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September 2014

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Prepared under Task No. ID14.1002

* Raytheon Polar Services, as contractor for the National Science Foundation, was the on-site logistics coordinator for the vehicles during the majority of the data-gathering component of this project.

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Table of Contents

Executive Summary ..... **iv**
Key Points from McMurdo EV Evaluation v
Key Points from McMurdo Conventional Vehicle Fleet Evaluation vii
Recommendations vii
1 Introduction **1**
2 McMurdo EV Evaluation **2**
2.1 Vehicle Description 2
2.2 Data Acquisition Equipment 2
2.3 Battery Description 4
2.4 EV Operation 9
2.5 EV Data 11
2.6 EV Maintenance 11
3 EV Energy Efficiency Analysis **13**
3.1 AC Charger Efficiency 14
3.2 AC Charger Efficiency vs. Temperature and Heater Effect 14
3.3 Battery Efficiency 15
3.4 Driveline Efficiency 15
3.5 Overall Vehicle Efficiency (Percent) 15
3.6 Overall Vehicle Efficiency (Watt-Hours Per Mile) 16
3.7 Parasitic Losses 16
3.8 Costs to Operate 16
4 McMurdo Conventional Vehicle Fleet Evaluation **18**
4.2 Vehicle Type Images 22
4.3 Data Review 23
4.4 Costs to Operate 35
4.5 EVs in Context of McMurdo Conventional Fleet Analysis 35
5 Conclusion **37**
6 Next Steps **38**
Appendix A: EV Operator Feedback Form **39**
Appendix B: EV Maintenance Logs **40**
Appendix C: Web Dashboard Plots **42**
Appendix D: Wiring Diagram of Sensors Inputs to Loggers Used in EVs **54**
Appendix E: AC and DC Voltage and Current Sensors Used in EVs **55**
Appendix F: Sample Data Files from EV Evaluation **57**
Battery Capacity 57
Discharge Cycle / Regen 57
Remaining Parameters 57

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Executive Summary

This is the third report on a collaborative effort of the U.S. Department of Energy (DOE) and the National Science Foundation (NSF) undertaken to examine the performance of two electric vehicles (EVs) at McMurdo, Antarctica (McMurdo). The study examined the performance of two e-ride Industries EVs initially delivered to McMurdo Feb. 16, 2011, and compared their performance and fuel use with that of conventional vehicles that have a duty cycle similar to that of the EVs as used at McMurdo. The period for this report is Feb. 16, 2011, through April 2013. This study addresses the operational capabilities of EVs at McMurdo and the business case for replacing the existing light-duty conventional fleet at McMurdo with EVs. It does not address the replacement of conventional fleet vehicles from social or environmental perspectives.

Using the customized data loggers, EV use data was collected over the course of 3 calendar years regarding usability, versatility, convenience, and functionality. The two EVs showed good performance and energy efficiency. In addition, drive-cycle data from a comparable component of the McMurdo conventional fleet vehicles (gasoline-powered vehicles) was collected.

The EVs were well accepted by McMurdo staff, who consistently and overwhelmingly took advantage of their availability. The only critical feedback offered was related to the location of the heater switch and seating space constraints for larger-sized vehicle operators. Requests to use the vehicles exceeded the availability of the EVs.

From the perspective of operating-cost efficacy, it is estimated that the cost per mile at McMurdo for EVs is approximately one-tenth of that of conventional vehicles. This includes the cost of transporting petroleum fuels to McMurdo. Specifically, the prices per mile are:

- $0.11/mile for the EVs
- $1.00/mile for conventional vehicles.

The yearly cost of electricity per EV is <$100 per year.

The result is that energy consumption per vehicle, just to keep the engines warm, for the comparable vehicles in the conventional vehicle fleet exceeds the electrical consumption of the EVs.

The sets of data collected and set forth in this report support the conclusion that there are clear opportunities in the form of improved cost and performance advantages to replace existing conventional vehicles at McMurdo with small EVs.

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Figure ES-1. Two EVs tested at McMurdo Station.

Key Points from McMurdo EV Evaluation

Two EVs employing lead-acid batteries were instrumented with two data loggers each, and data were recorded on numerous parameters in various use and charging scenarios over the course of 3 calendar years.

- Many driving trips at McMurdo are short and for in-town use, on the order of around 3 minutes. This duty cycle of short trips lends itself well to EVs, because the need for idling to keep conventional vehicle engines warm is eliminated. Other trips such vehicles might make include trips to the airfield, which are much longer trips/duty cycles. A reasonable use for the EVs could be as dedicated airfield vehicles.

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- For the EVs, in the warmer summer months, the average number of daily trips was nine, and the average number of times charged was almost three, for a 3:1 ratio. For the colder months the average daily trips dropped to five and the charges to two, or 2.5:1 ratio.
- In the warmer months, DC energy out per mile in the EVs is approximately 390 watt-hours (Wh). For reference, the battery manufacturer's estimate of DC energy out per mile is 250 Wh, not including the drive efficiency or DC cabin heater, so this value appears reasonable, given the hilly terrain at McMurdo and the need to use auxiliary equipment like heaters more regularly, even in the warmer months.
- For the colder months, the DC energy out per mile in the EVs increases to almost 465 Wh (a 19% increase from 390 Wh for warmer months). The colder temperatures could cause the EV driveline to be less efficient due to increased friction of moving parts. More importantly, the lights and DC cabin heater in the EVs are used more often, as is the case for the conventional vehicles as well, though with a significantly greater drain on the fuel supply for the EVs.
- For the EVs, the AC energy consumption per mile is 608 Wh for the warmer months, then jumps to 782 Wh for the colder months.
- Average efficiencies of key parameters on the EVs are:
    - Charger = 83%
    - Battery (DC out / DC in) = 71%
    - Overall efficiency based on the above two efficiencies is (DC out / AC in) = 59%
        - Regenerative braking (regen) as a source of energy for the EVs is of insignificant value for the purpose of being incorporated into the calculations.
- AC kWh used to drive an EV at McMurdo over a year is estimated between 400 kWh and 600 kWh.
- The EVs with new lead-acid batteries could be driven for 30–60 minutes before a recharge was necessary. This drive time, after nearly 3 calendar years of use, was reduced to 15 minutes. Anecdotal reporting also indicated that the dash display regarding battery life did not appear to provide a true indication of a complete cycle or remaining battery life. The apparent decline in battery capacity was steeper than expected after three summer and two winter seasons. The capacity of the batteries is expected to decrease over time, but the capacity loss may have been hastened by the way the vehicles were used and managed. There were reports that batteries were not charged or maintained properly (e.g., vehicles may have been left outside for 24–48 hours (-20°F to -40°F conditions) with the batteries discharged). This is important because if the vehicle batteries are allowed to freeze, capacity is lost rapidly. The number of charges a battery undergoes also can deplete the life of the battery. Optimizing when to charge and possibly adding more battery insulation to maintain battery temperature and prevent freezing may be helpful, as long as the vehicles are not left outside unplugged and with the batteries discharged.

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- A major concern of using EVs in a cold environment like McMurdo is the need to heat the batteries. This disadvantage from an energy perspective diminishes, however, if one considers that diesel and gasoline engines at McMurdo also need to stay warm, with engine and battery heaters or through engine idling. It is noteworthy that heating the batteries also heats the cabin and vice versa, which has a double benefit, while the engine heater only heats the engine compartment.
- The annual cost to fuel an EV at McMurdo is low. One EV would use in a typical summer month 80 kWh, and in a winter month 48 kWh (fewer personnel in winter), for a total of 375–600 kWh/year. Using an energy cost of $0.16/kWh, the annual cost to fuel an EV at McMurdo is $60 to $96. This cost, roughly $0.11/mile, is contrasted with an estimated cost of $1/mile to fuel a conventional pickup truck operating on the same duty cycle at McMurdo.

Key Points from McMurdo Conventional Vehicle Fleet Evaluation

Thirty conventional vehicles and the two EVs were instrumented with GPS and engine-recording loggers for duty cycle analysis. This instrumentation provided 232 days of stock vehicle use, 157 days of lifted (raised suspension) vehicle use, and 55 days of EV use.

- Vehicles restricted to in-town use were used similarly to the EVs in town, making replacement by EVs in the future a realistic possibility.
- EVs matched the stock conventional trucks in town on average driven speed, average maximum speed, average stops per mile, and average and maximum kinetic intensity. The conventional trucks averaged more daily miles, but the EVs demonstrated the ability to drive the miles recorded on 75% of the days that conventional vehicles typically logged as part of their duty cycle.
- Engine communications data show that the in-town use of the conventional trucks was dominated by low engine speeds and loads, indicating they were not heavily laden with equipment but rather being used primarily to transport people and hand-carried equipment.
- Data from one gasoline-powered light-duty truck and one light-duty van indicate that it costs at a minimum approximately $43/month and $103/month for a truck and van, respectively, to use electricity to keep the engine and battery warm. By comparison, the monthly cost to heat an EV's batteries and passenger compartment prior to use is approximately $27.
- The cost to fuel a conventional pickup truck at McMurdo is approximately $1.00/mile. This is in contrast to the EVs' calculated rating of $0.11/mile, which is almost a factor of 10 less.

Recommendations

There are real opportunities to advance the transition of the McMurdo light-duty conventional vehicle fleet to a more efficient future with a smaller greenhouse gas footprint in terms of both

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reduced vehicle emissions and need to import fuel for the vehicle fleet. Because EVs deployed at McMurdo hold great promise, the following are recommendations for the development of data that will provide greater insight into the deployment and application of EVs at McMurdo and other cold-climate locations and the future replacement of conventional vehicles with EVs in these locations:

- Collect additional and more refined data on both the electricity used to heat the light-duty conventional fleet's engines and batteries and the fuel used to idle these vehicles for the purpose of keeping the engines and batteries warm and operational.
- Examine the broader overall costs associated with transporting fuel for the light-duty conventional fleet to McMurdo and the emissions associated with both the transport of the fuel and the use of the fuel in Antarctica, and compare with costs to produce electricity in Antarctica for EVs.
- Additional efforts and examinations of other battery chemistries are needed to identify the most suitable EV models and types. Testing other vehicle designs and/or battery chemistries would improve the capability to determine the best replacement vehicles options. For example, new lithium batteries are estimated to double the miles/time between charges.
- Deploy an EV design that includes a controller area network (CAN), which would significantly reduce the complexity of the data logger needed and resources needed to undertake data collection. This also would reduce issues related to installing a variety of different sensors to acquire data, which at times made integration of the loggers into the vehicle difficult.
- Acquire data that would allow determination of how much energy is being used to heat the EV cabin, which would provide an even better sense of the efficiency improvements that the EVs offer and, by comparing with energy consumed to heat the cabin and engine in specific conventional vehicles that might be replaced, return on investment.
- Because of improvements in battery technology and the availability of new battery chemistries with e-ride Industries EVs, next steps might include:
    - Shipping the two EVs at McMurdo in 2014 to e-ride Industries to replace the existing battery packs with upgraded lithium battery packs, which would allow for direct comparison with the lead acid battery packs used in this study (or simply replace with the same lead acid battery pack products)
    - Purchasing two new-generation e-ride Industries EVs
    - Installing new and simpler data collection/monitoring systems package
    - Shipping all four vehicles to Port Hueneme by August 2014 and then all four vehicles to McMurdo either by special shipment for Winfly or Mainbody (two annual shipment periods) or on the 2014–2015 vessel to be added to the vehicle fleet the following season.
- Mandate LED lights for the next generation of EVs, as they draw far less energy from batteries and in turn would be expected to improve battery life.

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- Make improvements to the dashboard display battery life indicator to help avoid deep-cycle battery discharges. A meter on the EV dashboard can provide real-time feedback to the drivers to help them drive more efficiently. With greater confidence as to how far they could drive before charging, the drivers themselves could help extend battery life. The display should at a minimum include:
    - Percent battery capacity
    - Expected time or distance before charging.
- Provide operator training to improve the drivability and management of the vehicles, including battery-life management. This can help ensure the EVs are driven properly, charged when appropriate, and not left not charging or charged in the always-cold conditions at McMurdo. In turn, operator training on proper use of the EVs could increase the life of the batteries and thereby reduce the battery cost as a component of the operational cost of the EVs.
- Factor the cost of battery replacement every 2–3 years into the operational cost of the EVs. Replacement cost with the same AGM batteries is $1,890/vehicle (nine batteries/vehicle). The replacement cost to upgrade to smarter, new technology batteries (lithium-ion batteries) is $16,995/vehicle, which includes upgrades to the EV electrical system.
- Consider using renewable energy to power the EVs, which would increase the economic and environmental benefits respectively. Certainly the use of renewable energy would offer benefits across the entire McMurdo fleet because even the gasoline-powered vehicles connect to the electric grid at McMurdo roughly 75% of the non-operated time during the year, in order to keep the engine warm.[1] This suggests that dedicated renewable energy charging stations may be appropriate for the EVs.
- Improve communication between the users at McMurdo and technical resources supporting such a study as this.

[1] The current draw for keeping engines warm is up to ~1,000 W for a light-duty truck vehicle and ~1,750 W for the larger van vehicles.

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1 Introduction

There is keen interest in deploying EVs more broadly in the United States and in the U.S. federal fleet more specifically, including in extreme climate applications where moving fuel to the users can be both logistically difficult and expensive. Through a 2009 Memorandum of Understanding signed by Dr. Bement, Director of the National Science Foundation (NSF), and Dr. Chu, then-Secretary of the U.S. Department of Energy (DOE), DOE agreed to support the development and implementation of new energy technologies that enhance scientific productivity while reducing human impact on the environment and the long-term logistical requirements and costs of providing energy to cold-weather research stations operated by NSF. In support of this collaboration, the National Renewable Energy Laboratory (NREL) is tasked to assess and implement renewable energy and energy efficiency projects in existing or new NSF facilities and/or research stations.

NREL's tasks are specifically associated with the development of new projects that reduce dependence on imported fuels and support improved environmental conditions associated with remote NSF facilities. Through this effort, NREL is helping NSF advance its efforts to reduce fuel imports and less efficient energy systems, and to facilitate the deployment of alternative fuel vehicles (AFVs) and alternative fuel.

