

E-Truck Performance in Cold Weather

White Paper



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CALSTART is a non-profit organization that works with the public and private sectors to develop advanced transportation technologies and foster companies that will help clean the air, lessen our dependence on foreign oil, reduce global warming, and create jobs.



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1. INTRODUCTION

The Drive Clean Truck – Voucher Program (<http://www.drivecleanchicago.com/Default.aspx>) offers great incentives to help shift Chicago’s diesel fleet to zero-emission vehicles. Fleet owners that operate Class 3 to Class 8 trucks can apply for funding to purchase All-Electric trucks (E-Trucks) or an All-Electric Drivetrain Retrofit. Because E-Trucks are fuel and exhaust free, truck owners can benefit from the fuel savings, enhanced efficiencies and reduced maintenance. Advancing E-Trucks through Drive Clean Truck moves Chicago towards energy independence and a healthier environment.

After one of the coldest winters on record in the City of Chicago and reports of lower than expected performance in cold weather from early adopters of E-Trucks as well as passenger electric vehicle users, CALSTART set out to investigate the impact of cold weather on E-Truck performance. The purpose of this study is twofold: to better understand and quantify the impact of cold weather on E-Truck performance in order to manage fleet expectations, and to explore solutions to maintain E-Truck performance in cold weather.

We first reviewed weather data for the City of Chicago for the last 20 years. Next, we researched the impact of cold temperatures on the performance of two different battery chemistries used in commercial E-Trucks and looked at the impact of cabin heating on E-Truck driving range. This analysis allowed us to provide an estimate of E-Truck driving range expectations in the cold temperatures typical of Chicago. Lastly, we reviewed several solutions that would allow E-Trucks to maintain performance in cold weather.

We relied on CALSTART’s extensive internal knowledge, research of existing electric vehicle battery literature and interviews of several E-Truck stakeholders (E-Truck manufacturers and fleets). We received input from the following E-Truck manufacturers: AMP Electric Vehicles, Motiv Power Systems and Smith Electric Vehicles. We received input from the following E-Truck fleet users: FedEx Express, Testa Produce and UPS.

2. REVIEW OF CHICAGO CLIMATE

In order to better understand winter temperatures in Chicago, we reviewed hourly temperatures from 1994 up to April 2014 at the Chicago Midway International Airport. Data was retrieved from Weather Underground (www.wunderground.com), a commercial weather service that provides real-time weather information via the internet.

Figure 1 below shows the minimum temperatures (in Fahrenheit) recorded at the Chicago Midway International Airport in the “winter season” or “winter” that we defined as from October to March.

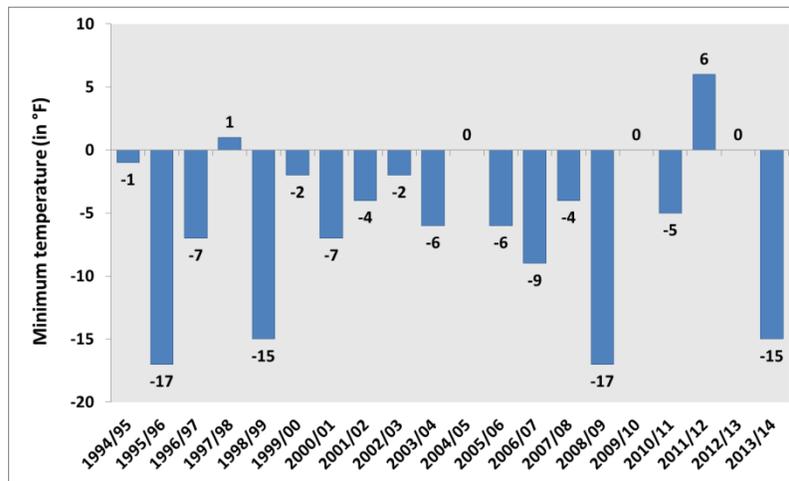


Figure 1: Minimum temperature (in °F) at the Chicago Midway International Airport

The minimum temperature ranges from -17°F (-27°C) on February 3rd, 1996 and January 16th, 2009 to 6°F (-14°C) on January 19th and 20th, 2012. The average minimum temperature is -6°F (-21°C).

