the rate at which a battery discharges in storage.

Introduction

Interest in electric vehicles (EVs) is increasing rapidly in Alaska. In 2009, the University of Alaska Fairbanks (UAF) Transportation Center investigated EVs in Alaska.³ Although the technology was at a very different state at the time (vehicles were either self-built or conversions), the report notes: “Electric Vehicles can be a viable option for certain users in the subarctic and arctic communities.” More recent work at UAF has included research on battery management strategies for cold climates.⁴ There has already been a large uptake of plug-in EVs in Southeast Alaska, where hydroelectric power enables low costs, the limited size of road systems largely negates driving range anxiety, the climate is relatively temperate, and consumers can directly access used EVs from the Lower 48 via ferry. As of June 30, 2020, the Chugach Electric Association (CEA) reported that over 1,100 EVs were registered in the entire state of Alaska, including 800 Battery Electric Vehicles (BEVs), which are fully powered by electricity, and 370 Plug-in Hybrid Vehicles (PHEVs), which combine electric motors and a gas-powered internal combustion engine (ICE).⁵

Because EVs interact directly with electrical generation systems (distributed and community) and have the potential to act as dispatchable loads or storage to support electric grid stability, ACEP is investigating research questions pertinent to EVs in Alaska. A survey distributed through ACEP’s weekly newsletter in November of 2019 showed that cold weather issues and performance were major concerns.⁶

Cold weather concerns are not limited to Alaska. As a region with a high uptake of EVs and ambitious goals for transitioning to EVs, Norway is a leader in operating EVs in cold climates. However, despite overall progress in Norway, driving range anxiety in cold temperatures remained a challenge to widespread EV adoption as recently as 2015.⁷

This report begins to address concerns related to driving anxiety in cold environments, such as operational performance and battery degradation. We review the EV literature for Alaska and other cold climates and explore anecdotal evidence of performance issues. The primary focus is on passenger BEVs, although the findings are applicable to other EV classes and PHEVs. We also pose research questions that could be examined in future studies.

³ Zhang, J., & Golub, M. (2009), *Feasibility Study of Electric Cars in Cold Regions*, Alaska University Transportation Center.

⁴ Thompson, I. D. (2018), *Modeling and exploring battery management strategies for use of LiCoO₂ lithium polymer cells in cold climates*, M.S. Thesis, University of Alaska Fairbanks.

⁵ Skaling, Sean (2020, Sep. 22) personal communication by email.

⁶ Whitney, E. (2019, Nov.) ACEP EVs in Alaska Survey.

⁷ Figenbaum, E., Assum, T., & Kolbenstvedt, M. (2015). Electromobility in Norway: Experiences and Opportunities. *Research in Transportation Economics*, 50, 29-38. doi:10.1016/j.retrec.2015.06.004

Overview of Cold Weather Effects on Operational Performance and Battery Degradation

Broadly speaking, cold temperatures can have two negative consequences on EVs: 1) reductions in operational performance and 2) battery degradation.⁸ Operational performance issues include a diminished driving range caused by the battery, cabin, and other heating loads as well as lower energy and power available from cold batteries. In addition to cold weather issues that are unique to EVs, reductions in operational performance could be caused by traction and other environmental conditions that affect all vehicles. On the other hand, battery degradation occurs when cold temperatures damage EV batteries, which can shorten the vehicle's lifespan.

The cold weather performance of different EV models may vary because battery technologies, battery heating and management systems, and cabin heating technologies sometimes differ. However, many of the proprietary details for commercially available models are not public knowledge.

Of publicly available knowledge, operational performance information is generally documented in the form of driving range and data reports from brief driving tests of a limited number of EVs by researchers and others and anecdotal evidence derived from owner experiences. Meanwhile, battery degradation has been investigated by researchers using battery models, theory, and lab testing.

Figure 1 summarizes the cold temperature effects on EV operational performance and battery degradation, along with strategies to ameliorate these effects.

⁸ Jaguemont, J., Boulon, L., & Dubé, Y. (2016). A comprehensive review of lithium-ion batteries used in hybrid and electric vehicles at cold temperatures. *Applied Energy*, 164, 99-114. doi:10.1016/j.apenergy.2015.11.034

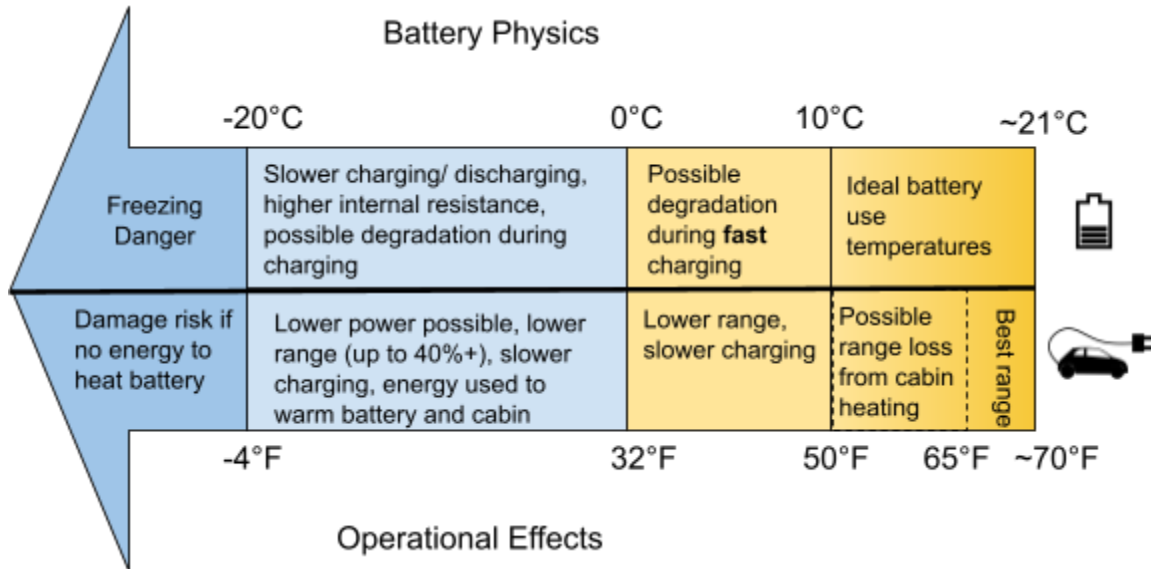


Figure 1. Low temperature regimes for EVs: The top half shows effects of cold temperatures on batteries due to their physics. Most of these effects are prevented through battery management and thermal management systems (e.g., heating the battery or charging it more slowly). The bottom half shows common operational effects, up to the possibility of battery damage if stored for extended periods at temperatures below -20°C (-4°F) without access to adequate power to run the battery heater. Source: Compiled by Michelle Wilber.