Two EVs were procured, one by DOE and one by NSF, and each is being used for operational testing at McMurdo Station, Antarctica (McMurdo). NREL is working with NSF and Polar Services staff, and HEM Data—a data-acquisition equipment supplier— has been supporting both entities, providing data acquisition equipment (data loggers), support for the transmission of data to the Polar Services (PS) server using WiFi, monitoring of the incoming data transmitted from the PS server located at McMurdo, assessing the validity of the data collected, and supporting periodic reports on the performance of EVs.

This research is examining the practicality of EVs in Antarctica and similar climates. This requires testing and documentation of their performance. It is well documented that EVs may be less efficient at low temperatures, but so too are standard diesel and gasoline vehicles. Because renewable energy from wind energy is available, and solar charge stations could be created for summer use at McMurdo, EVs may be both practical and suitable.

In addition, by documenting and categorizing the duty cycle of light-duty vehicles from a variety of departments and vehicle pools at McMurdo, the research anticipates being able to assess the capacity of the EVs to replace some of the existing conventional vehicles in the McMurdo fleet. The duty-cycle information can be used to identify which vehicles, if any, have duty cycles that can be fulfilled by the EVs, allowing NSF to pinpoint opportunities to reduce the amount of petroleum used to fulfill McMurdo fleet activities, as well as reduce the quantity of greenhouse gas (GHG) emissions associated with such activities, as undertaken by the current light-duty vehicle fleet at McMurdo.

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2 McMurdo EV Evaluation

2.1 Vehicle Description

Two e-ride Industries EVs were delivered to McMurdo. The vehicles arrived from e-ride in Princeton, Minnesota, via Golden and Centennial, Colorado; Port Hueneme, California; and Christchurch, New Zealand. Operationally, the vehicles are the same. They differ in that one vehicle has an enclosed rear bed (ET001) and the other has an open flatbed (ET002). Both trucks are outfitted with data acquisition wiring and sensors. The vehicles are pre-wired and ready for data acquisition loggers, with each vehicle capable of carrying and operating two separate loggers. Initially, one logger accompanied the two vehicles to Antarctica. During almost all of the testing, there was only one logger per vehicle due to some logger failures. The primary logger (B) was essential; the second logger (A) is valuable, but not essential. The history of which loggers were in each vehicle is shown below.

Table 1. Installed Logger History

Vehicle ID	Logger	Logger S/N	Date Installed	Date Removed
ET002	B	23114	2/16/11	Approx. 8/1/11
ET002	A	23113	12/14/11	
ET002	B	23115	12/14/11	
ET001	A	23117	12/17/11	
ET001	B	23118	12/17/11	

2.2 Data Acquisition Equipment

2.2.1 Data Loggers

Table 2 shows the parameters that have been and continue to be acquired. The data parameters from the second logger, which were not collected, are shown in Table 2. The wiring diagram is included in Appendix D. Appendix E provides datasheets for the sensors used on the loggers to acquire DC and AC voltage and current. Sensors adequate for operating in a harsh, cold climate like Antarctica were identified and procured to ensure the demanding climatic requirements could be met.

Figure 1. Photograph of data logger.[2]

[2] The data loggers used in this study were of prototype design and proprietary with selective single-source support, from HEM Data. The source code was also proprietary.

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As of contractor Kent Colby's Feb. 15, 2013, departure from McMurdo, vehicle/logger status was:[3]

- Vehicle 001: Logger #23124 is programmed as a "B" logger. The unit was successfully collecting and transferring data when in close proximity to Building 175 (the location of the WiFi transmission equipment). GPS unit was not connected.
- Vehicle 002: Logger #23122 is programmed as a "B" logger. The unit was successfully collecting and transferring data when in close proximity to Building 175. GPS unit was not connected. Logger #23125 is programmed as an "A" logger. The unit was successfully collecting and transferring data when in close proximity to Building 175.

2.2.2 Wiring and Sensors

Factory configuration of the data loggers receives a Clear-to-Send notice when the vehicle ignition is turned to the "Off" position. Data is then sent via WiFi. The logger then cycles to Standby status. When the ignition switch is turned "On," the logger cycles to Operate status and begins logging data. This full cycle does not log the charging cycle when the charger is plugged in and the key is in the "Off" position.[4]

To enable the logger to stay "On" and log the charging cycle with the ignition "Off," it was necessary to remove the Switch-Off/Stay-Off function. This field modification bypassed the ignition switch, leaving the logger in an Always On / Always Logging state.

Table 2. Logger B – Currently Available Parameters

Chan. No.	Description	Output Range	Requirements/Comments
B1	AC Charge Voltage	4–20 mA	0–110 V_{AC}. 0.004 amps is 0 V.
B2	AC Charge Current	4–20 mA	0–15 amps. 0.004 amps measured is 0 amps.
B3	Battery DC Voltage	4–20 mA	Range 0–100 V. Nominally 72 V. 0.004 amps is 0 V.
B4	Battery DC Current	-5–+1.5 V	Range 125 (regen) to 600 (drive) amps. Output is positive when charging and negative when driving (discharging).
B5	Battery Temperature	0–2 V	Semiconductor range −40°–125°C. Sensitivity is 10 mV/°C. (sensor location being examined).
B6	Ambient Temperature	0–2 V	Semiconductor range −40°–125°C. Sensitivity is 10 mV/°C.
B7	Cabin Temperature	0–2 V	Semiconductor range −40°–125°C. Sensitivity is 10 mV/°C.

[3] *E-Vehicle Project Status Report, Kent L. Colby, March 2013.*

[4] This feature was added in the second season of testing. With this feature in place, when the charger was charging, the logger stayed awake and did not cycle off until the charge cycle was complete.

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B8	Not used		
B9	Time Stamp		Loggers have a real-time clock (to be set to McMurdo time).
B10	Logger Internal Temperature		Loggers have internal temperature sensors and internal heaters. Temperature sensors confirm that the heaters are working in each logger.

Table 3. Logger A[5] – Currently Unavailable Parameters

Chan. No.	Description	Sensor Model	Input Type
A1	Motor Speed	e-ride supplied pulse sensor.	C/T, signal is 0–5 V pulse train. ±8 V range.
A2	Accelerator Pedal	e-ride supplied position sensor.	Signal is 0–5 V. ±8 V range.
A3	Brake Pedal	e-ride supplied on/off sensor.	Signal is 0–12 V, but is really off/on. ±8 V range.
A4	AC or DC Cabin Heater	e-ride supplied on/off sensor.	Signal is 0–12 V, but is really off/on. ±8 V range.
A5	Ignition ON	e-ride supplied on/off sensor.	Signal is 0–12 V, but is really off/on. ±8V range.
A6	AC Battery Heater (requires being plugged in)	e-ride supplied on/off sensor.	Signal is 0–12 V, but is really off/on. ±8 V range.
A7	Available		±8 V range.
A8	Available		±8 V range.
A9	Time Stamp		Sec
A10	Logger Internal Temperature		°C

2.3 Battery Description

Battery functionality is critical to the practicality of battery EVs. The e-ride Industries EVs in Antarctica employ VRLA (valve-regulated lead-acid) batteries, which are low-maintenance lead-acid rechargeable batteries. Because of their construction, VRLA batteries do not require regular addition of water to the cells. VRLA batteries are commonly further classified as:

- Absorbed glass mat (AGM) batteries
- Gel batteries (gel cell).

AGM batteries are just like flooded lead-acid batteries, except the electrolyte is held in the glass mats, as opposed to freely flooding the plates. AGM batteries are sealed, maintenance-free batteries.

Each cell of the batteries in the e-ride EVs is 2 V. There are four cells per pack. There are nine battery packs, each 8 V. Together the nominal DC voltage for the drive batteries is 72 V. The

[5] Logger A is not designed to operate when the vehicle is charging.

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voltage range per cell is 1.73 V to 2.04 V, or totaled the range is 62.3 V to 73.4 V. In the EVs, the batteries are located in a compartment that runs down the center of each vehicle, under battery covers.

2.3.1 Battery Capacity vs. Temperature

Table 4 shows the effect of temperature on battery capacity for the VRLA batteries employed. The table shows the reduction of the battery energy/capacity (Wh) due to colder temperatures. The data presented are with all vehicle accessories turned off. The DC Wh per mile and the total range are given as a reference.

Table 4. Battery Capacity vs. Temperature

Temp °F	Temp °C	DC Capacity (Wh)	% Capacity	DC Wh per Mile	Total Range (Miles)
80	26.7	6,745	109%	230	29.3
70	21.1	6,187.28	100%	238	26.0
60	15.6	5,629.56	91%	246	22.9
50	10.0	5,071.84	82%	254	20.0
40	4.4	4,514.12	73%	261	17.3
30	-1.1	3,956.4	64%	269	14.7
20	-6.7	3,398.68	55%	277	12.3
10	-12.2	2,840.96	46%	285	10.0
0	-17.8	2,283.24	37%	293	7.8
-10	-23.3	1,725.52	28%	301	5.7
-20	-28.9	1,167.8	19%	309	3.8

Colder temperatures clearly degrade the batteries' capacity significantly and, as a result, reduce vehicle range. To attempt to compensate for the effect of cold on battery capacity, the battery compartment in each vehicle is insulated and heated with AC power (i.e., shore power) only (not during driving). In Table 4, supplied by the battery manufacturer Discover Energy to e-ride, the row at 30°F is highlighted, because this is the range in which the batteries are believed to be operating most of the time based on review of the acquired data. At 30°F (-1.1°C), the usable capacity is reportedly 64% of the rated capacity at 70°F. Note that according to this table, driving range drops to 14.7 miles, due to battery capacity being diminished. The information in Table 3, however, does not account for parasitic losses from battery capacity due to operating heaters (e.g., the onboard DC heater, which is used more when temperatures are colder) or other auxiliary equipment (e.g., headlights, which are in use all the time during the dark winter months in Antarctica).

This suggests that there may be optimal driving distances for the EVs at McMurdo. For example, the maximum distances these vehicles might travel are 1.8 miles to the T-Site, 1.95 miles to Scott Base, 3.5 miles to the Sea Ice Runway, and 7–15 miles to the Pegasus airfield (shortcut available until mid-December). Most other trips are less than a mile, around town.

With the battery heaters, the battery temperatures hover around 0°C. Table 4 shows that the battery capacity is around 60% of its rated capacity at 20°C. Therefore, we should expect a typical maximum recharge amount of 4,000 Wh.

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In comparing the EVs to the conventional vehicles, it is important to note that the EV is driven to a location and then is off, even if the ignition key is left on, and while this still is drawing some power from the batteries if auxiliary equipment is on, this is contrasted with the gasoline vehicles, which typically idle when not in use, even for short trips, and even for long periods of time in cold weather, though less so during the high-use summer months.

2.3.2 Battery Capacity vs. Battery Age

Another factor to consider is that the battery capacity varies with time, and in most cases the lead-acid batteries used in this study would reach full capacity after 90–120 charge cycles, as shown in Figure 2. At the end of its life it should dramatically drop in capacity. From Figure 2 we see a slight increase in capacity as the number of charges rises, and then the capacity decreases as the number of cycles grows. One slight positive effect of cold-weather testing is that as the battery temperature decreases, the number of battery cycles before retirement/depletion increases, because the battery cannot fully discharge when it is colder (reduced depth of discharge in cold temperatures).

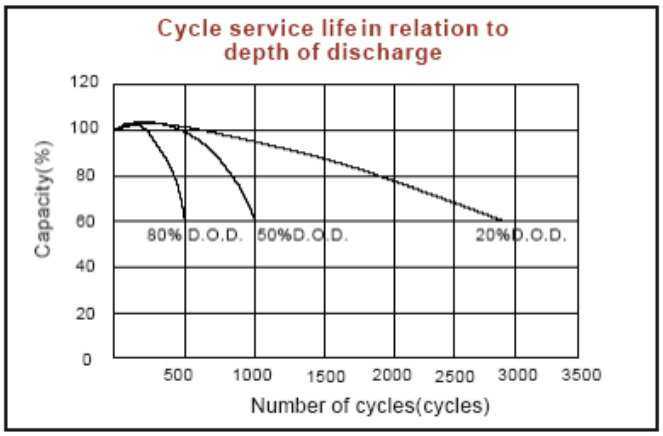

Figure 2. Battery capacity vs. number of cycles (Discover Clean Green, see http://www.discover-energy.com/ev-traction-dry-cell/evgc6a-v3).

The VRLA batteries do not have memory, which means they can be charged often and not fully yet without ill effects.[6] If they are only charged to half of their capacity, then this is considered a half-charge, and in this case, the batteries can be charged twice as many times.

From Table 4, we see at cold temperatures (between 20°F and 30°F) the batteries are only at 60% capacity. Applying this to Figure 2, the number of charge cycles increases to approximately 1,000. This determination may be important in considering battery life. For example, if one assumes batteries are charged six times per week, then 1,000/6 = 166 weeks or 3.2 years. If instead the batteries are maintained at 80% capacity instead of 60% capacity at a given temperature, then the number of charge cycles is 800, which translates to 2.5 years. The battery

[6] Some battery chemistries operate in a fashion that, after shallow discharge cycles, the unused portions of the electrodes "remember" the previous cycles and are unable to sustain the required discharge voltage beyond the depth of the previous cycles. The capacity is lost and can only be restored by slowly discharging completely. (generally outside the application), and properly recharging. VRLA lead-acid batteries do not exhibit this capacity robbing effect known as "memory."

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capacity change over time is important to monitor, as it is directly related to vehicle suitability and operational costs.

Based on information in Figure 2, for an EV whose batteries are charged frequently during the day (e.g., three times/day in summer months), it is likely that the batteries will show significant degradation within a few years of use. It is not clear, however, that this was an issue for the batteries in this study, because frequent shorter charges did not bring the batteries to full charge, suggesting that the amount of time in these short charges may have been insufficient to cause the harm to the batteries that is frequently associated with short, frequent top-off charges. Full charging for these batteries generally took 7 hours.