One fleet reported using 9°F (-13°C) as a threshold that triggers changes to their operation. For simplicity and to analyze data faster, we then used 10°F (-12°C) as the threshold for further analysis. We calculated the number of days when the temperature went below 10°F and the number of days when the temperature went below 10°F for 12 hours or more in a day.

Figure 2 below shows the number of days per winter (from October to March) when the temperature went below 10°F at the Chicago Midway International Airport.

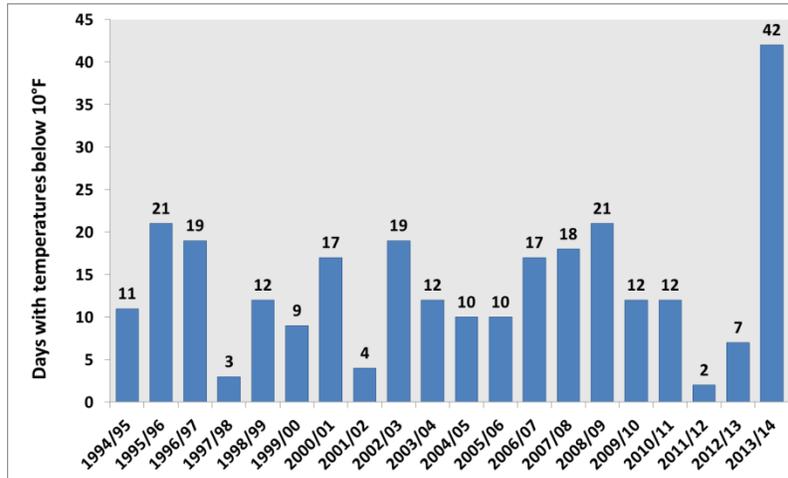


Figure 2: Number of days per winter with temperatures below 10°F at the Chicago Midway International Airport

The number of days per winter with temperatures below 10°F ranges from 42 days in the winter 2013/14 to two days in the winter 2011/12. The average number of days per winter with temperatures below 10°F is 14 days.

Figure 3 below shows the number of days per winter when the temperature went below 10°F for 12 hours or more in a day at the Chicago Midway International Airport. We chose 12 hours as a good estimate of the length of time E-Trucks would be parked overnight.

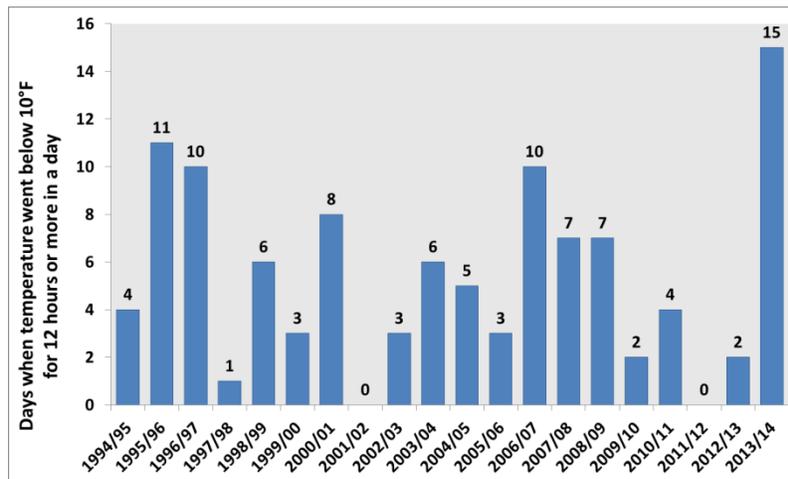


Figure 3: Number of days per winter when temperature went below 10°F for 12 hours or more in a day at the Chicago Midway International Airport

The number of days per winter when temperatures went below 10°F for 12 hours or more in a day ranges from 15 days in the winter 2013/14 to 0 days in the winters 2001/02 and 2011/12. The average number of days per winter when temperatures went below 10°F for 12 hours or more in a day is five days per winter.