The Battery

Laboratory Tests on How Cold Affects Batteries

Early EVs used lead acid batteries, but modern EVs primarily use lithium ion (Li-ion) batteries (Figure 2). Li-ion batteries are popular due to their relatively high specific energy, high energy density, and low self-discharge rate. However, cold temperatures not only reduce the available energy capacity and power of Li-ion batteries, but can cause degradation.^{9,10} There are multiple mechanisms contributing to lower battery performance and permanent battery degradation at cold temperatures, including increased resistance to charge transfer, increased electrolyte viscosity, and lithium plating.¹¹

Laboratory tests show that lower temperatures cause slower chemical reactions, less electrolyte conductivity, and decreased diffusivity of ions in the anode, which contribute to lower energy and

⁹ *Id.*

¹⁰ Hu, X., Zheng, Y., Howey, D. A., Perez, H., Foley, A., & Pecht, M. (2020). Battery warm-up methodologies at subzero temperatures for automotive applications: Recent advances and perspectives. *Progress in Energy and Combustion Science*, 77, 100806. doi:10.1016/j.pecs.2019.100806

¹¹ *Id.*

power availability.^{12,13,14} In describing batteries, discharge current is often expressed as a C-rate to normalize against battery capacity, which often varies between batteries. C-rates express the rate at which a battery is discharged relative to its maximum capacity. A battery with a 1C rate will entirely discharge in 1 hour. For a battery with a capacity of 100 Amp-hrs, this equates to a discharge current of 100 Amps. A 5C rate for this battery would be 500 Amps, and a 0.5C rate would be 50 Amps. The C-rate is not a quality of the battery, and the same battery may be discharged at different C-rates.

Below 0°C (32°F), the discharge capacity of Li-ion batteries is greatly reduced, which results in a shorter driving range.¹⁵ At -10°C (14°F), tested batteries retain about 77% of the energy capacity at 25°C (77°F) at a standard 1C discharge rate. At a faster C-rate of 4.6C, the battery retains about 40% of its room temperature energy capacity.¹⁶ Other experiments have confirmed the theoretical power drop from increased resistance at colder temperatures. For example, a standard Li-ion battery showed 1.25% of its nominal power density at -40°C (-40°F).¹⁷

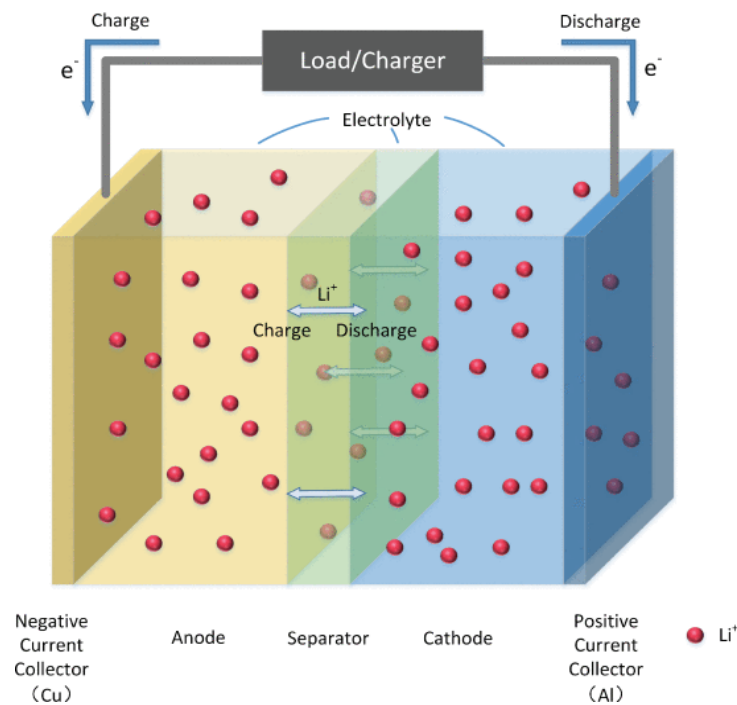


Figure 2. Schematic of the Lithium-ion battery. From: J. Zhang et al.¹⁸ Under [Creative Commons Licence](#).

¹² Jaguermont, *Supra* at note 4.

¹³ Hu, *Supra* at note 6.

¹⁴ Jaguermont, J., Boulon, L., Dube, Y., & Martel, F. (2016). Thermal Management of a Hybrid Electric Vehicle in Cold Weather. *IEEE Transactions on Energy Conversion*, 31(3), 1110-1120. doi:10.1109/tec.2016.2553700

¹⁵ Hu, *Supra* at note 6.

¹⁶ *Id.*

¹⁷ *Id.*

¹⁸ Zhang, J., Zhang, L., Sun, F., and Wang, Z. (2018). An Overview on Thermal Safety Issues of Lithium-ion Batteries for Electric Vehicle Application. *IEEE Access*, 6, 23848-23863. doi: 10.1109/ACCESS.2018.2824838.

As context for the C-rates mentioned above, we can use publicly available information for one EV model to look at sample C-rates appropriate to typical EV use: according to the Tesla website, the 2020 Model 3 Long Range has a driving range of 322 miles and can (one assumes under optimum conditions) be partially charged in 15 minutes with 172 miles of range added in that time. Assuming this is an approximate upper limit to the recommended charging rate, and given that 172 is approximately half of 322, the maximum recommended C-rate would be 2, which is a fast charging rate. Slow charging rates (1.6 to 17kW for charging Levels 1 and 2, respectively) are about a third or less than fast charging rates (50kW on up). Driving at a constant 55 mph would run out the range in 6 hours, for a 0.16C discharge. Top speed is given at 162 mph, which would discharge at 0.5C. All of these calculations assume optimal ambient temperatures and the range is constant with speed.