2.3.3 AC Inputs

There are two AC receptacles on the front bumper of each vehicle. Either one or both receptacles can be plugged in. Facing the vehicle, on the right side is Receptacle #1, the battery charger OR auxiliary cabin heater. On the left side is Receptacle #2, a battery warmer.

Figure 3. AC Receptacle #1 (charger or cabin heater).

This receptacle serves as either a vehicle battery charger or as a power supply for a cabin pre-heater (1,500 W heater).[7] Additional information on each of these two states is provided below.

A switch within the cabin determines whether electricity delivered through this receptacle will charge the EV or heat the cabin. When data is collected, it can be determined whether the vehicle is being charged or the cabin is being heated, because the DC current (channel B4) will be positive for either operation. This can also be verified by viewing the battery temperature (channel B5) over time. The cabin heater status is measured with channel A6.

[7] While at first this seemed like a useful approach, in the end it led to less than suitable charging at times, as operator error too easily left the heater on, which disabled the charger. When this happened, the batteries were not "topped off" for the following day's operation.

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Due to the "on/off" switch design/location, vehicle operators have accidentally flipped the cabin heater switch, causing the vehicle not to charge when in fact the operators intended to charge the vehicle. In the future, consideration should be given to changing this switch design/location to alleviate this issue.[8]

2.3.3.1 Battery Charging

Charge time will vary depending on the depth of discharge. Seven hours is the normal time required to fully charge the EVs. The maximum supply power is 1,800 W at 120 V and 15 amps. Continuous charging is 1,440 W (120 V and 12 amps). Frequency is 45–65 Hz.

Once the charge is completed, the charger shuts off automatically. When a power cord is plugged into Receptacle #1 of the vehicle and power is present, the vehicle can be turned on, but it will not move. This eliminates the possibility of moving the vehicle and damaging the plug (as frequently happens with gasoline vehicles).

When the charger AC cord stays connected to the vehicle, a new charge cycle is triggered 24 hours after the end of the last charge cycle, to compensate for any discharge during this period while the vehicle is sitting unused. If the vehicle sits in conditions of 0°C (32°F) or below with a state of charge (SOC) of 20% or less, the batteries could freeze. If the batteries freeze, they may be damaged, permanently reducing their capacity. The battery heaters and insulated battery compartment are intended to help avoid such a situation, but these do not function if the vehicle is not operated or otherwise plugged in. Therefore, the EVs should be kept in a location where the temperature is greater than 0°C, and they are allowed to warm up before charging. The EVs should not be charged if the batteries may be frozen.

2.3.3.2 Cabin Heating (120 V AC)

The cabin heating option is designed to preheat and defog the cabin and front windshield before driving the vehicle without drawing power from the drive batteries. This is done by plugging the cord into the charger receptacle on the right of the two receptacles located in the center of the front bumper. When the power cord is initially plugged into the receptacle, the onboard charger will start. To turn on the heater (and the charger off), there is a switch on the center console that is labeled Heater. This switch has three possible positions: Off, On, and Start. To start the heater, the rocker switch is moved to the On position, and then momentarily the rocker switch is moved all the way up to the Start position. After a few seconds, the heater will turn on. At the same time, the onboard charger will shut off. If the power is disconnected from the front receptacle and then reconnected, the heater will be off and the charger will be on. The center console heater switch must be restarted in order for the heater to turn on again. This heater has an amp draw of 15 amps at 120 V.

The vehicle is equipped with anti-drive so that it cannot be driven if power is present at the front charger/AC heater receptacle. Any power supply plugged into Receptacle #1must be unplugged before the vehicle is driven.

[8] Additional options might include changing the cabin heater to the B plug or installing a thermostat on the heater to turn it off when the temperature reaches a set point.

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2.3.3.3 AC Receptacle #2 (Battery Warmer)

Receptacle #2 feeds electricity to a 480 W (4 amps at 120 V) battery warmer that can be powered using AC power. The warmer will turn on if the battery temperature is less than 60°F and will shut off when the temperature reaches 80°F. In Antarctica's ambient temperatures, the warmer is always on when plugged in. Channel A4 measures the battery warmer operation. There is an anti-drive feature for Receptacle #1, but not for #2. For safety reasons, any power cord should be removed before the vehicle is driven.

2.4 EV Operation

The following summary and interview are from contractor Kent Colby's report.

2.4.1 Summary

Year 1: Both vehicles could be driven (nearly constantly) to and from work centers for 30 –60 minutes before dropping to approximately 40% power on the display. At this level, the power level is compromised and the vehicle labors to maneuver the hilly terrain of McMurdo. To accomplish a full charge from this level (green light on the charger) required 7 hours.

Year 2: There was a noticeable decline in battery life to a maximum of 30 minutes in the above scenario. Contractor did not check the recharge time.

Year 3: The vehicle operates satisfactorily for 15 minutes of drive time before the charge level drops to 40% or less. Note that this is still adequate for most station-related tasking, such as making deliveries and short trips between work centers. The average driving trip at McMurdo appears to be 3 minutes or less. Data collected from the HEM Data data loggers indicate drive times of up to an hour at various times; however, it may be that the vehicle operators were not turning the ignition key off when they were getting in and out of the vehicle (much as they are accustomed to doing when operating conventional fuel vehicles), or the data loggers were not properly cycling.

2.4.2 EV User Feedback

Anecdotal information and user/operator reports indicated the operators liked using the vehicles. To capture qualitative information about the vehicles from users, operators were asked to complete user surveys following each trip during the first season of use of the vehicles at McMurdo. The survey form used is included in Appendix A. User feedback included the following:

- "Good on ice and snow. Drive slowly on bumps."
- "Would use additional EVs."
- "Easy to use."
- "Very serviceable."
- "Very helpful for our operational efficiency."
- "Saves a lot of time."
- "Perfect vehicle for job."

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- "Handled load very well. Easy lifting heavy object into and out of."
- "Low bed was much easier to get heavy motor in and out. Vehicle ops were good."
- "Top rack was easy to get the ladder on and off. Easier than transporting in a truck. Vehicle operation was good."
- "Impressed with drivability."
- "Vehicle very quiet. Hard to make pedestrians see the vehicle."
- "Driver door hard to close."
- "The seat is a tight fit."
- "The cabin heater switch location can be improved as it is accidentally turned on sometimes and doing so can prevent proper charging of the vehicle."
- "Traction poor going up icy slopes, but this was easy to work around."

The EVs were used to haul a variety of materials and equipment, including: debris, personnel, mattresses and bed parts, extension ladders, tool bags, motors, hoses, space heaters and blankets, propane, glycol, absorbents, pumps, and beverages.

A change in operations at McMurdo led to the surveys no longer being undertaken. Nonetheless, information from an interview with Harold House, McMurdo Station winter-over site manager for the 2012 and 2013 winter seasons, set forth below, provides a sense of how the EVs have been used and how they have been regarded by users at McMurdo more recently.

1. Who are the primary users this season? Do you coordinate their use or is that someone else?
    - Myself, the UTs [Utility Technicians], janitors, a bit with Supply. I run one machine pretty much on my own, and the others share the rest. I do not coordinate the use of the others' EV, but because the UTs use it the most, I assume they will manage it. The head of the UTs is James St. Onge, so I would guess he is in charge of it, or knows who is.

2. Where are they most frequently parked? We are not receiving any data from 001 and only partial from 002.
    - Mine is outside of Building 175, and I will use #2. The other one will be outside of Building 155, near the boiler room (or parked inside of it). That will be #1 this season. Last year, I used #1, and they used #2, but each of the vehicles we used was parked in the same place.

3. You said you use one of the trucks—is it exclusively yours?
    - Yes, I very occasionally use a truck. I share it with George Lampman, Bill Henriksen, and anyone else that occasionally needs a truck.

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4. In reviewing last winter's data, 002 collected significantly more data. Was it used more or did the logger not track everything?
    - It was used much more than #1, which is the one I used.

5. In addition, some trips on 002 were an hour or so. Do you think it is safe to assume whoever was driving did not turn the key off at stops?
    - Probably yes, especially in colder temps as it is unlikely the battery could have powered the vehicle for that much continuous driving time in the cold.

2.5 EV Data

Full plots of data collected and explanations are provided in Appendix C. The plots and data also are available on the Web at http://antarctica.hemdata.com.

2.6 EV Maintenance

The EVs are low-maintenance vehicles at McMurdo. In the 3 calendar years the EVs have been at McMurdo, there have been limited issues involving the vehicles' mechanics. Appendix B includes a list of the work order history for both EVs. Combined, the EVs required 106 labor hours to address several issues, including: a door latch adjustment, a sticky throttle pedal (new throttle control provided under warranty), battery charger re-programming (to adjust for colder temperatures—the default setting had the charger shutting down at -20°C, so it was changed to -30°C), and installation of one new gearshaft assembly that had snapped in one transaxle (e-ride Industries offered newly redesigned, heavier-duty parts to replace all as a warranty upgrade).

In one vehicle, a windshield cracked. This is believed to have been due to subjecting the windshield to a sudden increase in temperature rather than the gradual increase that is recommended for all vehicles, conventional and electric.

After more than 2 years of use in Antarctica, the shock absorber bushings began to show wear and are due for replacement. Mechanics overseeing the vehicles recommend that this maintenance occur annually or bi-annually.

Figure 4. Shock absorber bushings. Left: Vehicle 001. Right: Vehicle 002.

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In terms of interior wear and tear, Figure 5 below shows that the seat covers are showing considerable wear and tear and will require either repair or a new seat covering. It is recommended a higher-grade fabric be required on new seat coverings and/or new vehicle purchases.

Figure 5. Interior seat covers. Left: Vehicle 001. Right: Vehicle 002.

Notably, e-ride Industries provided assistance with problem solving and training for normal operation and countless hours of support for all phases of the data-logger installation and the modifications.

Based on the low maintenance experience to date, a simple maintenance plan can be developed to manage the EVs. Any such plan, which might include a weekly/monthly/annual checklist for the service along with a detailed standard operating plan, should include a section to fortify operating training to ensure proper care and management of batteries and lessons learned.

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3 EV Energy Efficiency Analysis

The overall energy efficiency of an EV and its drain on the energy/power supply at McMurdo can be calculated based on the data acquired. By measuring the AC voltage and current, the power input to the vehicle is calculated. Integrating this over time yields the amount of energy provided to the vehicle.

The energy efficiency of various vehicle components are calculated and shown in Table 5 (on a trip-by-trip basis). These values may be used to assess the impact of each on overall vehicle efficiency, and an overall value for vehicle efficiency can be calculated.

The parameters of primary interest in relation to vehicle energy efficiency include the AC charger, battery, and driveline. The potential sources of parasitic energy losses are also important, and to this point they have been identified as the AC- or DC-powered cabin heater, the AC-powered battery heater, and the headlights.[9]

Table 5. Efficiency Calculations

File Name	State	Hours Total	Minutes Delta	Miles Total	Miles Delta	AC WH In	DC WH In	AC to DC Eff.	DC W-H Out	Amb Avg C	Batt Temp	Over'l W-H/Mi	Over'l Watt-Hour	AC WH In Delta	AC Total In	DC Total In	Org. Eff	DC Out Total	DC Eff	Overall Eff
1D201849	C	**92.1**				0	0													
1D202122	C	**92.1**				0	0													
1D202233	B					1533	1169	0.77	323	-28	-6				1533	1169	0.76	323	0.28	0.21
1E101647	B			243.4		57.7	6.6	0.11	1407	-2.2	11				1591	1176	0.74	1730	1.47	1.09
1E101837	B					2723	1764	0.645	16.2	6.6	11.5				4314	2940	0.68	1746	0.59	0.40
1E112129	C														4314	2940	0.68	1746	0.59	0.40
1E112130	B					38.7	20.5	0.48	1271	-29	1.1				4352	2960	0.68	3017	1.02	0.69
1E112305	B					1087	790	0.73	368	-28.5	6				5439	3750	0.69	3385	0.90	0.62
1E120012	C					2602	1887	0.73	0	-51	0.31				8041	5637	0.70	3385	0.60	0.42
1E121635	C					102	78.7	0.75		-29	1				8143	5716	0.70	3385	0.59	0.42
1E121635	B					101	78.6	0.75	729	-29	0.7				8244	5794	0.70	4114	0.71	0.50
1E121837	B					1482	1049	0.71	422	-24	-1.1				9726	6843	0.70	4536	0.66	0.47
1E132201	C					3887	3006	0.77	0	-29	-2.7				13613	9849	0.72	4536	0.46	0.33
1E151629	D	154.2		254.7		0	0		232	-49	-12				13613	9849	0.72	4768	0.48	0.35
1E152216	C					1364	857	0.63	0	-27	-4.7				14977	10706	0.71	4768	0.45	0.32
1E161559	C					122	74	0.51		-50	-2.4				15099	10780	0.71	4768	0.44	0.32
1E161559	B					122	73.8	0.51	315	-51	-2.3				15221	10854	0.71	5083	0.47	0.33
1E161746	C					2400	1822	0.76	0	-28	-6.7				17621	12676	0.72	5083	0.40	0.29
1E176151	D	155.1		257.0		0	0		389	-49	-15				17621	12676	0.72	5472	0.43	0.31
1E181623	B					2269	1682	0.74	1526	-24	3				19890	14358	0.72	6998	0.49	0.35
1E182144	B					936	700	0.75	550	-51	0.37				20826	15058	0.72	7548	0.50	0.36
1E182325	B					269	206	0.76	251	-25	5.1				21095	15264	0.72	7799	0.51	0.37
1E190013	B					245	181	0.72	846	-35	-5.5				21340	15445	0.72	8645	0.56	0.41
1E201043	B	155.7				927	629	0.68	269	-16	-51				22267	16074	0.72	8914	0.55	0.40
1E201851	B	155.9		261.3	17.9	327	211	0.63	2137	-24	-0.8	1173	9321	21004	22594	16285	0.72	11051	0.68	0.49
1E202234	B					7371	4925	0.67	54.1	-18	-1				29965	21210	0.71	11105	0.52	0.37
1E251710	I	161.4		266.0	22.6	0	0		12	10	13.6	1256		28375	29965	21210	0.71	11117	0.52	0.37
1E251730	I								3.5	12	-50									

[9] Headlights draw 156 W, are on at all times in winter Antarctica months, and compromise battery power and output.