3. IMPACT OF COLD TEMPERATURES ON BATTERY PERFORMANCE

Several different battery chemistries are used in transportation applications:

- Lead-Acid
- Nickel Metal Hydride
- Lithium-Ion
- Sodium Nickel

Because of their high power and high energy, Lithium-Ion batteries are currently the energy storage of choice for E-Trucks as shown in Table 1:

Table 1: Selected E-Truck models and their respective battery chemistries

Selected E-Truck Models	Manufacturers	Battery Chemistry
E-100	AMP Electric Vehicles	Lithium-Ion
DV-500	Boulder Electric Vehicles	Lithium-Ion (LiFePO ₄)
BYD Electric Bus	BYD Motors	Lithium-Ion (LiFePO ₄)
EVI-MD	Electric Vehicles International	Lithium-Ion (LiFeMgPO ₄)
Zero-Emission FE4 Shuttle Bus	Motiv Power Systems	Sodium Nickel Chloride
eStar	Navistar	Lithium-Ion (LiFePO ₄)
EcoRide BE35	Proterra	Lithium-Ion (Lithium-titanate)
Newton Step Van	Smith Electric Vehicles	Lithium-Ion (LiFePO ₄)

In the sample above, only Motiv Power Systems is using a different battery chemistry. We looked in more details at the impact of cold temperatures on the performance of Lithium-Ion and Sodium-Nickel batteries.

Lithium-Ion

Both high and low temperatures impact Lithium-Ion battery performance. At high temperatures, side reactions happen faster leading to faster battery degradation. At cold temperatures, battery performance (power and energy) is lower due to poor ion transport. This leads to poor vehicle acceleration, limited capability to recover braking energy and lower driving range than experienced in warmer temperatures.

Each battery chemistry has its own unique performance degradation curve. Lithium-Ion batteries generally see their performance decrease gradually when ambient temperature drops from 80°F (27°C) to 32°F (0°C). However, performance falls off sharply when ambient temperature drops below 32°F (0°C). For instance Figure 4 below shows how the capacity of a particular lithium iron phosphate battery is affected by temperature:

- At 32°F (0°C), relative capacity is about 90% of the capacity at the testing temperature of 77°F (25°C).
- At 14°F (-10°C), relative capacity is about 80% of the capacity at the testing temperature of 77°F (25°C).
- At -4°F (-20°C), relative capacity is about 60% of the capacity at the testing temperature of 77°F (25°C).

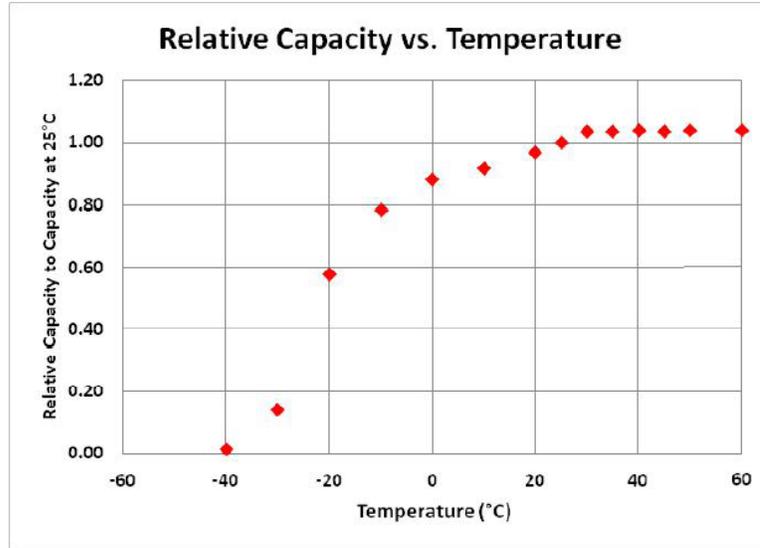


Figure 4: Relative Capacity to Capacity at 25°C for a lithium iron phosphate battery¹

In addition, Lithium-Ion battery charging is much more challenging at cold temperatures as battery degradation is accelerated and the probability of a catastrophic failure is increased. As a result, Lithium-Ion batteries are generally inhibited from charging below 32°F (0°C).