The most dangerous effect of cold temperatures on batteries is lithium plating, the formation of metallic lithium around the anode during charging, which can cause batteries to malfunction.¹⁹ Li-ion batteries have a lithium metal oxide cathode, but the standard anode material is layered graphite, where lithium ions are stored during charging. Cold temperatures bring the anode potential close to that of lithium metal, leading to slowed diffusion of ions into the anode and causing metallic plating during charging.²⁰ This results in a reduction in battery performance, some of which is permanent. In extreme cases, lithium plating can take the form of dendrites that can grow large enough to pierce the battery separator and cause internal electrical shorts and fire risk.^{21,22}

Lithium plating is a risk in EVs charged at battery temperatures below 0°C (32°F),²³ or fast charged below 10°C (50°F).²⁴ In a 2014 study, researchers found that batteries charged at -20°C (-4°F) led to the formation of metallic lithium; the faster the charging process, the more metallic lithium formed, locking up to 19% of the lithium ions normally involved in the charging and discharging process.²⁵ Although a 20-hour rest following a fast charge allowed some of the metallic lithium to react with the graphite in a delayed, slow charging process, part of the lithium plating was permanent. In an experiment at -10°C (14°F) and a 0.5C rate, the battery permanently lost 25% of its capacity after only 40 charge cycles.²⁶ One charge cycle at 0°C (32°F) at a 1C-rate caused a 3.6% irreversible capacity loss. For these reasons, charge rate is generally severely limited at low temperatures (and charge times greatly increased) to protect the life of the battery. Even up to temperatures as high as 10°C (50°F), lithium plating can occur during fast charging. Slow charging (i.e., Levels 1 or 2) is the only way to avoid lithium plating at

¹⁹ Jaguemont, *Supra* at note 4.

²⁰ *Id.*

²¹ *Id.*

²² Hu, *Supra* at note 6.

²³ *Id.*

²⁴ Penn State. (2018, June 28). Self-heating, fast-charging battery makes electric vehicles climate-immune. *ScienceDaily*. Retrieved January 20, 2021 from www.sciencedaily.com/releases/2018/06/180628171445.htm

²⁵ Zinth, V., von Lüders, C., Hofmann, M., Hattendorff, J., Buchberger, I., Erhard, S., Rebelo-Kornmeier, J. (2014). Lithium plating in lithium-ion batteries at sub-ambient temperatures investigated by in situ neutron diffraction. *Journal of Power Sources*, 271, 152, doi: 10.1016/j.jpowsour.2014.07.168.

²⁶ Hu, *Supra* at note 6.

battery temperatures below 10°C (50°F), and in practice charging speeds are limited and/or the battery prewarmed to avoid damage.²⁷

To ensure safe and normal operation below -20°C (-4°F), some researchers have begun investigating battery materials, such as varying the electrolyte and anode materials.²⁸ Lithium titanate batteries, for instance, use lithium titanate instead of graphite on the anode and have a reported operating range down to -30°C (-22°F) and up to 55°C (131°F).²⁹ Additionally, lithium titanate batteries have a longer cycle life (meaning they can endure many more charge and discharge cycles before being considered at the end of life), lower fire risk, and higher allowable charge and discharge rates. However, they are more expensive and almost twice as heavy as Li-ion batteries for the same energy content. The Honda Fit EV was the only passenger EV in the US to use lithium titanate batteries, but the Fit's short 100 mile driving range seriously affected demand, eventually leading to its removal from the U.S. market. Balancing the trade-offs between these materials is a research challenge with the potential for long-term payoffs.³⁰

In summary, the cold temperature testing of Li-ion batteries has exposed three temperature thresholds of concern:

- Under 10°C (50°F): Lithium plating and permanent degradation can occur with fast charging below this temperature.
- Under 0°C (32°F): This is the recommended lowest temperature for normal use of standard Li-ion batteries. Below this temperature, anything faster than Level 1 charging may cause lithium plating degradation.
- Under -20°C (-4°F): In addition to significantly reduced charging and discharging power capabilities,³¹ the recommended storage range (no active charge or discharge) is generally down to about -20°C (-4°F) for standard Li ion batteries used in EVs. The battery may not survive prolonged temperatures below this threshold.³²

The Battery Thermal Management System

Strategies to Manage Cold Weather Effects on EV Batteries

To manage cold weather effects on batteries, operational strategies are used³³, such as a battery thermal management system (BTMS) which allows battery heating to maintain an optimal temperature range. When EVs are not plugged in to an external power source, they

²⁷ Penn State, *Supra* at note 20.

²⁸ Hu, *Supra* at note 6.

²⁹ Category : LTO Batteries. (n.d.). Retrieved January 21, 2021, from <https://www.batteryspace.com/Lithium-Titanate-Battery.aspx>

³⁰ Hu, *Supra* at note 6.

³¹ Frydenlund, S. (2018, March 21), The biggest electric car test in winter wonderland ever. *Norsk elbilforening*. Retrieved January 21, 2021, from <https://elbil.no/the-biggest-electric-car-test-in-winter-wonderland-ever/>

³² Professor Eric Cheng, Seattle Pacific University, personal communication, January 3, 2020.

³³ *Id.*

must power the BTMS from the battery itself, although some vehicles do not power the BTMS unless it is plugged in.³⁴ Any solution must balance the cost and other trade-offs between reduced battery health (and thus life) and the cost of the system to heat the battery. The BTMS costs accrue from the complexity and extra weight of components, the cost of electricity, and reduced battery cycle life. One study concluded that parking outside at work or overnight without plugging in are issues with the actual BTMS strategies of common EVs/HEVs, mainly because aging (incremental degradation of the energy capacity of the battery) as a result of cold temperatures is not considered in the development of the BTMS.³⁵

Xiaosong Hu et al conducted their own review of the literature published about battery heating research, finding that there are two primary battery heating strategies.³⁶ In the first strategy, an external source transfers heat to the battery convectively or conductively. Convective options include air, liquid, and heat pump heating, whereas conductive options include resistance, Peltier-effect, heat pipe, phase change materials, and burner heating. In the second strategy, internal resistance is generated from a current applied to the battery itself, thereby heating the battery from the inside. The self-heating Li-ion battery (SHLB) is one recent example of this technology. Both strategies have their weaknesses. On the one hand, external heat sources result in longer warm up times, less temperature uniformity (which affects battery performance and health), and more energy consumption. On the other hand, internal heating must be carefully designed to use current levels and durations that do not cause excessive damage and are thus harder to implement.