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3.1 AC Charger Efficiency

The AC charger efficiency is calculated as the ratio of (DC energy into the Battery) / (AC energy in). The AC charger in warm weather has a reported efficiency of 0.95, according to e-ride Industries. The highest value collected in Antarctica is 0.87. This value was collected when neither the battery nor cabin heaters were operating, a rare situation in Antarctica operation. Although AC power can be used for either of these heaters, as well as for battery charging, for the purposes of this report, it is treated as part of the charging because measuring the purpose the AC input was used was not undertaken with the available instrumentation. Test results to date show that in cold weather the value for AC charger efficiency is 0.75. In some instances it is as low as 0.63. It is assumed that the cabin heater is the cause of the lower efficiency value. Monthly efficiency values to date range from 0.8 to 0.87, with an average of 0.83.

Table 5 is an excerpt of AC charger efficiency vs. temperature from 2011 data. It is representative of data collected as the study continued.

Because 0.86 is the best achieved efficiency in cold weather (Table 6), it is assumed the drop in efficiency from 0.95 to 0.86 is due to the effect of cold weather on the charger. The remaining drop to 0.75 or less is likely due to one or more heaters being on. Future testing, when summer Antarctica temperatures allow for testing without the heaters being on, could examine this issue more fully.

It appears clear that warming the batteries should also be included in any calculation of the AC energy needed to power the vehicles. Future data collection efforts should better define the energy used to heat the batteries and cabin. When compared to conventional vehicles, the power used to heat the vehicle is part of the miles per gallon (MPG), except for power consumed while parked and plugged in. Of course, a benefit of the gasoline and diesel engines is that their waste heat is used to heat the vehicle while running. Using a logger that takes data directly from the OBD-II connector is a plug-and-play way to monitor the fuel economy of the conventional vehicle, and acquiring the coolant temperature will let us know when the engine heater is on.

Knowing the DC voltage and current also yields DC power, and integrating DC power yields DC energy provided to the battery. Taking the ratio of (DC energy / AC energy) yields the efficiency of the charger. It appears that the charger is not as efficient in colder temperatures.

3.2 AC Charger Efficiency vs. Temperature and Heater Effect

Table 6 shows how temperature affects the efficiency of the AC charger. The highest efficiency value attained to date was 0.86, and this was at the highest average battery temperature and when the cabin heater was not on. As the battery temperature decreases and when the cabin heater is on, charger efficiency is expected to decrease.

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Table 6. AC Charger Efficiency vs. Temperature and Heater Effect (2011)

Row	Avg. Battery Temp °C	Charger Efficiency	Temp Min	Temp Max	Temp Delta	Comment
1	12	0.86	9	14	5	
2	8	0.82	7	10	3	
3	-2.7	0.77	-9	3	12	Heater on
4	-6	0.77	-18	0	18	Heater on less than row 3, which had the same charger efficiency
5	0.37	0.75				
6	-1.1	0.71	-8	2	10	
7	-1	0.67				
8	-0.8	0.63	-10	3	13	Heater on

3.3 Battery Efficiency

The DC battery efficiency is calculated as the ratio of (DC energy out of the battery) / (DC energy into the Battery). The battery efficiency in warm weather (e.g., summer at e-ride Industries in Princeton, Minnesota) is 89%, according to e-ride. Less energy can be drawn from the battery in cold weather. Specifically, the energy is still within the battery, but the battery will not output this energy until it is warmed up. From Table 4, in the operating temperature range, the battery efficiency is expected to be 40% to 90%, depending on both the battery temperature and whether the DC cabin heater is on. Use of the DC cabin heater will cause the vehicle to be less efficient, due to the energy draw needed to operate the heater. The range of battery efficiency determined from the data was 0.64–0.82, with an average of 0.71. The overall efficiency of the AC charger and battery was 0.59.

Collecting data regarding when the heaters are on might allow better accounting for their energy draw.

3.4 Driveline Efficiency

In warm weather (e.g., summer at e-ride Industries, in Princeton, Minnesota), the driveline efficiency is 85%, according to e-ride. In cold weather, such as that experienced in Antarctica, this value is presently unknown, but it is logical to assume that it would be less efficient due to increased friction in operating the vehicle. The reduced driving efficiency does show up in the Wh/mile calculation. Future data collection may provide information to support this calculation. The drain on efficiency simply from cold-weather operation could also be tested and confirmed in a cold chamber with a dynamometer.

3.5 Overall Vehicle Efficiency (Percent)

If all the efficiencies are multiplied, the overall vehicle efficiency can be determined. Alternatively, calculating (DC energy out of the battery) / (AC energy into the battery) would provide the overall efficiency (excluding driveline efficiency). Available data to this point reveal a range of overall efficiency (without driveline) of 20%–60%, with a usual efficiency of 40%. The wide range is due to the range of battery efficiencies obtained to this point, and is mostly influenced by operation of the cabin heater.

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3.6 Overall Vehicle Efficiency (Watt-Hours Per Mile)

An alternative and excellent measure of overall vehicle efficiency is derived from Wh/mile. Table 4 provides values for the battery capacity only. It does not include the AC charger efficiency, the driveline efficiency, or any parasitic energy losses. Therefore, because of these other factors, overall calculated efficiency numbers should be lower than those defined in Table 4 by the battery manufacturer for the battery only. Table 4 displays a representative value as 269 Wh/mile assuming a typical operating temperature of 30°F. Our calculations of the measured AC energy in divided by the miles driven yield a value of 890 Wh/mile, which is 3.3 times larger. The driveline efficiency is likely a major contributor to this difference. In addition, the cabin heater and lights are clear parasitic losses that must be accounted for.

A next report could investigate this significant difference further, by virtue of the additional parameters for which data could be collected. In addition, DC voltage measurement is important to nearly all of the key calculations.

When taking into account the AC energy into the vehicle, the vehicle efficiency value is approximately 1,200 Wh/mile. This value was obtained by summing all energy input (in Wh) during that period, and dividing that value by the miles driven over that same period (information provided by operators). When potential sources of error are addressed, the vehicle efficiency value is expected to rise by as much as 15% or more.

3.7 Parasitic Losses

The parasitic losses are quantified below based on their supplier specifications.

3.7.1 AC- or DC-Powered Cabin Heater

The cabin heater is on or off. It consumes 1,500 W.

3.7.2 AC-Powered Battery Heater

There is a 500 W heater for the batteries.

3.7.3 Headlights

When the headlights are on, they draw 156 W. Headlights are on at all times in winter months in Antarctica.

3.8 Costs to Operate

3.8.1 Analysis of Energy and Cost to Run One EV for a Year

- In 8 months, logged 250 kWh on Vehicle 002 (incomplete data for some months; see http://antarctica.hemdata.com/vehicle/2/)
- Typical summer month: 80 kWh.
- Winter month: 48 kWh (fewer personnel in winter)
- Using 375–600 kWh/year with an energy cost of $0.16/kWh (supplied to Kent Colby by McMurdo Station personnel)
- Yearly cost: $60–$96.

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3.8.2 Cost per Mile

- About 700 Wh AC in / mile (see Energy per Mile vs. Month plot in Appendix C).
- Cost per mile driven: $0.11.

3.8.3 Cost per Hour Driving

- About 5 kWh AC in / hour driving (see Energy per Hour Driving vs. Month plot in Appendix C).
- Cost per hour: $0.80.

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4 McMurdo Conventional Vehicle Fleet Evaluation

4.1.1 Objective

The objective of this component of the study was to document and categorize the duty cycle of light-duty vehicles from a variety of departments and vehicle pools at McMurdo, Antarctica. This information can be used to identify which vehicles, if any, have duty cycles that can be fulfilled by the EVs studied in the EV portion of this report. In turn, this effort will allow NSF to pinpoint opportunities to reduce the amount of petroleum used to fulfill McMurdo fleet activities, as well as reduce the quantity of GHG emissions associated with such activities as those undertaken by the current light-duty vehicle fleet.

4.1.2 Study Vehicles

The light-duty vehicle fleet at McMurdo is primarily comprised of 2000–2002 model year F-350 4x4 pickups and E-350 vans. There are some newer and older versions of these vehicle models. NSF is prioritizing for potential replacement with more efficient vehicles those vehicles that see daily use with lower cargo weight. One-ton vehicles that are regularly heavily loaded would not be suitable for replacement with EVs as compared to the same vehicles primarily transporting people and lighter equipment. Similarly, vehicles that are used infrequently may not burn enough fuel to warrant replacement with more expensive vehicles that nonetheless offer the opportunity to deploy technologies that would reduce GHG emissions. Light-duty emergency vehicles and vehicles otherwise assigned to the McMurdo Fire Department were excluded from selection for this study.

4.1.3 Vehicle Instrumentation

Two different styles of data loggers were used in this portion of the study at McMurdo. The more advanced loggers are Isaac DRU900/908 data loggers, which have both Global Positioning System (GPS) and on-board diagnostics (OBDII) communication capabilities. Six of these loggers were programmed to be triggered at engine start (using an engine speed threshold of 100 rpm). GPS parameters recorded at 5 Hz, while OBDII channels recorded at 1 Hz with an expected actual update rate of ½ Hz due to the limitations of older OBDII communications protocols. Additionally, some channels were not available on all vehicles.

The simpler TSI trip loggers were employed to obtain a broader and more general understanding of vehicle duty cycle at McMurdo. Twelve of these GPS-only loggers were deployed. Because these vehicles have an always-on auxiliary power port, there was no key switch signal to turn them on and off, and a "smart mode" had to be used to trigger recording of GPS time/speed/location at 1 Hz. This feature did not work properly and resulted in the loggers being in record mode all the time, which necessitated frequent downloading of data because the data capacity filled after a couple of days, after which they would stop recording.

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Table 7. Isaac Data Logger Channel List

Isaac Box Temp	Isaac Box Voltage
GPS Time	GPS Latitude
GPS Longitude	GPS Number of Satellites
GPS Altitude	GPS Speed
Engine Load	Engine Coolant Temperature
Inlet Air Temperature	Barometric Pressure
Ambient Air Temperature	Manifold Air Pressure (MAP)
Engine Speed	Wheel-Based Vehicle Speed
Mass Air Flow (MAF)	Throttle Position

4.1.4 Evaluation Periods

Vehicles were evaluated in roughly three recording periods spanning a total of 68 days, or a maximum of 1,032 vehicle days. Because of the difficulty locating and catching desired vehicles (they were in frequent use and moving between work stations) for installation and removal of logging devices, the recording periods were not uniform. Some high-priority vehicles were assigned a logger for two or three of the recording periods. The vehicle selection was designed to provide information regarding the duty cycle for a wide array of vehicles, but also to gain an understanding of any changes in use pattern over an extended period on select vehicles. Additionally, both e-ride Industries EVs were equipped with a TSI logger to provide same-format duty-cycle data for comparison to the conventional fleet. The evaluation periods in 2011-2012 were as follows:

- Nov. 24–29 to Dec. 1–4
- Dec. 1–4 to Dec. 6–9
- Dec. 7–14 to Dec. 29 (Isaac) or Jan. 30 (TSI)

Thirty conventional vehicles (out of roughly 65 light-duty vehicles at McMurdo) and the two EVs were instrumented for some period of time recording over 660 vehicle operational days at McMurdo. After removing days with unrealistically high kinetic intensity (over 15 1/mile)[10] or days with less than 0.5 miles accumulated, 444 good days of vehicle data were left to be analyzed and compared. Use on stock and lifted conventional vehicles was captured, as well as information on snow-road and "in-town" driving behavior. The breakdown of data captured was 55 days of EV operation, 232 days of stock pickup truck in-town operation, and 157 days of lifted truck and van operation.

Table 8 below documents the periods for which each vehicle was instrumented. Yellow highlighted vehicle numbers indicate that a vehicle was instrumented for multiple data evaluation periods in a row with the same logging device. Blue highlighted vehicle numbers indicate that a vehicle was instrumented multiple times with different loggers. Table 9 details the descriptions of each vehicle in Table 8 that was instrumented.

[10] This value for kinetic intensity represents a level that is higher than the most aggressive transit bus test cycles.