The example in Figure 5 shows the impact of cold temperature on an E-Truck equipped with Lithium-Ion batteries with an advertised maximum range of 100 miles. We assumed there is no cabin heating usage.

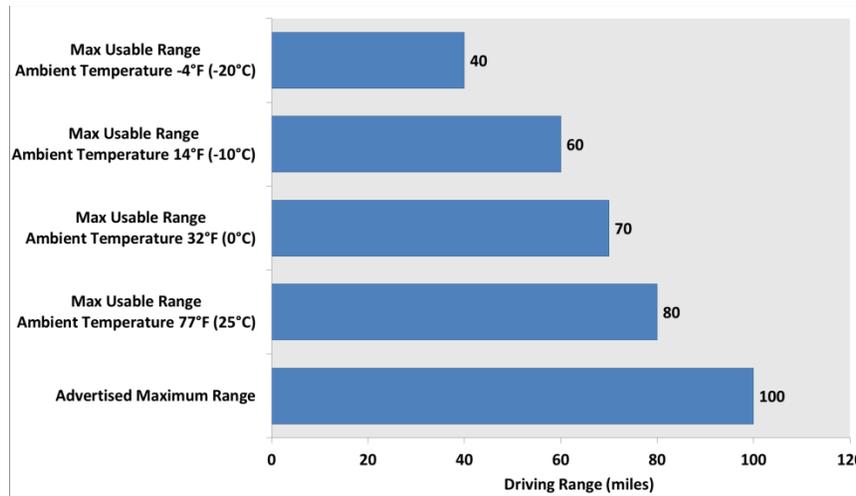


Figure 5: Impact of Lithium-Ion battery operating temperature on the driving range of an E-Truck

When fleets deploy E-Trucks, they generally include a “buffer” to the advertised maximum range to limit “range anxiety”. This buffer is in addition to the OEM programmed battery buffer needed to preserve battery life. While every fleet may chose a different buffer, we chose a reasonable 20% that decreases

¹ Pesaran A., Ph. D, S. Santhanagopalan, G. H. Kim, *Addressing the Impact of Temperature Extremes on Large Format Li-Ion Batteries for Vehicle Applications*. National Renewable Energy Laboratory, NREL/PR-5400-58145. 30th International Battery Seminar, Fort Lauderdale, FL, March 11-14, 2013

the 100-mile advertised maximum range to an 80-mile maximum usable range with ambient temperature at 77°F (25°C).

From this 80-mile maximum usable range, we can then see the impact of cold temperatures on driving range:

- With ambient temperature throughout the day at 32°F (0°C), the E-Truck maximum usable range would decrease to 70 miles.
- With ambient temperature throughout the day at 14°F (-10°C), the E-Truck maximum usable range would decrease to 60 miles.
- With ambient temperature throughout the day at -4°F (-20°C), the E-Truck maximum usable range would decrease to 40 miles.

Lithium-Ion battery performance is affected by cold temperatures. The extent of the performance degradation will depend on various factors:

- Starting temperature (at which temperature are the batteries when the E-Truck starts its day?),
- Drive cycle (do the batteries have time to cool down when the vehicle is stopped on a delivery?),
- Outside temperature (what is the ambient temperature the batteries are exposed to?).

We estimate that Lithium-Ion batteries used in current E-Trucks could lose 10 to 20% state of charge in typical Chicago winter weather (from 14°F to 32°F) and up to 40% in extreme cold weather (-4°F). For a 100-mile truck, this would represent a 10 to 20-mile reduction in driving range and up to a 40-mile reduction in extreme cold weather.