The SHLB attempts to minimize the tradeoffs between pre-heating performance, energy consumption, and degradation.³⁷ This battery was developed to self-heat to avoid power drain at temperatures below 0°C (32°F) and has been upgraded to allow fast charging down to at least -43°C (-45°F). Two aspects of the SHLB—nickel foil inside the battery cell (attached to the negative terminal on one end and forming a third external terminal on the other end) and a temperature sensor attached to a switch—allow current to flow through and heat the foil. Once the battery is internally heated above room temperature, the switch automatically opens to allow charging. Research has indicated the SHLB can perform 4,500 cycles of fast charging at 0°C (32°F) before it reaches 20% capacity loss, where a standard Li-ion battery would only perform 50 cycles to the same capacity loss. This gives EVs with SHLBs approximately 280,000 miles of driving with a lifetime of 12.5 years, which is longer than most warranties.

Energy Costs for Battery Heating Strategies

According to lab testing, an external heating source for an EV BTMS generally requires less energy than an engine block heater for an internal combustion engine (ICE). Of the lab-tested external heating options reviewed by Hu et al, most options required no more than 40W in 35

³⁴ Nissan (2019) *2019 Nissan Leaf owners manual*, Retrieved January 21, 2021, from <https://owners.nissanusa.com/content/techpub/ManualsAndGuides/LEAF/2019/2019-LEAF-owner-manual.pdf>

³⁵ *Id.*

³⁶ Hu, *Supra* at note 6.

³⁷ Penn State, *Supra* at note 20.

minutes to heat the batteries by 20-40°C (68-104°F) in temperatures as low as -25°C (-13°F).³⁸ EV batteries must be maintained above -20°C (-4°F) to prevent permanent degradation and consumer acceptance may be greater for a vehicle that is always ready to drive without waiting to warm the battery and this may necessitate continual heating throughout the day, instead of a single heating event before driving.

In a real world setting, energy use data logged by Chugach Electric Association (CEA) for their Chevrolet Bolt while plugged in outdoors overnight in Anchorage, Alaska, indicated that the car drew an average of about 500W at -18°C (0°F), as seen in Figure 3 below.³⁹ The energy consumption of a BTMS is expected to be even greater in colder temperatures.

By comparison, most ICE block heaters require 400-750W and are recommended to be plugged in for 2 hours at -7°C (20°F) and 4 hours when temperatures are below -20°C (-4°F).⁴⁰ Despite these recommendations, many people plug in car block heaters (often in conjunction with battery blankets and oil pan heaters) at home and at work continuously during extremely low temperatures. ICEs generally do not suffer permanent damage if stored unheated in extreme cold, except perhaps to the starter battery which can be brought indoors.

Energy costs for battery heating strategies can be extrapolated from real world data. In Anchorage, Alaska, energy use for CEA's Chevrolet Bolt was logged when fully charged and plugged in outdoors overnight (see Figure 3).⁴¹ These data show that heating energy use is approximately linear with temperature, at least between about -18°C (0°F) and 13°C (55°F). Parking outdoors in Anchorage for 11 hours at about -7°C (20°F) costs roughly \$0.75 (with electricity priced at \$0.20/kWh). For comparison, it is estimated that the cost of cold-starting a gas engine is \$0.30/day.⁴² A 400 watt engine block heater plugged in at -7°C (20°F) for 2 hours would cost \$0.16. This is about an extra \$0.60 for the EV overnight.

If the trend stays linear, this means about 0.87 to 1.01 kWh/hr average use while parked fully charged at -40°C (-40°F). For a full 24 hours, this is about 24kWh, or \$4.80 total to keep warm. A block heater plugged in for 24 hours would have to draw more than 1000 watts of power (1kW) to be more expensive. This impacts the economics of 'fueling' an EV in extremely cold climates.

The data currently available for energy used while parked and driving are incorporated into an online calculator for Alaskans to investigate the cost and emissions of an EV vs. an ICE. This tool is available online.⁴³

³⁸ Hu, *Supra* at note 6.

³⁹ Skaling, S. (2019, February 11). Electric Vehicles in Alaska. *Alaska Forum on the Environment*, Anchorage, Alaska. (Updated by presenter March, 2019)

⁴⁰ Manitoba Hydro (2011) Car warmers, block heaters and energy controls. Retrieved January 21, 2020, from https://web.archive.org/web/20110927134325/http://www.hydro.mb.ca/your_home/home_comfort/block_heaters.pdf

⁴¹ Skaling, *Supra* at note 35.

⁴² *Id.*

⁴³ Wilber, M. (2020). Alaska Electric Vehicle Calculator. Retrieved January 21, 2020, from https://share.streamlit.io/mmwilber/ak_ev_calculators/main/EV_Emissions.py

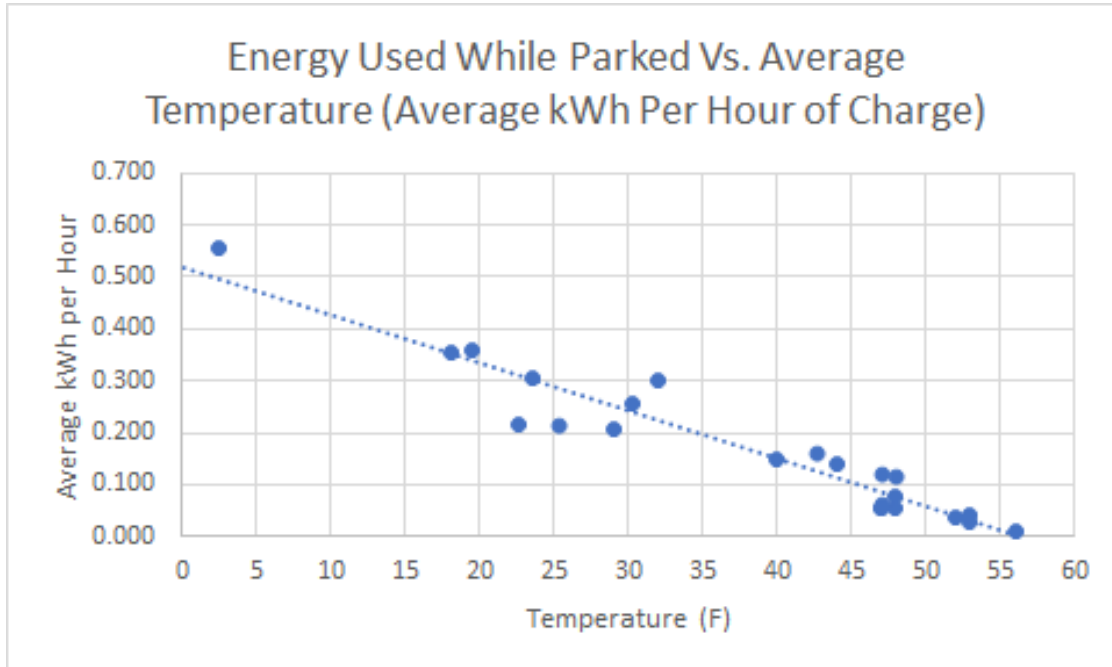


Figure 3. Data for Chugach Electric Association’s 2018 Chevrolet Bolt parked outside in Anchorage, Alaska showing average energy usage overnight while plugged in and already fully charged. Data courtesy of Sean Skaling.