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Table 8. Vehicles Chosen for Instrumenting for Each Recording Period

	Logger Unit #	Recording Period 1	Recording Period 2	Recording Period 3
1	Isaac 2 (PG10-7012)	TL00147	TL00147	TL00147
2	Isaac 4 (PG10-6471)	TL00108	TL00108	TL00108
3	Isaac 5 (PG10-6057)	TL00140	TL00424 E-350 shuttle	TL00424 E-350 shuttle
4	Isaac 6 (PG10-6477)	TL00134	TL00138	TL00113
5	Isaac 7 (PG10-7007)	TL00142	TL00103	TL00103
6	Isaac 10 (PG10-7010)	TL00127	TL00146	TL00109
1	TSI t5	TL00112	TL00112	TL00112
2	TSI t6	TL00116	TL00116	TL00116
3	TSI t7	TL00100	TL00100	TL00100
4	TSI t8	TL00141	TL00141	TL00141
5	TSI t9	TL00113	TL00121	TL00101
6	TSI t10	TL00103	TL00107	TL00117
7	TSI t11	TL00101	TL00135	TL00217
8	TSI t12	TL00137	TL00149	TL00110
9	TSI t13	TL00119	TL00132	TL00132
10	TSI t14	TL00151	TL00153	TL00133
11	TSI t15	ET00001	ET00001	ET00001
12	TSI t16	ET00002	ET00002	ET00002

Table 9. Vehicle Descriptions

EQUIP #	TYPE	VEHICLE DESCRIPTION	YEAR	MODEL	DEPT	POOL
ET00001	TRUCK, EV	e-ride Industries EV with enclosed utility bed	1/1/2010	EXV2		
ET00002	TRUCK, EV	e-ride Industries EV with open flat bed	1/1/2010	EXV2		
TL00100	TRUCK, CAB	2000, 1 TON 4 X 4 WITH LIFT KIT, 5.4L V-8 WITH O/H CAM,TRANS MOD	1/1/2000	F-350	AGE	OPS
TL00101	TRUCK, CAB	2000, 1 TON 4 X 4 WITH LIFT KIT, 5.4L V-8 WITH O/H CAM,TRANS MOD	1/1/2000	F-350	FEMC	FEMC
TL00103	TRUCK, CAB	2000, 1 TON 4 X 4, 5.4L V-8 WITH O/H CAM,TRANS MOD	1/1/2000	F-350	FEMC	FEMC
TL00107	TRUCK, CAB	2000, 1 TON 4 X 4 WITH LIFT KIT, 5.4L V-8 WITH O/H CAM,TRANS MOD	1/1/2000	F-350	FEMC	FEMC
TL00108	TRUCK, CAB	2000, 1 TON 4 X 4, 5.4L V-8 WITH O/H CAM,TRANS MOD	1/1/2000	F-350	IT	SSC
TL00109	TRUCK, CAB	2000, 1 TON 4 X 4, 5.4L V-8 WITH O/H CAM,TRANS MOD	1/1/2000	F-350	FEMC	FEMC
TL00110	TRUCK, CAB	2000, 1 TON 4 X 4, 5.4L V-8 WITH O/H CAM,TRANS MOD	1/1/2000	F-350	SSC	SSC
TL00112	TRUCK, CAB	2000, 1 TON 4 X 4, 5.4L V-8 WITH O/H CAM,TRANS MOD	1/1/2000	F-350	SUPPLY	ATO/LOG
TL00113	TRUCK, CAB	2000, 1 TON 4 X 4, 5.4L V-8 WITH O/H CAM,TRANS MOD	1/1/2000	F-350	ATO/MCC	ATO/LOG
TL00116	TRUCK, CAB	2000, 1 TON 4 X 4, 5.4L V-8 WITH O/H CAM,TRANS MOD	1/1/2000	F-350	SUPPLY	FEMC
TL0011	TRUCK,	2000, 1 TON 4 X 4 WITH LIFT KIT,	1/1/200	F-350	FEMC	FEMC

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7	CAB	5.4L V-8 WITH O/H CAM,TRANS MOD	0			
TL00119	TRUCK, CAB	2000, 1 TON 4 X 4 WITH LIFT KIT, 5.4L V-8 WITH O/H CAM,TRANS MOD	1/1/2000	F-350	SSC	SSC
TL00121	TRUCK, CAB	2000, 1 TON 4 X 4 WITH LIFT KIT, 5.4L V-8 WITH O/H CAM,TRANS MOD	1/1/2000	F-350	VMF	ATO/LOG
TL00127	TRUCK, CAB FLAT	2000, 1 TON 4 X 4 WITH LIFT KIT, 5.4L V-8 WITH O/H CAM,TRANS MOD	1/1/2000	F-350	IT	SSC
TL00132	TRUCK, CAB FLAT	2000, 1 TON 4 X 4, 5.4L-V-8 WITH O/H CAM,TRANS MOD	1/1/2000	F-350	SSC	SSC
TL00133	TRUCK, CAB FLAT	2000, 1 TON 4 X 4 WITH LIFT KIT, 5.4L V-8 WITH O/H CAM,TRANS MOD	1/1/2000	F-350	VMF	OPS
TL00134	TRUCK, CAB FLAT	2000, 1 TON 4 X 4 WITH LIFT KIT, 5.4L V-8 WITH O/H CAM,TRANS MOD	1/1/2000	F-350	VMF	OPS
TL00135	TRUCK, CAB FLAT	2000, 1 TON 4 X 4 WITH LIFT KIT, 5.4L V-8 WITH O/H CAM,TRANS MOD	1/1/2000	F-350	FEMC	FEMC
TL00137	TRUCK, CAB FLAT	2000, 1 TON 4 X 4, 5.4L-V-8 WITH O/H CAM,TRANS MOD	1/1/2000	F-350	FLEET OPS	OPS
TL00138	TRUCK, CAB FLAT	2000, 1 TON 4 X 4 WITH LIFT KIT, 5.4L V-8 WITH O/H CAM,TRANS MOD	1/1/2000	F-350	AGE	OPS
TL00140	TRUCK, CAB FLAT	2000, 1 TON 4 X 4, 5.4L-V-8 WITH O/H CAM,TRANS MOD	1/1/2000	F-350	SUPPLY	ATO/LOG
TL00141	TRUCK, CAB FLAT	2000, 1 TON 4 X 4, 5.4L-V-8 WITH O/H CAM,TRANS MOD	1/1/2000	F-350	BFC/HELO	SSC
TL00142	TRUCK, CREW	2000, 1 TON 4 X 4 WITH LIFT KIT, 5.4L V-8 WITH O/H CAM,TRANS MOD	1/1/2000	F-350	SURVEYORS	OPS
TL00146	TRUCK, CREW	2000, 1 TON 4 X 4 WITH LIFT KIT, 5.4L V-8 WITH O/H CAM,TRANS MOD	1/1/2000	F-350	SSC	SSC
TL00147	TRUCK, CREW	2000, 1 TON 4 X 4 WITH LIFT KIT, 5.4L V-8 WITH O/H CAM,TRANS MOD	1/1/2000	F-350	WASTE	OPS
TL00149	TRUCK, CREW	2000, 1 TON 4 X 4 WITH LIFT KIT, 5.4L V-8 WITH O/H CAM,TRANS MOD	1/1/2000	F-350	FLEET OPS	OPS
TL00151	TRUCK, EXT	2002, EXTENDED CAB, 4X4 LONG BED,PICK-UP TRUCK WIT	1/1/2002	F-350	SSC	SSC
TL00153	TRUCK, EXT	2002, EXTENDED CAB, 4X4 LONG BED, PICK-UPTRUCK WIT	1/1/2002	F-350	SSC	SSC
TL00217	VAN, PASSENGER	E350 VAN, 16 PASSENGER, 4 X 4 WITH LIFT KIT		E350		
TL00424	VAN, PASSENGER	2011, E350 VAN, 16 PASSENGER, 4 X 4 WITH LIFT KIT		E350	ATO/MCC	ATO/LOG

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4.2 Vehicle Type Images

Stock 1-ton 4x4 pickups, which are limited to "in-town" use, were the primary focus of the conventional study. See Figure 6.

Figure 6. Stock 1-ton 4x4 pickup truck.

One-ton 4x4 pickups with lift kits, larger tires for flotation on snow roads, and even track modifications were captured on a smaller scale for comparison. See Figures 7 and 8.

Figure 7. Lifted 1-ton 4x4 pickup truck with larger tires.

Figure 8. One-ton 4x4 pickup truck with track conversion.

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4.3 Data Review

4.3.1 Drive-Cycle Statistic Summary

Drive-cycle data from the use of the two EVs matched well with the 1-ton conventional trucks used only in town with stock-sized tires. McMurdo has a posted 20 mph speed limit and is a relatively small and compact facility of roughly 1 square mile. Largely because of these limitations, the EVs had very similar average and maximum speeds, daily driven miles, and kinetic intensity ranges as the in-town only, unlifted pickup trucks. See Table 10 below. Not surprisingly, the lifted trucks and lifted shuttle vans that operate on the snow roads out to the airfield and other areas had significantly different duty-cycle statistics. See Figures 9 and 10 for samples of normal driving distance and driving elevation profiles for in-town and snow road vehicles, respectively.

Table 10. Duty-Cycle Statistics

	Selected Duty-Cycle Statistics (average of all vehicle days, maximum vehicle day)					
	Days of Operational Data	Average Speed (mph)	Max Speed (mph)	Daily Miles Driven	Number of Stops per Mile	Kinetic Intensity
EVs	55	8, 12	19, 31	4, 15	7, 19	8, 14
Stock Pickups	232	9, 22	22, 53	8, 102	7, 39	7, 15
Lifted Pickups	109	11, 30	25, 56	16, 92	7, 130	6, 13
Lifted Shuttle Vans	48	18, 30	34, 51	98, 311	1.8, 9	2.5, 10

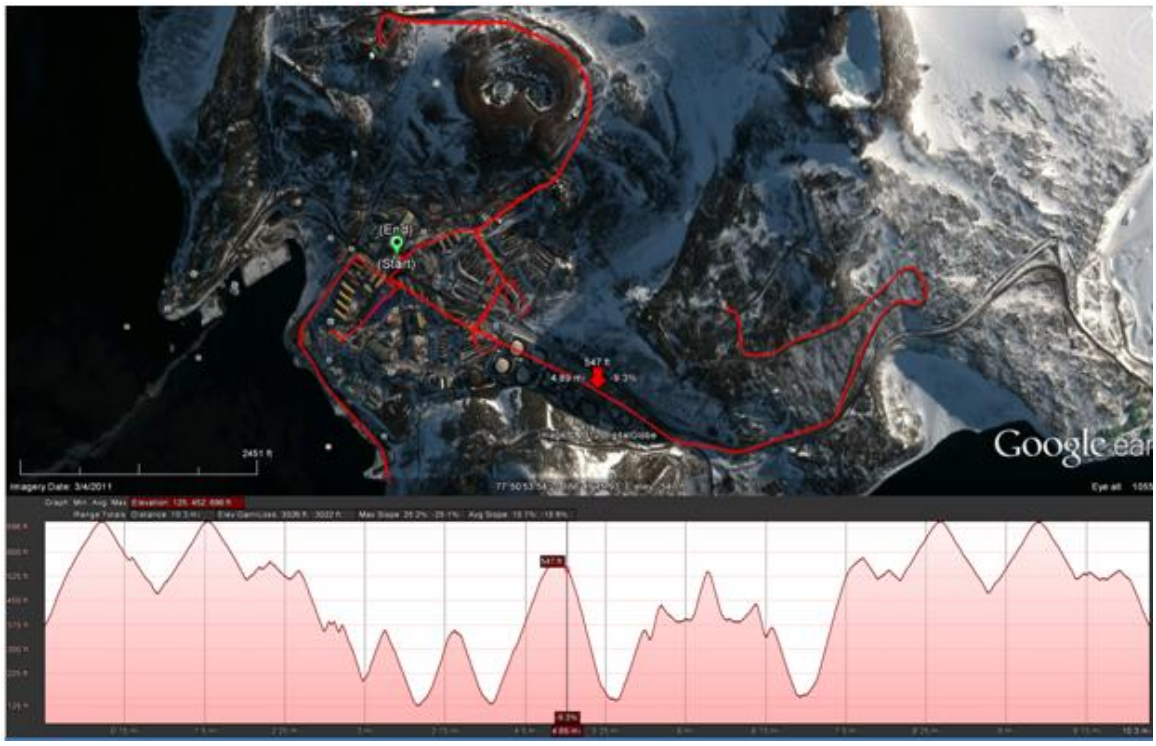

Figure 9. McMurdo in-town driving map with elevation profile.

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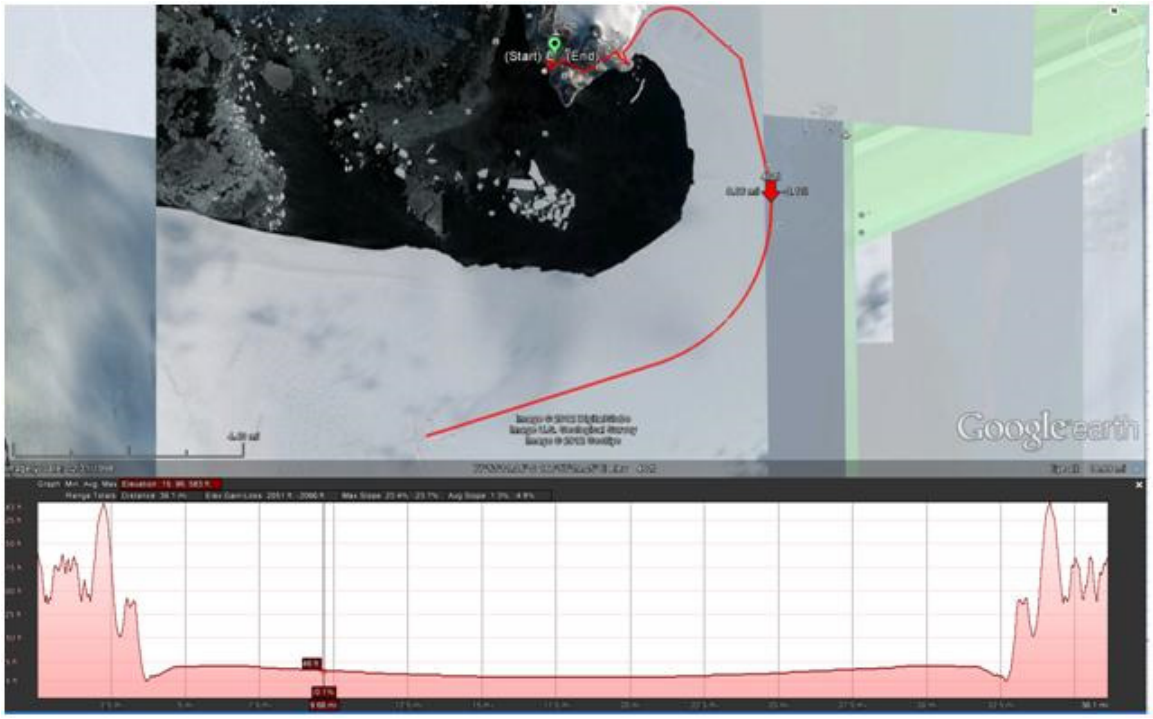

Figure 10. McMurdo snow road driving map with elevation profile.

4.3.2 Drive-Cycle Analysis – In-Town Vehicles

The EVs had an average driven speed spread that closely matched that of the conventional in-town vehicles, with both groups peaking at 9 mph, although the EVs did drop off more sharply after that than the stock pickups. See Figure 11. The lifted pickups had average speeds above 14 mph on 38% of the recorded days.