Sodium-Nickel

Sodium-Nickel batteries present the advantage of being able to operate at extreme temperatures from -40 to 149°F (-40 to +65°C) with no performance degradation. Since the electrolyte used in Sodium-Nickel batteries is solid and inactive at normal ambient temperatures, batteries are continuously kept at their internal working temperature of 518°F (270°C) in order to keep the electrolyte molten and the battery ready to use. Thus, Sodium-Nickel batteries provide consistent performance regardless of the outside temperature and charge normally at cold temperatures.

In 2012, Motiv Power Systems was awarded a contract with a total value of \$13.4 million from the City of Chicago to electrify up to 20 garbage trucks. In order to meet the range requirements provided by the City of Chicago (drive 60 miles all year-round), Motiv Power Systems uses Sodium-Nickel Chloride batteries. Figure 6 below shows the first US all-electric Class 8 refuse truck from Motiv Power Systems.



Figure 6: The first US all-electric Class 8 refuse truck from Motiv Power Systems.

During initial testing in December 2013, no degradation of performance was observed. Between 50% and 60% of total battery capacity is used for driving regardless of the outside temperature, leaving enough battery capacity to run trash compaction and vehicle accessories.

Sodium-Nickel batteries present several drawbacks compared to Lithium-Ion batteries:

- Sodium-Nickel batteries have lower power density than Lithium-Ion batteries. Thus, they are not suited for every truck application.
- Sodium-Nickel batteries are not shipped at their operating temperature and thus need 24 hours to heat up to 280°C prior to being used.
- Sodium-Nickel batteries are better for high usage applications (such as refuse), as the batteries will cool down if not in use or not connected to a power source. While this would not damage the batteries, a 24-hour period would be needed to reheat them to their 280°C operating temperature.
- While connected to a power source, Sodium-Nickel batteries will draw power to keep batteries warm (less than 100 W).
- There is currently only one commercial-stage supplier of Sodium-Nickel batteries for E-Truck applications (FIAMM), which is a limiting factor for the further adoption of Sodium-Nickel batteries.

4. IMPACT OF CABIN HEATING ON DRIVING RANGE

We reviewed the different cabin heating options currently in use on commercial E-Trucks. All of them currently draw energy from the same batteries used to drive the E-Truck. Our review indicates that current cabin heaters used on commercial E-Trucks have a power draw between 4 and 6 kW. Table 2 below shows the energy draw of three different cabin heater options at different usage patterns.

Table 2: Energy draw of different cabin heater option at different usage rates

Cabin Heater Options	4-hr. Energy Draw	6-hr. Energy Draw	8-hr. Energy Draw
Option A / 6 kW	24 kWh	36 kWh	48 kWh
Option B / 5 kW	20 kWh	30 kWh	40 kWh
Option C / 4 kW	16 kWh	24 kWh	32 kWh

We can see that cabin heating represents a significant energy draw on E-Truck batteries: from 16 kWh for a 4 kW cabin heater operated for four hours in a day, to 48 kWh for a 6 kW cabin heater operated for eight hours in a day. Chassis dynamometer testing of a Smith Electric Newton Step Van at the Argonne National Laboratory (see Chapter 7 for reference) showed a 40% increase in energy consumption (and thus a 40% decrease in driving range) at cold temperatures of 20°F (-7°C) compared to ambient temperatures of 70°F (-21°C).

The example in Figure 7 shows the impact of cabin heating on an E-Truck equipped with a cabin heater with a power draw of 5 kW and an advertised range of 100 miles.² Although outdoor temperatures would be low enough to require cabin heating, in order to quantify the impact of cabin heating on driving range, we assumed in that case cold temperatures would not affect battery performance.