The Vehicle

Direct User Experiences

Much of the cold weather performance information for commercially available EVs is based on anecdotal reports. Traction and general winter road feel are reported as good, and most drivers report more satisfaction with winter performance than they expected.^{44,45,46} Snow and ice can affect doors, locks, traction (due to wheel-well snow buildup), and clearance, and also require plugging in and high quality winter tires.^{47,48} Of course, snow and ice affect all passenger vehicles in these ways. That said, the lack of engine heat near front wheel wells may exacerbate snow buildup on EVs.⁴⁹ Winter charging rates can be lower than expected, with two sources noting a Chevrolet Bolt charging at about half the rated 50kW of a fast charger as

⁴⁴ Frydenlund, *Supra* at note 27.

⁴⁵ Voelcker, J. (2018, Jan. 30), Chevy Bolt EV electric car range and performance in winter: one owner’s log, *Green Car Reports*, retrieved from https://www.greencarreports.com/news/1115039_chevy-bolt-ev-electric-car-range-and-performance-in-winter-one-owners-log.

⁴⁶ Whitney, *Supra* at note 2.

⁴⁷ Voelcker, *Supra* at note 41.

⁴⁸ Whitney, *Supra* at note 2.

⁴⁹ Voelcker, *Supra* at note 41.

temperatures dropped to around -16°C (3°F), even when only charged to 80% capacity, as the last 20% typically charges at a slower rate^{50,51} One interviewee reported a maximum winter driving range drop of 48% from nominal at -29°C (-20°F) in Cantwell, Alaska.⁵² One significant factor in cold weather driving range loss is use of cabin heating,⁵³ which can be avoided or reduced by the driver to minimize the range loss. Owners of Nissan Leafs in Alaska have noted poor cold weather performance, with 50-60% of the battery used for heat at temperatures below -18°C (0°F) and total inoperability at -32°C (-27°F).^{54,55}

Anecdotal reports of user experiences corroborate the findings from the previous section on the energy used while parked by the battery thermal management system. Leaving a car unplugged in the extreme cold is possible but generally uses energy from the battery, and is not recommended by EV user manuals (Table 1). As an example, one car was parked outdoors in temperatures below -20°C (-4°F) for 30 hours and readings showed 24 miles of range were used to heat the battery.⁵⁶ Another car was parked for four days without a plug with temperatures as low as -32°C (-26°F); the owner used an app to preheat the EV and drove away several minutes later.⁵⁷ A driver that parks their Bolt outside all winter in Cantwell, Alaska reports that, at the most, the battery requires 20 to 30 minutes of heating before operation in extremely cold weather. The EV driver in Cantwell reports that his EV may warn of "reduced propulsion" when initially started in the cold, but the driving range and power both increase after some driving. Similar observations have been noted by others.⁵⁸ From a driver comfort standpoint, interviewees report that cabin temperatures in EVs increase more quickly as they do not rely on internal combustion engines that need to warm first. Indeed, some EV models allow drivers to direct their vehicles to warm the cabin before the vehicle is started.

⁵⁰ Frydenlund, *Supra* at note 27.

⁵¹ Voelcker, *Supra* at note 41.

⁵² Whitney, *Supra* at note 2.

⁵³ Argue, C. (2020, May 25). To what degree does temperature impact EV range? Retrieved January 21, 2021, from <https://www.geotab.com/blog/ev-range/>.

⁵⁴ Whitney, *Supra* at note 2.

⁵⁵ Bergen, M. (2020, Oct. 20), email message to the author.

⁵⁶ Voelcker, *Supra* at note 41.

⁵⁷ Lewis, M. (2020, Feb. 11), How does a Tesla Model 3 perform in an Arctic Circle winter?, *Electrek*, Retrieved January 21, 2021, from <https://electrek.co/2020/02/11/tesla-model-3-arctic-circle-winter/>

⁵⁸ Voelcker, *Supra* at note 41.

Table 1. Information on low-temperature storage for selected EVs from owner’s manuals. The Plug-In Threshold is the ambient temperature below which the manual recommends plugging in or storing the car in a heated space. The last column lists the conditions under which the manual warns of damage or freezing.

| Year/Make/Model | Plug-In Threshold | Permanent Damage or Battery Freezing Threshold |
|--|-------------------|--|
| 2018 Chevrolet Bolt ⁵⁹ | 0°C (32°F) | - |
| 2019 Tesla Model 3 ⁶⁰ | - | -30°C (-22°F) for more than 24 hours at a time |
| 2019 Nissan Leaf - 40kWh ⁶¹ Battery | -17°C (-1°F) | -25°C (-13°F) for more than seven days |
| 2019 Nissan Leaf - 62kWh ⁶² Battery | -20°C (-4°F) | -25°C (-13°F) for more than seven days |

Driving Range vs. Temperature

In a 2016 study of two EV models, the Nissan Leaf and the Mitsubishi i-MiEV,⁶³ researchers drove the EVs to depletion in temperatures ranging from 28°C (82°F) to -26°C (-15°F) in Winnipeg, Canada. Analysis of the travel range as a function of ambient temperature for both EVs showed three linear segments: an upper plateau above about 20°C (68°F), a lower plateau below about -15°C (5°F), and a linearly varying segment within this temperature range. The shortest driving range was 30 to 35% of the nominal range (a decrease of 65 to 70%). One interpretation of this decrease is that it was not necessary to heat the batteries and cabin in temperatures above 20°C (68°F), while the battery and cabin heaters were running at full power in temperatures below -15°C (5°F). In temperatures between the extremes, proportional amounts of cabin and battery heat produced a draw on the battery. Data at even colder temperatures would be useful to investigate if the lower plateau is truly flat. One might expect that as the temperature continues to drop, the battery temperature will fall after the battery heating system reaches maximum output, and the driving range will continue to decrease from the physical effects of the cold on the battery. This effect appears to have a smaller correlation

⁵⁹ Chevrolet (2018), *2018 Bolt EV Owner’s Manual*, Retrieved January 21, 2021, from <https://my.chevrolet.com/content/dam/gmownercenter/gmna/dynamic/manuals/2018/Chevrolet/Bolt/2018-chevrolet-bolt-ev-owners-manual.pdf>.