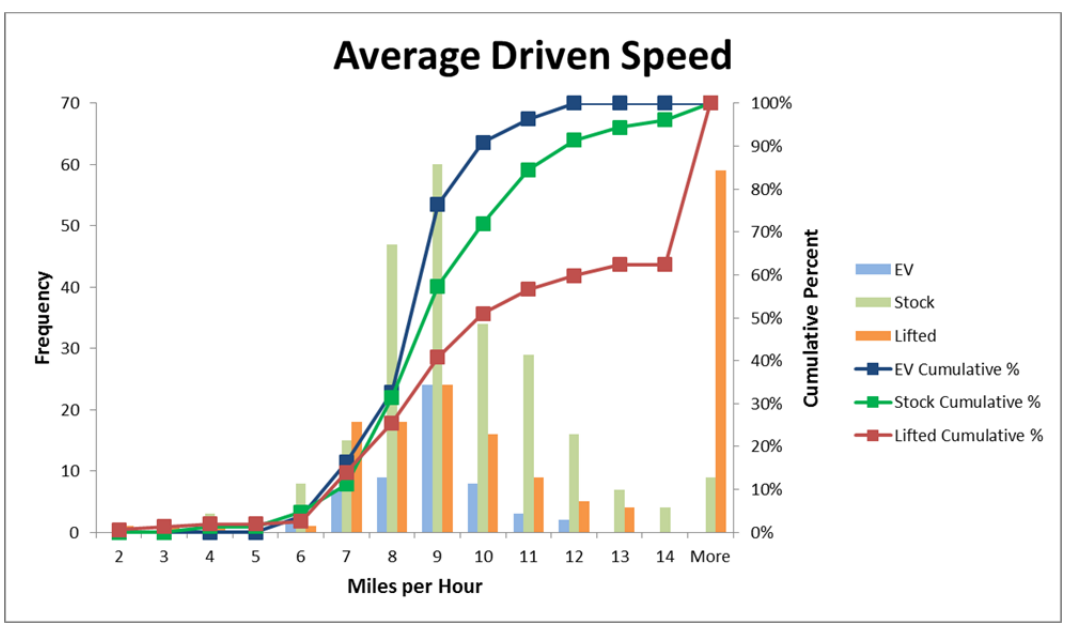

Figure 11. McMurdo average driven speed.

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The EVs had a maximum speed spread that also closely matched that of the stock pickup in-town vehicles. Both groups peaked at 20 mph, with 56% of EV days below that speed and 43% of stock pickup days below that speed. See Figure 12. This close matching of average driven speed and maximum speeds is largely driven by the slow speed limit and short distances available to drive in town at McMurdo. The lifted group by comparison only had 31% of days with a maximum speed of 20 mph or less.

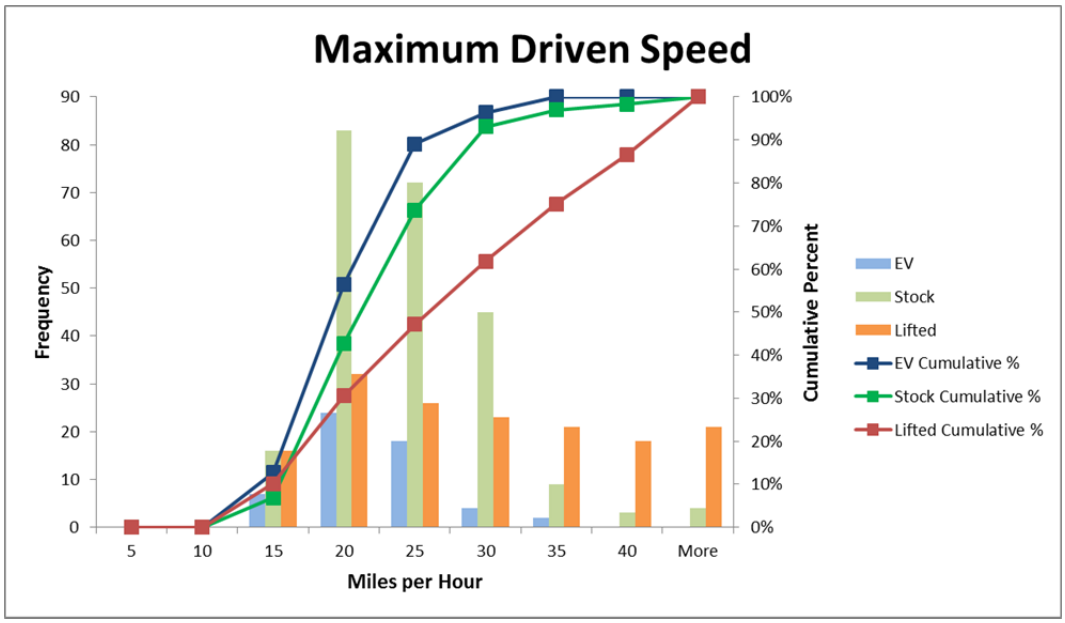

Figure 12. McMurdo maximum driven speed.

The EVs had a daily driven distance spread that again closely matched that of the conventional in-town vehicles, although they were biased slightly towards fewer miles. See Figure 13. Of note, 75% of days the stock pickups drove less than or equal to 10 miles, which the EVs demonstrated they were capable of with three days in the 10-mile bin and 1 day each in the 15- and 17.5-mile bins. Driver "range anxiety" may be lowering EV daily miles below their capability, and this could be addressed with driver training. The lifted group drove more than 30 miles on 32% of recorded days.

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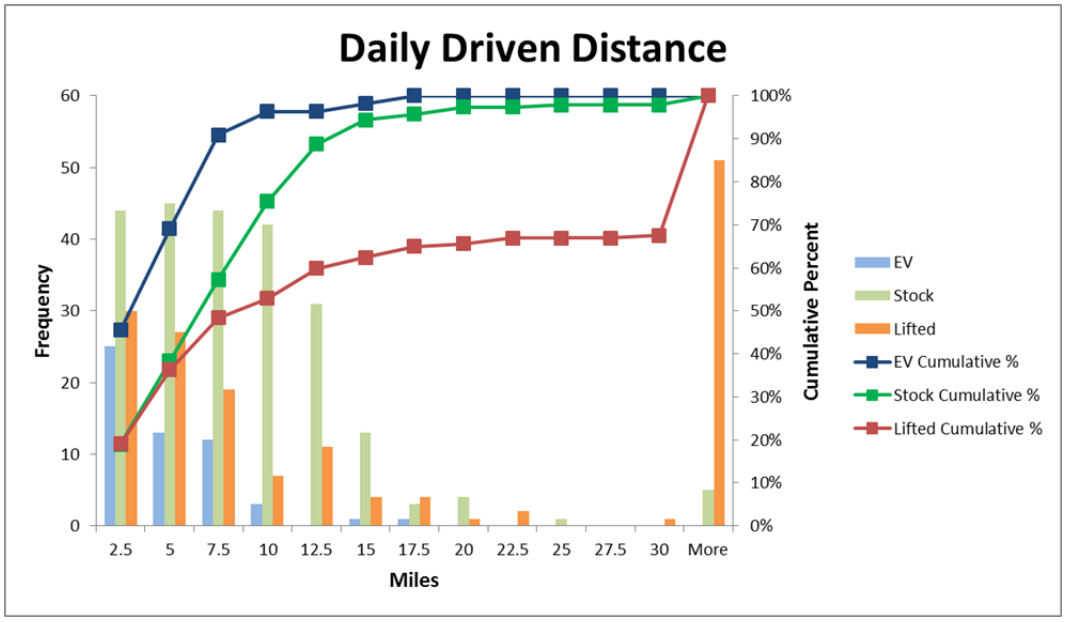

Figure 13. McMurdo daily driven distance.

The EVs had a kinetic intensity spread that once again closely matched that of the conventional in-town vehicles. See Figure 14. This shows that the EVs are able to drive with similar stop-and-go dynamics currently demonstrated by the V8-powered pickup trucks in town. Because the lifted vehicles drive longer distances at more constant speeds, they are biased towards lower kinetic intensity.

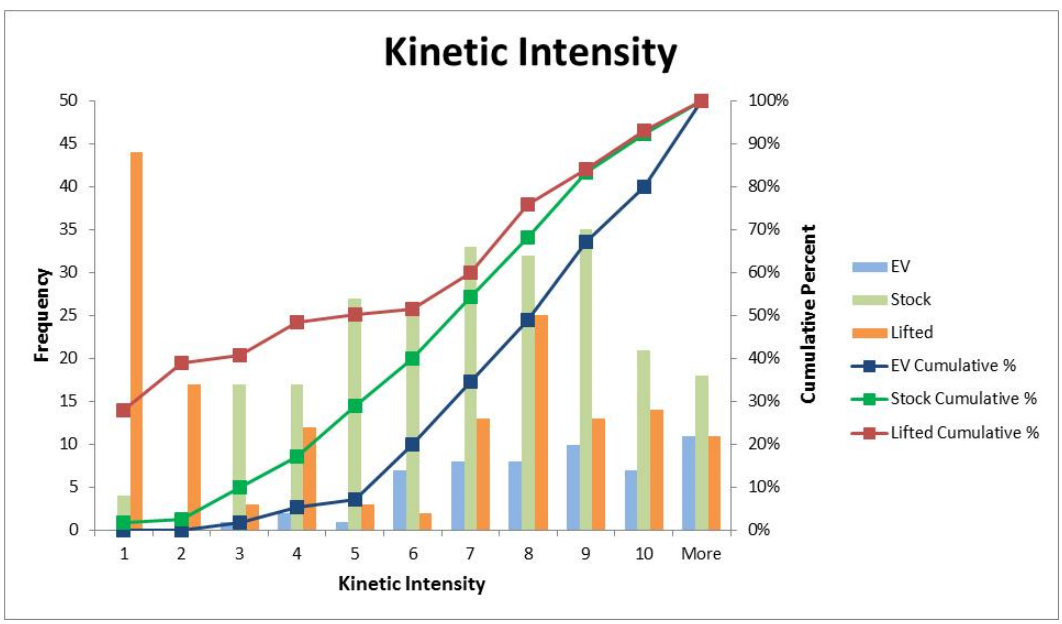

Figure 14. McMurdo kinetic intensity.

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Additionally, in-town vehicles make many short trips with short or moderate stop durations that could be charging opportunities for EVs if they were widely deployed in the future to replace the conventional trucks. Figures 15 and 16 show stop durations of less than 1 hour and more than 1 hour, respectively. The in-town vehicles mostly made 6–18-minute stops in addition to many 1–2-hour stops that could be used to recharge an EV. In-town vehicles are largely used as errand runners and people movers, and these gasoline vehicles are plugged in when they are not driving or are left idling to maintain engine and battery temperatures.

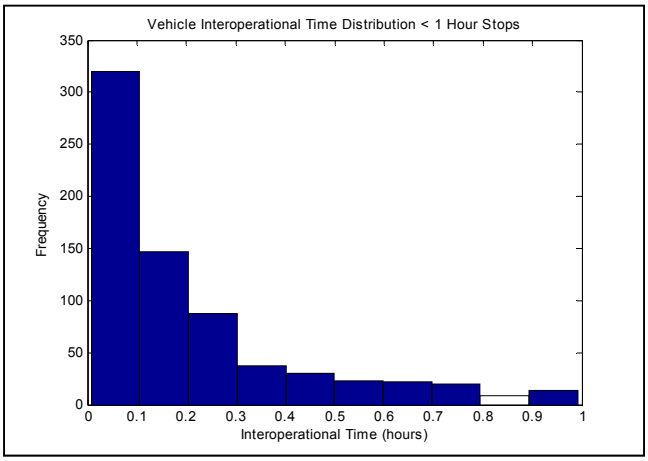

Figure 15. McMurdo stop durations less than 1 hour.

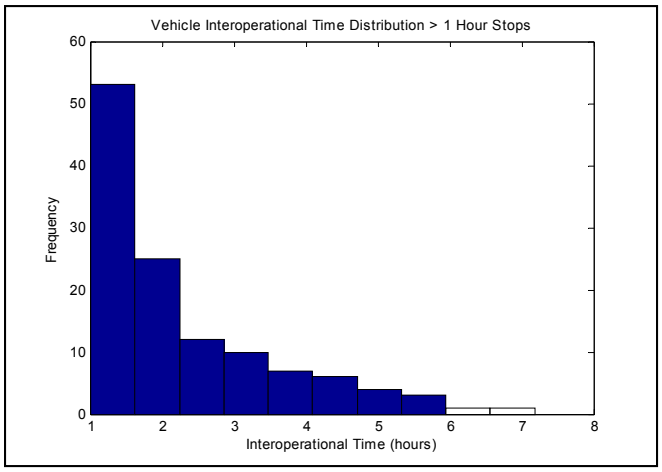

Figure 16. McMurdo stop durations greater than 1 hour.

4.3.3 Conventional In-Town Vehicle – Engine Speed and Load Distribution

The conventional pickups used only in town at McMurdo had very low engine speeds and loads for all driving, which makes it plausible that many of the tasks they perform could be accomplished by small EVs such as the e-ride EVs. See Figures 17 and 18 below. The V8 engines rarely exceeded 25% reported engine load even at higher road speeds for McMurdo. This indicates they are not carrying heavy loads and are not being asked to accelerate the vehicles very quickly. OBDII reported engine load percent is a calculation of current air flow divided by maximum air flow and correlates with percent torque.

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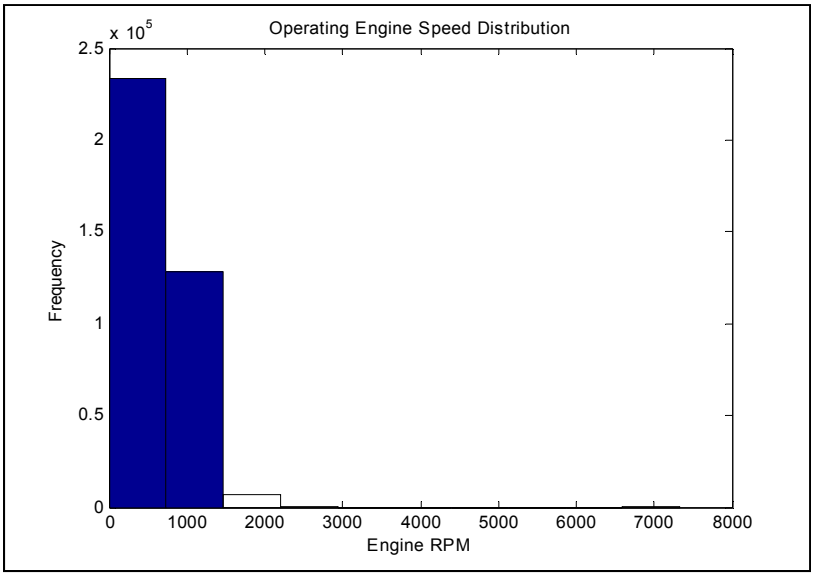

Figure 17. Stock in-town engine speed.