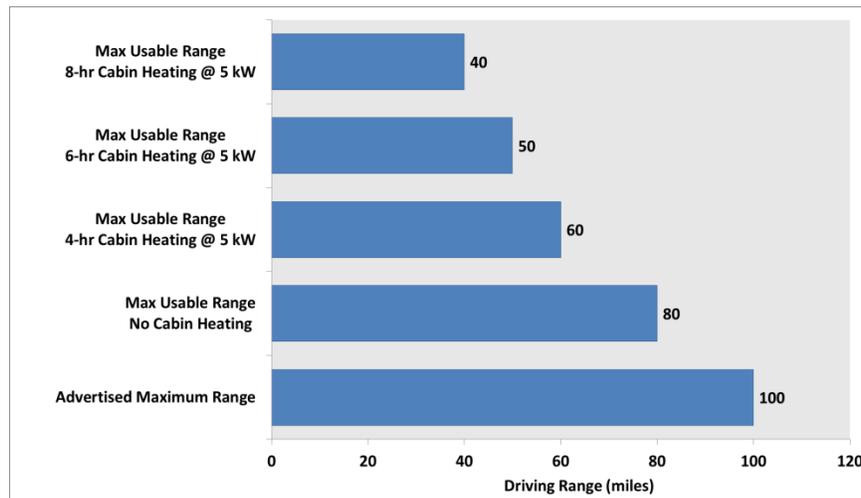


Figure 7: Impact of cabin heating on the driving range of an E-Truck

² Assumes a 100 kWh battery and efficiency of 1 kWh / mile.

From the 80-mile maximum usable range, we can then see the impact of cabin heating on driving range:

- With 4 hours of cabin heating at 5 kW power draw, the E-Truck maximum usable range would decrease to 60 miles.
- With 6 hours of cabin heating at 5 kW power draw, the E-Truck maximum usable range would decrease to 50 miles.
- With 8 hours of cabin heating at 5 kW power draw, the E-Truck maximum usable range would decrease to 40 miles.

E-Truck driving range is affected by cabin heating. The extent of the performance degradation will depend on various parameters:

- Power draw of the cabin heater (how much energy will the cabin heater use?)
- Drive cycle (how many hours will the operator need cabin heating?)
- Outside temperature (what is the ambient temperature the cabin is exposed to?).

We estimate that cabin heating use could decrease state of charge (SOC) by 20% in typical delivery operation and up to 40% in operation where the driver requires longer periods of cabin heating.

5. DRIVING RANGE EXPECTATIONS

The findings presented in the Sections 4 and 5 help us better understand how cold temperatures affect E-Truck driving range. The example in Figure 8 shows the combined impact of cold temperatures and cabin heating on an E-Truck equipped with a cabin heater with a power draw of 5 kW and an advertised range of 100 miles.³