⁶⁰ Tesla (2020), *Model 3 Owner’s Manual*, Retrieved January 21, 2021, from https://www.tesla.com/sites/default/files/model_3_owners_manual_north_america_en.pdf.

⁶¹ Nissan, *Supra* at note 30.

⁶² *Id.*

⁶³ Delos Reyes, J. R., Parsons, R. V., & Hoemsen, R. (2016). Winter Happens: The Effect of Ambient Temperature on the Travel Range of Electric Vehicles. *IEEE Transactions on Vehicular Technology*, 65(6), 4016-4022. doi:10.1109/tvt.2016.2544178

with temperature than the range decrease from auxiliary heating loads, but data is limited and the trend may be nonlinear.

The same authors repeated the experiment on the Leaf periodically over about 7 years as seen in Figure 4.⁶⁴ Figure 4 also shows the relationship between range and temperature noted above. The authors note that at lower temperatures the vehicle range appears to be unaffected by aging. This suggests, among other things, that used or older electric vehicles may be particularly suitable for colder climates, given that the cold weather performance is relatively less impacted over time.

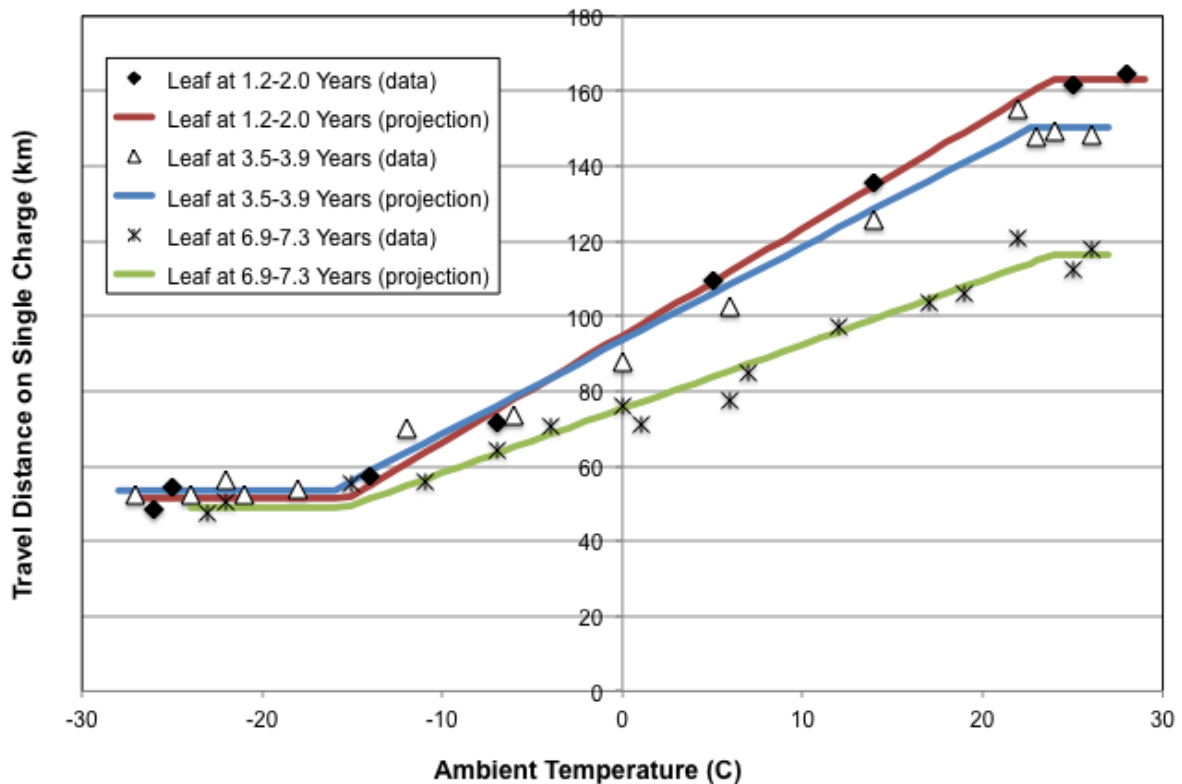


Figure 4. Travel distance as a function of ambient temperature for Leaf based on interpretation as linear segments. From Delos Reyes et al.,⁶⁵ used with permission.

This effect of temperature on driving range seems to be universal among tested passenger BEVs. The percent reduction in range with temperature is reasonably independent of the EV model. Data from the first spring and summer for CEA's 2018 Chevrolet Bolt in Anchorage, Alaska also exhibit a linear decrease in driving range with decreasing temperatures (Figure 5). During warmer weather, 16-18°C (60-65°F), the driving range is about 240 miles. The driving

⁶⁴ Delos Reyes, J. R., Parsons, R. V., & Hoemsen, R. (2019, October). Impacts of Further Aging on Maximum Travel Distance for the Nissan Leaf over a Range of Ambient Temperatures. *Vehicle Technology International Conference*, Winnipeg, Manitoba, Canada.

⁶⁵ *Id.*

range decreases to about 170 miles at 4°C (40°F), a difference of 30%, which is consistent with the percent decrease seen in Figure 4 for a Leaf under 2 years of age.