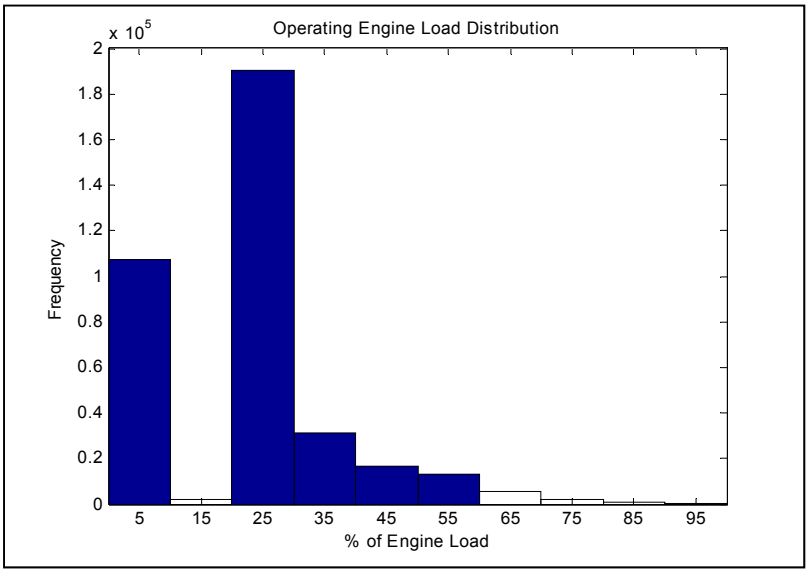

Figure 18. Stock in-town engine load.

Unit number 108, an in-town vehicle that was instrumented with an Isaac logger for the duration of the study, is used here as an example of one statistically typical day (Dec. 6, 2011) of the engine duty cycle. Figure 19 below compares vehicle speed to engine load. Note the significant period of time that the engine is on with the vehicle at zero speed, with the next grouping of points occurring in the 10–20 mph range—well within the capability of the EVs. Also note that while there are individual points above 60% load, the vast majority of the time engine load is in the 20%–30% range.

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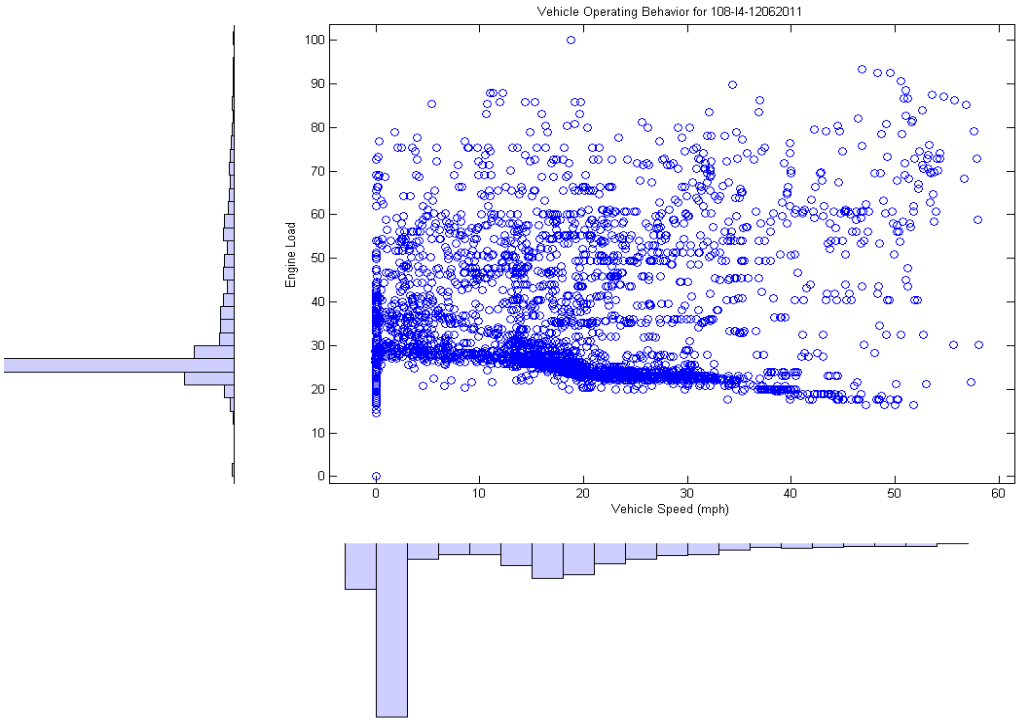

Figure 19. Vehicle speed vs. engine load.

Figure 20 below compares engine speed to engine load. Note the significant density of points between idle and 1,000 rpm and below 40% engine reported load. There are excursions to higher load, but these are likely momentary hard accelerations that are not required for the vehicle to complete its mission.

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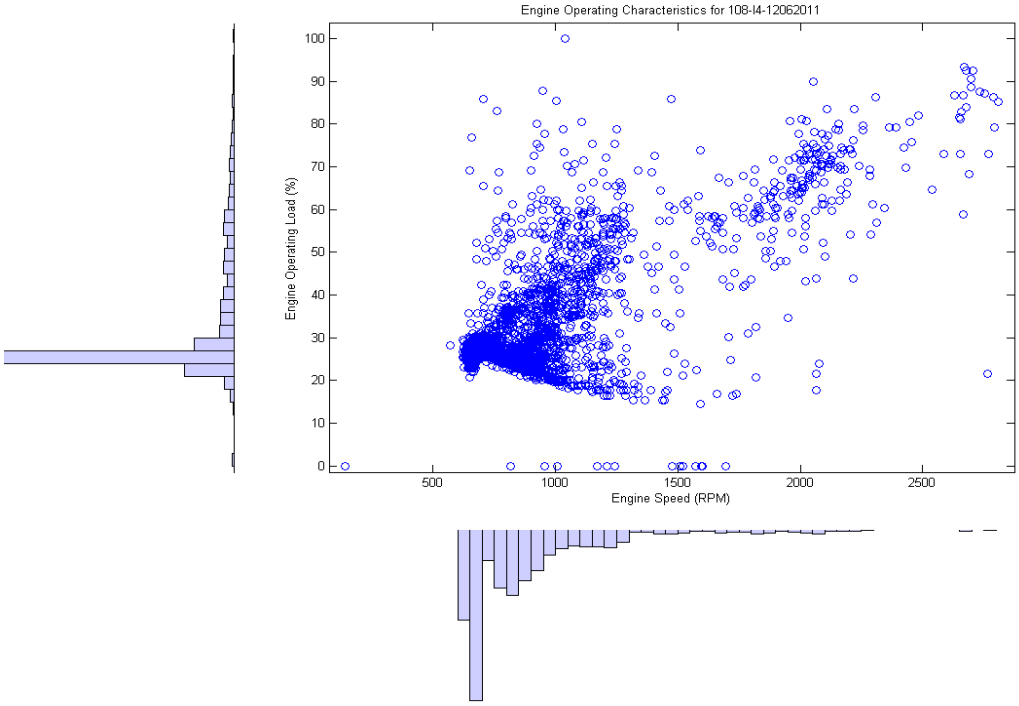

Figure 20. Engine speed vs. engine load.

Figure 21 below compares engine speed to engine mass air flow, which relates to fueling on these stoichiometric engines. Note again that the density of points is at low rpm and low air flow, indicating that the driver is not opening up the throttle to request additional power from the engine.

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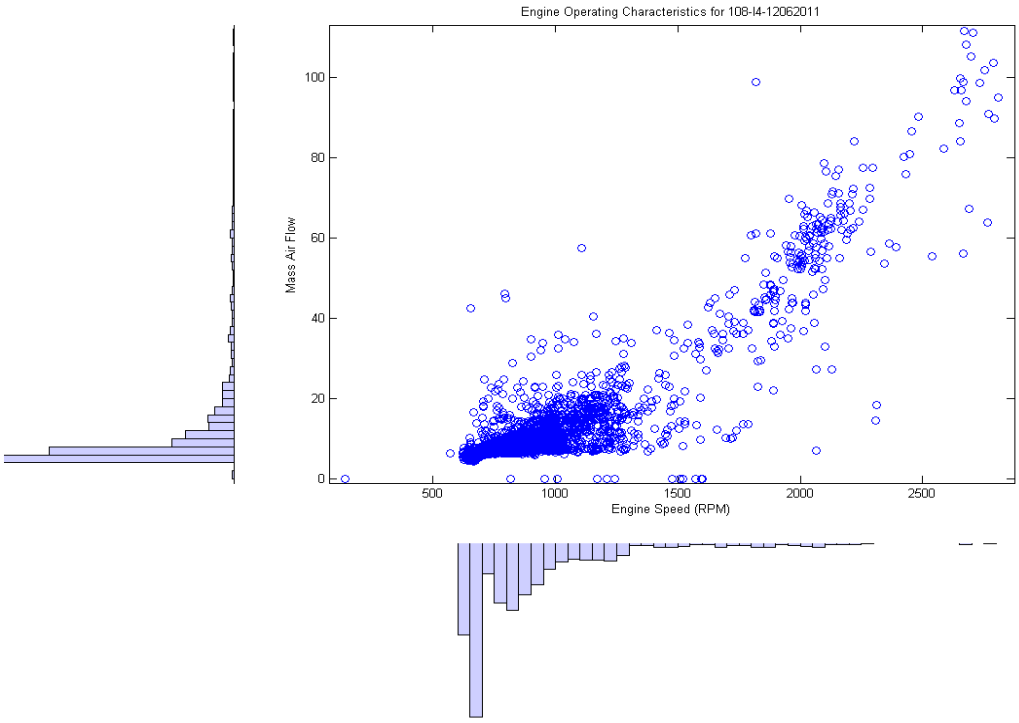

Figure 21. Engine speed vs. mass air flow.

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Figure 22 below compares engine load, vehicle speed, and GPS-reported elevation over the course of the day. The vehicle is basically driving up and down a 600-foot hill with varying dwell times at each location. During the first two round trips, the vehicle is idled for periods of time at the top of the hill. On the third trip the vehicle is shut down for a longer stay. Between these trips the vehicle is also shut down and not in use—opportune times for charging an EV to extend range as opposed to times when the conventional vehicle is likely plugged in only to keep the engine warm. GPS reported elevation error can be seen during all periods without vehicle motion; GPS system elevation reporting is not as accurate as position.

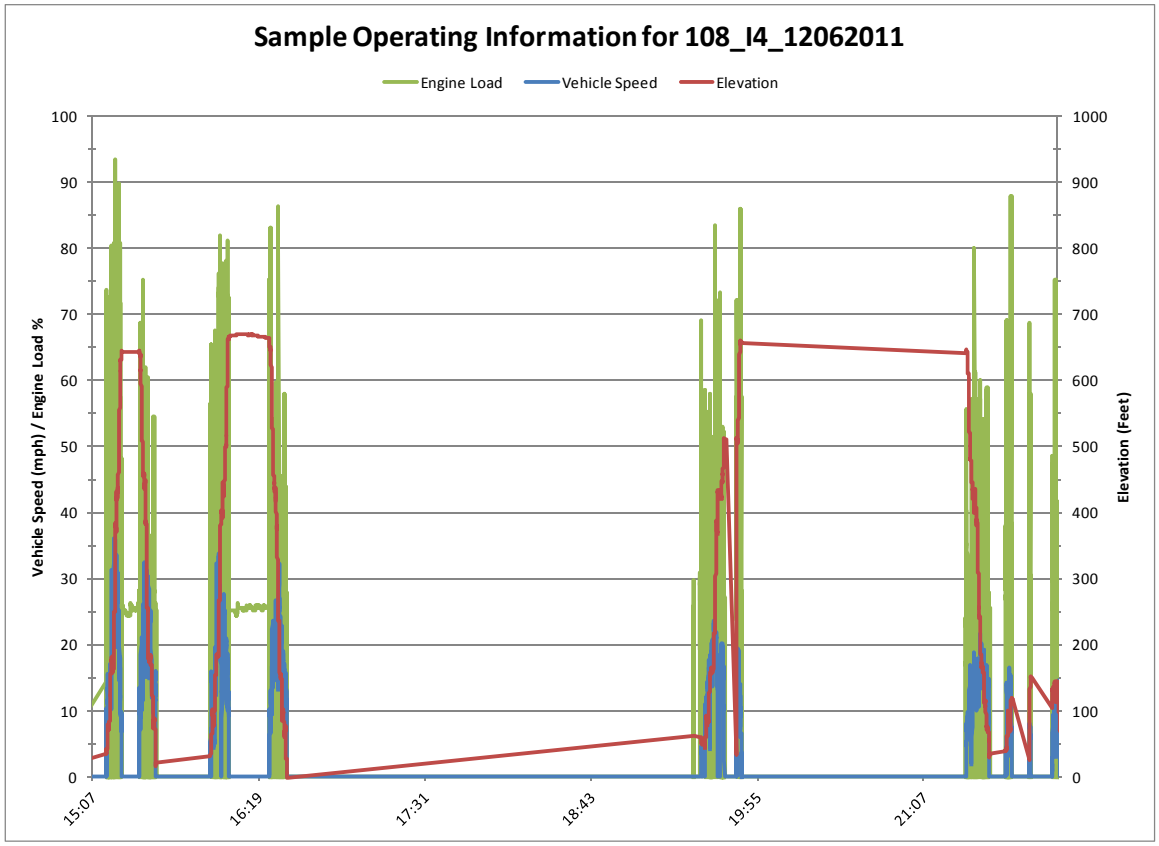

Figure 22. Engine load, vehicle speed, and elevation over the course of a day.