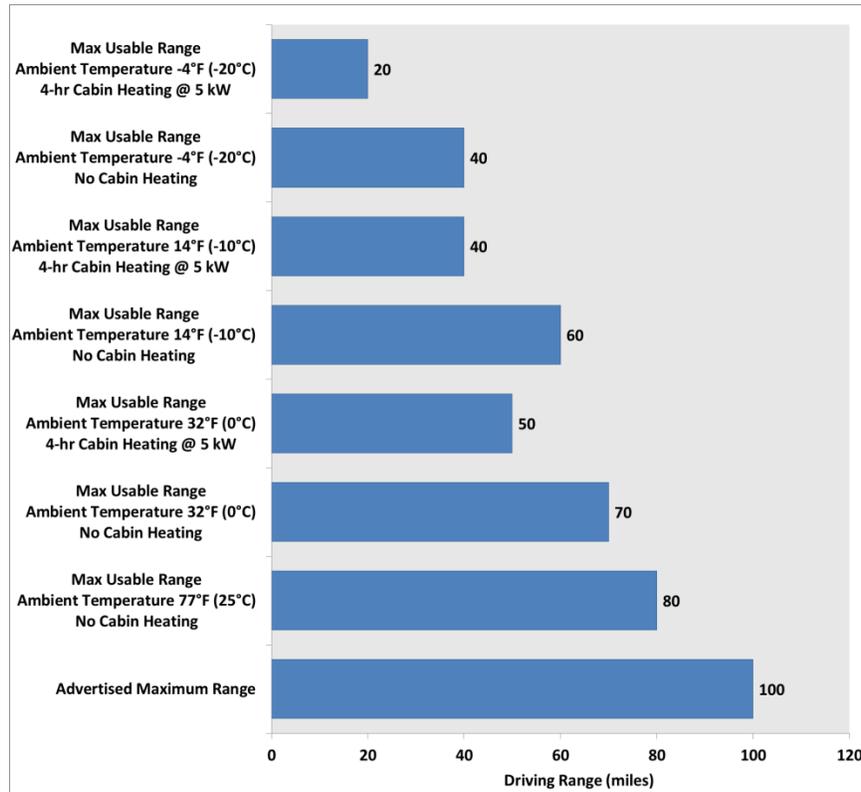


Figure 8: Impact of cold temperatures and cabin heating on the driving range of an E-Truck

From the 80-mile maximum usable range, we can then see the impact of cold temperatures and cabin heating on driving range:

- With ambient temperature throughout the day at 32°F (0°C), the E-Truck maximum usable range would decrease to 70 miles with no cabin heating and 50 miles with four hours of cabin heating at 5 kW power draw.
- With ambient temperature throughout the day at 14°F (-10°C), the E-Truck maximum usable range would decrease to 60 miles with no cabin heating and 40 miles with four hours of cabin heating at 5 kW power draw.
- With ambient temperature throughout the day at -4°F (-20°C), the E-Truck maximum usable range would decrease to 40 miles with no cabin heating and 20 miles with four hours of cabin heating at 5 kW power draw.

³ Assumes a 100 kWh battery and efficiency of 1 kWh / mile.

6. SOLUTIONS

Lastly, we researched potential solutions that would help maintain E-Truck driving range in cold climate. Table 3 lists all the solutions that we considered, their functions, as well as their benefits and drawbacks.

Table 3: List of potential solutions to help maintain E-Truck driving range in cold climate

Solution	Function	Benefits	Drawback	Cost Estimate	Commercialization Status
Driver Education	Educate drivers to use their E-Trucks to preserve range	Low cost Simple to implement	Benefits are uncertain and may differ widely from driver to driver	Low cost	N / A
Park E-Truck Indoors	Prevent batteries from reaching extreme temperatures	Thermal inertia could keep batteries warm all day Low cost	Not feasible for every fleet Benefits uncertain	Low cost	N / A
Programmed Charging	Use heat generated during charging to keep batteries warm before E-Truck usage	Thermal inertia could keep batteries warm all day Low cost Some vehicles have charge programmers Can be done manually	Complexity for fleets Not all vehicles have charge programmers Benefits uncertain Better solution would require “smart” charging	\$0 - 1,000	Commercial
Fuel-Fired Heater	Heat the cabin without using energy from traction batteries	Low energy consumption Low emissions Allowed by voucher program	Added costs & complexity Not a “zero-emission” truck	\$2,000 - 5,000 + fuel	Commercial
Heat Pump Heater	Heat the cabin using less energy from traction batteries	Lower energy draw on batteries No emissions	Added costs & complexity New technology for transportation	N / A	Concept
Waste Heat	Use waste heat from electrical components to heat the cabin	Lower energy draw on batteries No emissions	Added costs & complexity Currently not available	N / A	Concept
Efficient Driver Comfort	Provide heat to the driver (radiant heat, heated seats and steering wheel) instead of keeping the whole cabin warm	Low cost Lower energy draw on batteries No emissions	-	\$500 – 1,000	Commercial
Reduce Cabin Heat Loss	Minimize heat loss in cabin with door location change and/or insulation	Reduces demand on cabin heater	Added costs Complex design change	Engineering design cost	Commercial
Pre-Heat Cabin & Batteries	Use AC power when plugged in to pre-heat cabin and batteries	Thermal inertia could keep batteries warm all day	Added costs & complexity Consume energy Benefits uncertain	N / A	Prototype