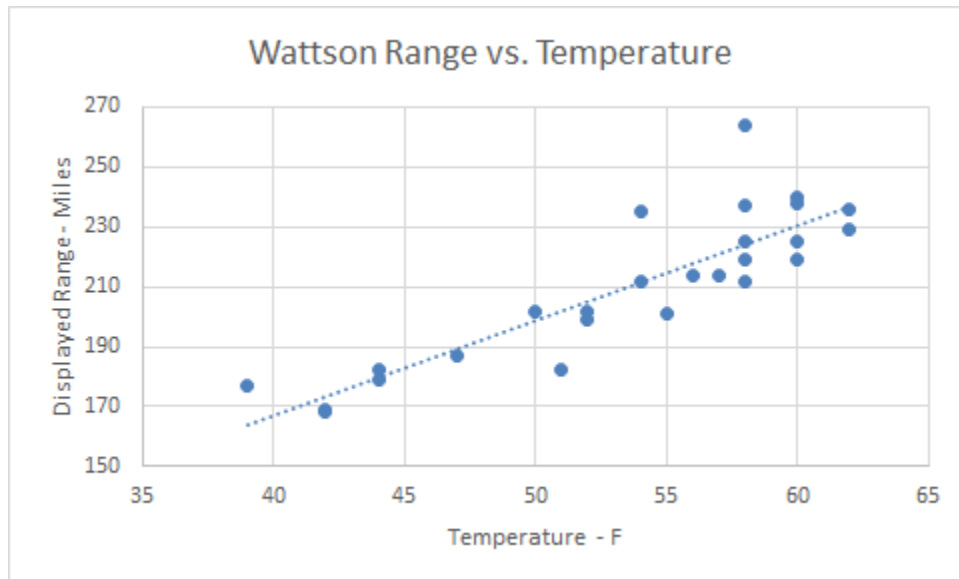


Figure 5. Data for Chugach Electric Association’s 2018 Chevrolet Bolt for trips in Anchorage, Alaska showing range vs. average ambient temperature. Data courtesy of Sean Skaling.

In 2013, Fleetcarma compiled data from more than 5,400 trips of Nissan Leafs in North America, to investigate the effect of temperature on driving range in real world conditions.⁶⁶ At the lowest average trip temperature of -25°C (-13°F) outside and 23°C (74°F) inside the car, they found a 45% decrease in driving range. This is quite a bit less than the 65% to 70% range loss seen in Figure 4 for the same outdoor temperature for a 2 year old Leaf or the approximately 60% range loss seen for the same Leaf at 7 years of age. However, it is in the range seen for real world driving data captured by Geotab for 4200 EVs (Figure 6), showing that real world conditions can yield a range of losses.

⁶⁶ Ingram, A. (2013, Feb. 1), Nissan Leaf Range: How Much Does It Lose In The Cold?, *Green Car Reports*. Retrieved January 21, 2020, from https://www.greencarreports.com/news/1082048_nissan-leaf-range-how-much-does-it-lose-in-the-cold.

Real-world range vs. rated range

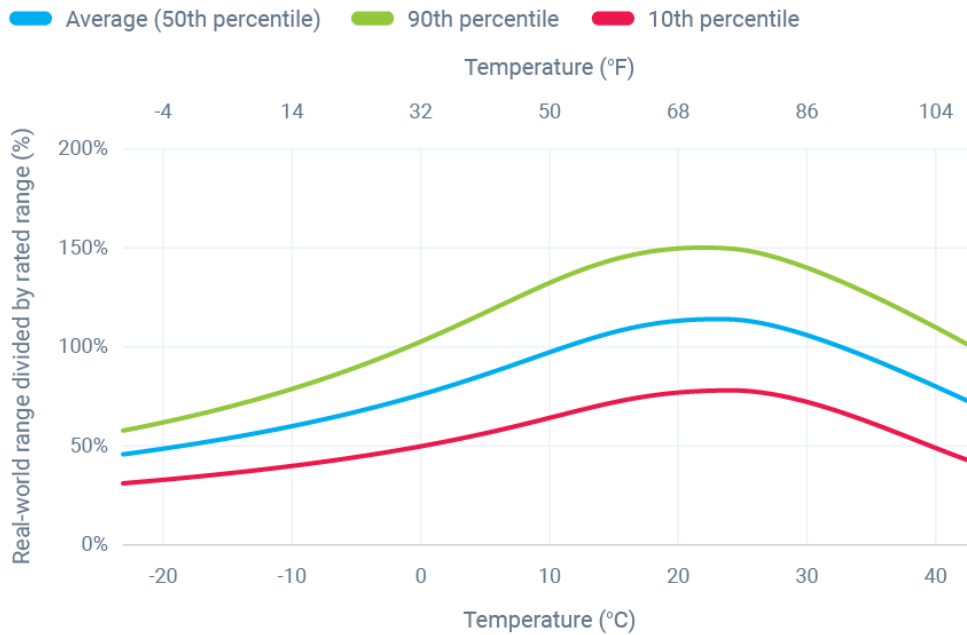


Figure 6. Range curve with 10th and 90th percentiles shows the distribution of trip efficiency one might expect at any given temperature. Figure is taken from Geotab’s blog on a study of 4200 EVs.⁶⁷

Since heating the cabin so greatly affects the driving range of BEVs, researchers are actively developing strategies to minimize the effects. NREL reports a decrease in heating load of 7-19% from simulations run in 2016 at around 0°C (32°F).⁶⁸

Temperature Effects on Long Term Battery Degradation

As a new and quickly evolving technology, there is little real-world data on the long term health of EVs, although theory predicts that battery health will have a period of nearly linear degradation before a precipitous drop off near the end of life (Figure 7).⁶⁹

Geotab analyzed over 6000 EVs of different makes, models, and years.⁷⁰ They found that most EVs experienced sustained battery health, but damage caused by sustained heat from hot climates or fast charging caused the most dramatic effects on battery health. Although the sample of EVs in this study did not include many from cold regions, this could mean that cold temperatures may prolong battery life (given that vehicles use a BTMS to avoid battery damage

⁶⁷ Argue, *Supra* at note 49.

⁶⁸ Jeffers, M. A., Chaney, L., & Rugh, J. P. (2016). Climate Control Load Reduction Strategies for Electric Drive Vehicles in Cold Weather. *SAE International Journal of Passenger Cars - Mechanical Systems*, 9(1), 75-82. doi:10.4271/2016-01-0262

⁶⁹ Argue, C. (2020, July 7). What can 6,000 electric vehicles tell us about EV battery health? Retrieved January 21, 2021, from <https://www.geotab.com/blog/ev-battery-health/>

⁷⁰ *Id.*

from low temperatures). Figure 4 above, from Delos Reyes et al., confirms this conclusion for the Nissan Leaf they studied.⁷¹

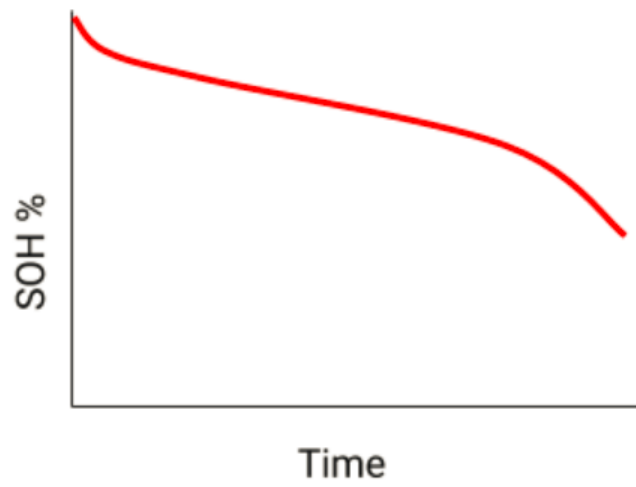


Figure 7. Theoretical normal degradation curve of a lithium ion battery. Figure from Geotab⁷²

⁷¹ Delos Reyes, *Supra* at note 60.

⁷² Argue, *Supra* at note 65.

Conclusions and Opportunities for Future Research

ACEP worked with the University of Washington DIRECT program to bring the above findings together into a set of metrics with a visualization. This resulted in the creation of an online EV Temperature Map (Figure 8) that shows three metrics related to temperature effects on performance.⁷³ One metric is a normalized EV score based on the average daily range loss for any location on land, calculated from a fit of driving range loss vs. temperature, using 10 years of NASA temperature data. The second metric is the Maximum Expected Range Loss based on the coldest temperature reached in the last 10 years. The third metric is “Must-Plug-in-Days” or MPID, which is the maximum number of consecutive days in the 10 year temperature record in which the average temperature does not exceed -20°C (-4°F), as this is the approximate temperature at which an unplugged EV may be permanently damaged.

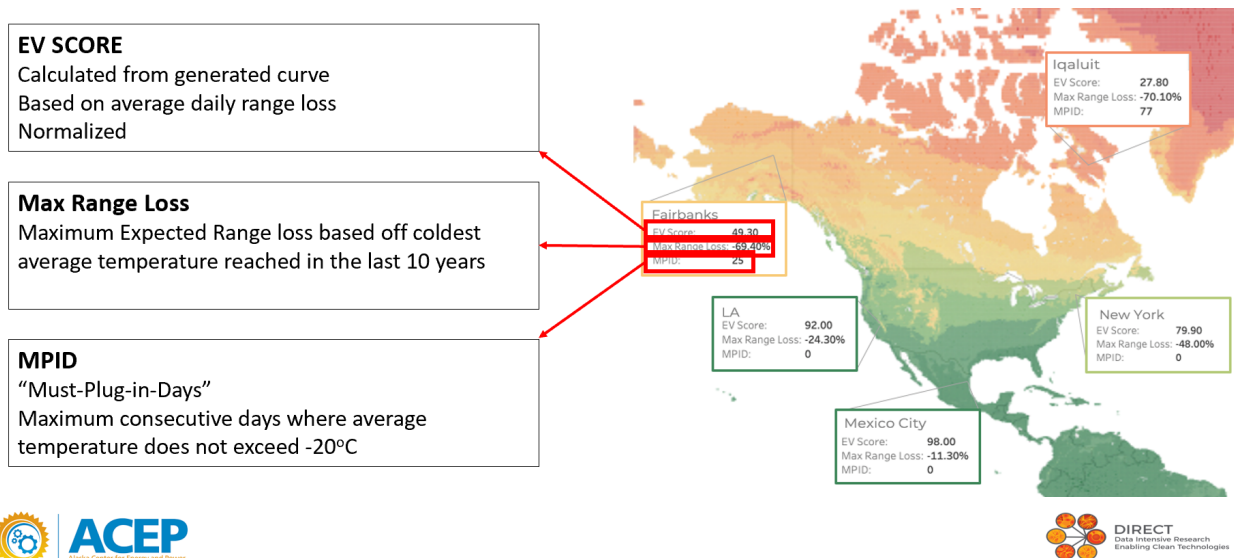


Figure 8. ACEP EV Map⁷⁴

These metrics may be used to predict performance and efficiency or inform EV strategies in regions of the world. Looking at the EV score, much of China, Russia, Europe, Iceland, Greenland, Canada, the northern US, and mountainous regions of the world have scores overlapping with those found in Alaska.

To put this into the context of battery considerations for EVs, most of the vehicles in these areas can be expected, at least occasionally, to get temperatures low enough in their home range to affect performance, fast charging, and battery longevity (below 10°C (50°F), and more severely below 0°C (32°F)). Many home ranges and destinations for longer trips in these regions will bring EVs into temperatures approaching the lower-end of the safe storage range for standard

⁷³ Kitt., M, Gu, D., Kau, Z. H., Suh, J., Wilber, M., Pike, C., Leach, T. (2020, June). ACEP EV Map. Retrieved January 8, 2021, from

https://public.tableau.com/profile/michelle1506#!/vizhome/ACEPEVMAP_16061795177860/Home

⁷⁴ *Id.*

Li-ion batteries (around -20°C (-4°F)), which could limit the time that unplugged EVs could be parked outside without affecting battery health. Although populations may be limited in extremely cold regions (lows of -30°C (-22°F) or below), these regions are widespread and demand for EVs exists.

It can be seen that little to no data exists in the literature below -30°C (-22°F). Also, given the number of communities in Alaska with very short driving distances (because of limited connecting roads), and extremely cold temperatures, Lithium titanate batteries may have a niche application in vehicles suited to rural Alaska. Given the performance noted above in extreme cold for today's commercially available EVs, we also see a need for better battery thermal management or cabin heating strategies for cold regions.

Opportunities for further research by ACEP, which would benefit from being conducted in a cold climate like Fairbanks, include the following.

- Test self-heating batteries.
- Collect and analyze data on power draw vs. temperature for different EV models while charging and while fully charged.
- Test Levels 1, 2, and 3 nominal charging speeds vs. temperature.
- Collect and analyze data on maximum range and energy use per mile vs. temperature for different EV models.
- Evaluate the change in maximum range over time (years) for several EV models parked outside in ambient air temperatures.
- Investigate effects of extreme cold on EVs parked in ambient air temperatures but not plugged in (e.g., minimum starting temperature, loss in battery state of charge with time, and battery recovery when brought back into a warm environment). Testing to the point of significant damage or failure (i.e., partial or total loss of battery capacity) would provide useful information, but would also incur substantial expenses.
- Develop a workable electric ATV and/or snow machine for rural Alaska using lithium titanate batteries for their superior cold performance.
- Investigate secondary/external/portable cabin heat sources that could alleviate the draw on the main battery for heating (e.g., heat packs).