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Larger Battery Packs	Increase battery capacity	More energy available	Added costs	\$500 - 1,000 per extra kWh	Commercial
Sodium-Nickel Batteries	Use batteries with constant performance	No battery degradation at cold temperatures	See page 8	10-30% more than Li-Ion	Commercial
Sodium-Sulfur Batteries	Use batteries with constant performance	No battery degradation at cold temperatures	Currently not commercially available	N / A	Prototype
Thermal Insulation	Insulate battery packs	Low cost	Added complexity Consume energy if heated Uneven cell temperatures	\$500 – 1,000	Commercial
Battery Air Heating with Forced-Heat	Heat the batteries to their optimum operating temperature	Batteries are kept at their optimum temperature all day	Added costs & complexity Needs energy to heat air (fuel fired heater or electrically powered)	\$2,000 - 10,000	Commercial
Battery Liquid Heating	Heat the batteries to their optimum operating temperature	Batteries are kept at their optimum temperature all day	Added costs & complexity Needs energy to heat liquid (fuel fired heater or electrically powered) Risk of water damage	\$2,000 - 10,000	Commercial

7. REFERENCES & HELPFUL LINKS

For more information about electric vehicles performance in cold weather, see:

- FleetCarma. The Truth About Electric Vehicles (EVs) in Cold Weather. On-Demand Webinar. <https://www.fleetcarma.com/Resources/the-truth-about-electric-vehicles-in-cold-weather-webinar> (last accessed on April 3rd, 2014).
- American Automobile Association (2014). *Extreme Temperatures Affect Electric Vehicle Driving Range, AAA Says*. <http://newsroom.aaa.com/2014/03/extreme-temperatures-affect-electric-vehicle-driving-range-aaa-says/> (last accessed on April 3rd, 2014).
- Duoba, M., E. Rask, M. Meyer, APRF & Co (2012). *Advanced Powertrain Research Facility AVTA Nissan Leaf testing and analysis*. Argonne National Laboratory, October 12th, 2012. http://www.transportation.anl.gov/D3/data/2012_nissan_leaf/AVTALeafTestingAnalysis_Major%20summary101212.pdf (last accessed on April 3rd, 2014).
- Pesaran A., Ph. D, S. Santhanagopalan, G. H. Kim, *Addressing the Impact of Temperature Extremes on Large Format Li-Ion Batteries for Vehicle Applications*. National Renewable Energy Laboratory, NREL/PR-5400-58145. 30th International Battery Seminar, Fort Lauderdale, FL, March 11-14, 2013. <http://www.nrel.gov/docs/fy13osti/58145.pdf> (last accessed on April 3rd, 2014).
- Jehlik F., G. Keller, C. Pavlich, E. Rask, K. Stutenberg & D. Santini, *Electric Heater Effects on two Medium Duty Electric Trucks, from Argonne & FedEx EV Evaluations*. Handout for the National Governor's Association Workshop on Advanced Vehicle Technologies and Infrastructure. Indianapolis, IN. May 19th, 2014.

For more information about California Air Resources Board approved and verified fuel-fired heaters, see

- California Air Resources Board (2014). Idle Reduction Technologies for Sleeper Berth Trucks. <http://www.arb.ca.gov/msprog/cabcomfort/cabcomfort.htm> (last accessed on April 3rd, 2014).

About CALSTART

CALSTART is a non-profit organization focused on the growth of the clean transportation technology industry. CALSTART has 150 member companies representing a broad array of clean vehicles, fuels, and technologies. CALSTART provides services and consulting help to spur advanced transportation technologies, fuels, systems and the companies that make them. CALSTART's main activities include:

- Providing value-added services for member companies
- Working with teams to commercialize new technologies
- Helping fleets and ports cost-effectively "green" their operations
- Supporting positive pro-environment and business public policy

One of CALSTART's main strengths is its access to an unparalleled array of information sources through its diverse activities and extensive network. The clean transportation technology industry is rapidly changing and CALSTART's close contact with fleet managers, policymakers, researchers, scientists, technology developers and manufacturers puts the organization in a unique and valuable position.