4.3.4 Snow Road Data Analysis

The lifted vehicles on the snow roads had twice as high average driven speeds as vehicles in town. All vehicle groups operating in town had roughly the same average speed distribution. See Figure 23.

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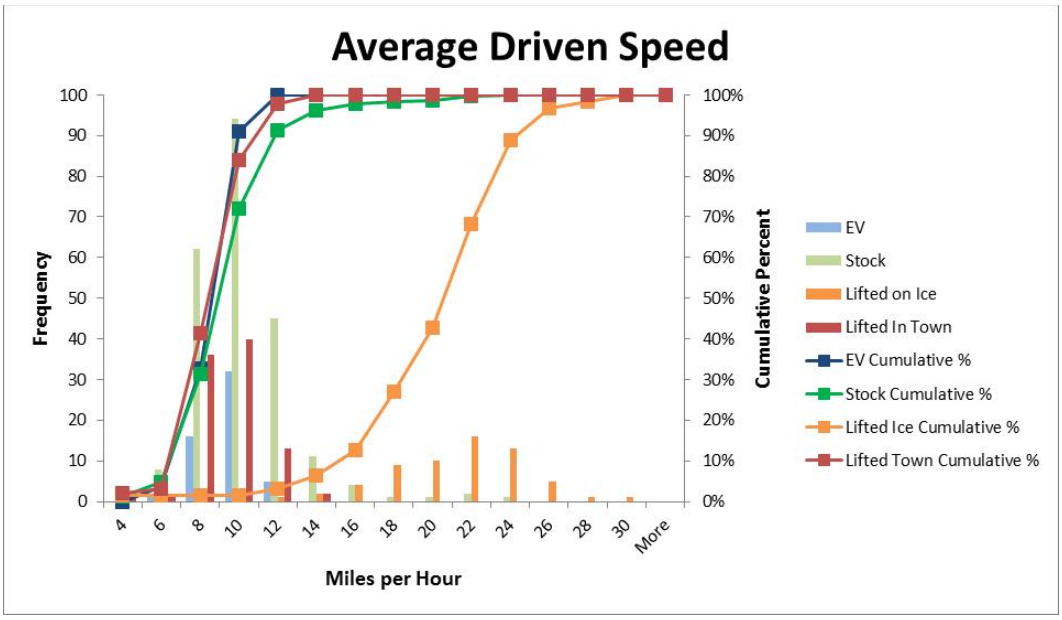
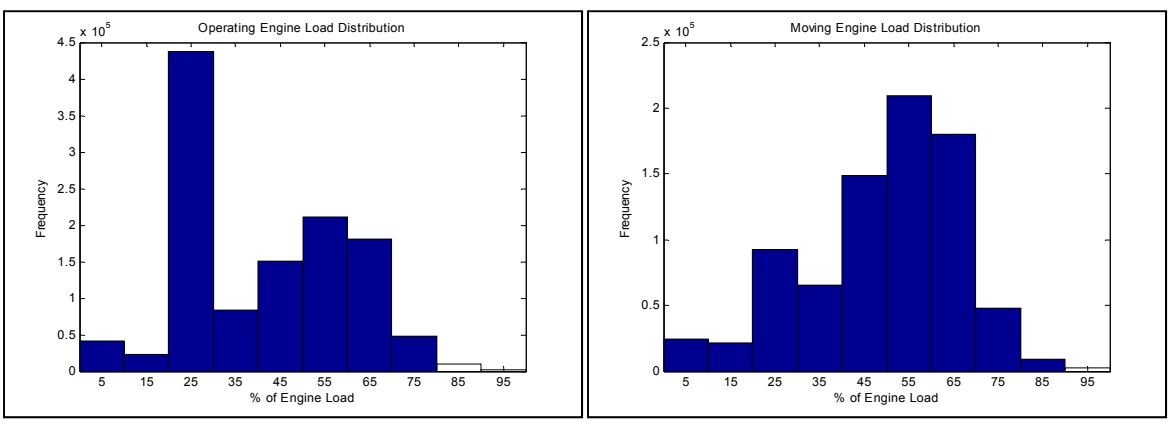


Figure 23. Average driven speed.

The lifted vehicles on the snow roads demonstrated higher engine loads than vehicles in town, spending much more time in the 45%–65% range. See Figure 24 for the operating engine load distribution and Figure 25 for the moving engine load distribution. Note the high occurrence of 25% load in Figure 24, indicating the vehicle is idling while the vehicle is stationary.



Figures 24 and 25. Operating engine load and moving engine load.

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Figure 26 shows the lifted vehicles operating in town. Note the dominance of 25% load, indicating the vehicle is idling much of the time. The 5% load column includes 0% and occurs when the vehicle is going downhill or slowing down.

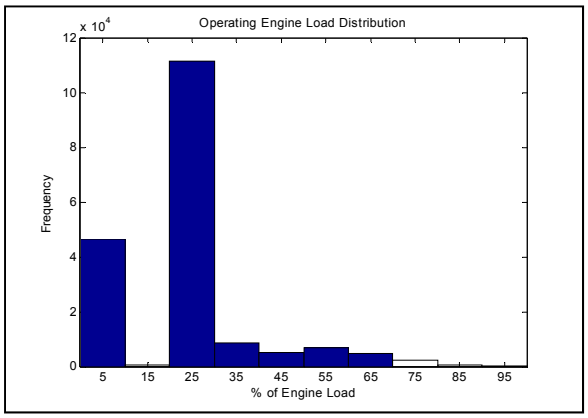
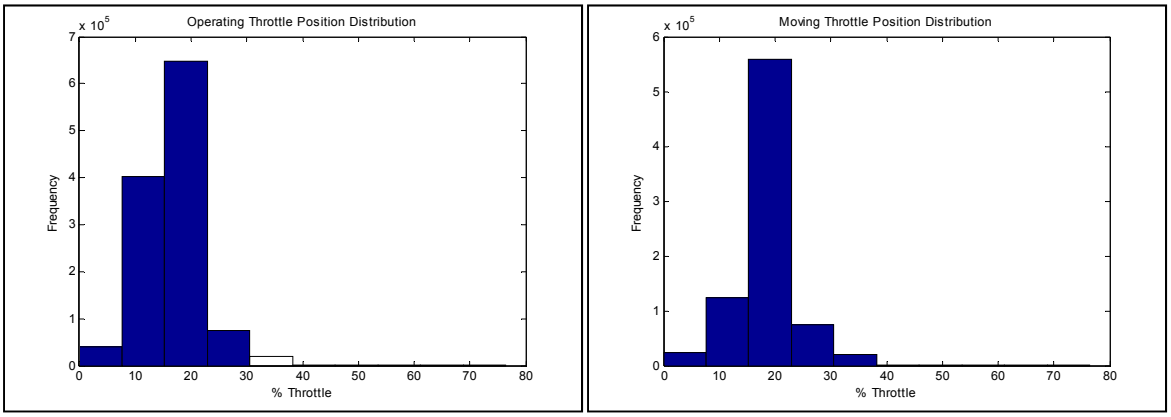


Figure 26. Lifted vehicles' in-town engine load.

Figures 27 and 28 show the lifted vehicles' throttle position throughout all operation and throttle position only while in motion, respectively. Again, idling is evident in Figure 27, but also note that even these vehicles rarely see high throttle demand from the driver, as it rarely exceeds 40%.



Figures 27 and 28. Lifted vehicles' operating engine load and moving engine load.

The higher average driving speeds, longer daily trips (miles), and higher engine loads all indicate these vehicles are not obvious candidates for replacement with small EVs. An additional challenge is the need for flotation tires and four-wheel drive to operate on the snow roads when they are not in pristine condition. The EVs could be considered for dedicated airfield use, but the airfield duty cycle was not independently analyzed. With a dedicated lane in good condition on the snow roads, the light-duty EVs might be able to perform that task.

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4.4 Costs to Operate

4.4.1 Electricity Use by Conventional Vehicles

Engine and battery heater electricity consumption data from one gasoline-powered light-duty truck and one light-duty van were collected when parked for extended periods of time. The data were gathered to enable a comparison of the electrical usage of the existing light-duty truck fleet (pickups and vans) to that of the EVs tested. A Watts up? .Net line plug load meter provided by Think Tank Energy Products, Inc. was used to collect power use from Truck 146 and Van 410.

Truck 146 consumed on average 750 W, and Van 410 consumed on average 1,790 W. Based on an electricity cost of $0.16/kWh, the monthly cost to use electricity to keep an engine and battery warm in a conventional vehicle that is plugged in 50% of the time is calculated as follows to be at a minimum:

Truck 146: 750/1,000 KW * $0.16/kWh * 12 hours * 30 days = $43.2/month

Van 410: 1,790/1,000 KW * $0.16/kWh * 12 hours * 30 days = $103.1/month

These values are considered to be conservative because during normal duty cycles, many of the vans and light-duty trucks are plugged in and drawing electricity more than 50% of the time, especially in colder months.

By comparison, the EV battery heater uses 480 W and is assumed to be on 12 hours/day. Thus, the monthly cost to heat an EV's batteries and passenger compartment prior to use is approximately:

480/1,000 KW * $0.16/kWh * 12 hours * 30 days = $27.6/month

4.4.2 Conventional Vehicle Fuel Cost per Mile

The fully burdened price of diesel and gasoline as dispensed at McMurdo is approximately $6/gallon. Typical pickup trucks might have a 15 MPG rating in warm climates, after 15 minutes or more for the engine to warm up. It was learned that the pickup trucks are believed to achieve 6 MPG or more at McMurdo due to the cold temperatures, short trips of 3 minutes or less, and excessive idling to keep the vehicle and cabin warm. Assuming this value:

($6/gallon)/6 MPG = $1/mile

This is in contrast to the EVs' rating of $0.11/mile, which is almost a factor of 10 less.

4.5 EVs in Context of McMurdo Conventional Fleet Analysis

Analysis of 440 recorded days of stock conventional vehicles, lifted conventional vehicles, and EV operation suggests that many of the tasks stock vehicles do in town may be successfully completed by the EVs. Vehicles restricted to in-town use were used similarly to the EVs in town, making replacement by EVs in the future a real possibility. EVs matched the stock conventional trucks in town on metrics including average driven speed, average maximum speed, average stops per mile, and average and maximum kinetic intensity. The conventional trucks averaged more daily miles, but the EVs demonstrated the ability to drive the miles recorded on 75% of the

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conventional days. Range anxiety may inhibit EV users from using the full capability of the vehicles but may be addressed through driver training to get the most out of the EVs.

Engine OBDII communications data show the in-town use of the conventional trucks was dominated by low engine speeds and loads, indicating they were not heavily laden with equipment but rather being used primarily to transport people and hand-carried equipment, which the EVs would be capable of. In addition, the conventional vehicles are plugged in to maintain engine and battery temperature more than 50% of the time, and this is energy that might otherwise be used to power EVs. Costs associated with electricity used to keep batteries and engines warm in the conventional vehicle fleet as well as the fuel costs for the conventional vehicles supports expanded deployment of EVs at McMurdo. Future replacement of more stock gasoline-powered trucks by small EVs should be considered.

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5 Conclusion

Vehicles restricted to in-town use were used very similarly to the EVs in town in terms of route and cargo loads, making future replacement of these vehicles at McMurdo by EVs a real possibility. EVs matched the stock conventional trucks in town on average driven speed, average maximum speed, average stops per mile, and average and maximum kinetic intensity. The conventional trucks averaged more daily miles, but the EVs demonstrated the ability to drive the miles recorded on 75% of the days that conventional vehicles typically logged as part of their duty cycle.

The data show that the EVs are inexpensive to use at McMurdo compared with conventional vehicles of similar duty cycles, and primarily in the warmer months in Antarctica, when the personnel population at McMurdo is higher. This is especially the case because most of the vehicle trips are 3 minutes or less. The low cost to operate the EVs should be balanced with the cost and effort to replace batteries for the EVs on the current vehicle model.

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6 Next Steps

Additional efforts and examination of other battery chemistries can help identify the most suitable EV models and types. Testing other vehicle designs and/or battery chemistries would improve the capability to determine the best replacement vehicle options. For example, new lithium batteries are estimated to double the miles/time between charges.

Because of improvements in battery technology and the availability of new battery chemistries with e-ride Industries EVs, it is recommended that next steps might include:

- Shipping the two EVs at McMurdo in 2014 to e-ride Industries to replace the existing battery packs with upgraded lithium battery packs, which would allow for direct comparison with the lead acid battery packs used in this study (or simply replace with the same lead acid battery pack products)
- Purchasing two new-generation e-ride Industries EVs
- Installing a new and simpler data collection/monitoring systems package
- Shipping all four vehicles to Port Hueneme by August 2014 and then all four vehicles to McMurdo either by special shipment for Winfly or Mainbody or on the 2014–2015 vessel to be added to the vehicle fleet the following season
- Collecting more refined data on both the electricity used to heat the light-duty conventional fleet's engines and batteries, and the fuel used to idle these vehicles for the purpose of keeping the engines and batteries warm and operational
- Examining the broader overall costs associated with transporting fuel for the light-duty conventional fleet to McMurdo and the emissions associated with both the transport of the fuel and the use of the fuel in Antarctica.
- Developing data necessary to calculate a robust return on investment associated with replacing specific conventional vehicles with EVs.

Taking these steps can help advance the transition of the McMurdo light-duty conventional vehicle fleet to a more efficient future with a smaller GHG footprint in terms of reducing both vehicle emissions and the need to import fuel for the vehicle fleet.

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Appendix A: EV Operator Feedback Form

E-Vehicle Feedback Survey Form

Driver Name: _____

Date: _____

Questions on Vehicle Use:

1. Start Mileage: _____
2. Start Time: _____
3. Battery Charge level at start: _____ percent
4. Destination/Tasking: _____
5. Load? If yes, briefly describe: _____

_____

6. Any comments on vehicle operation and functionality for task or problems given road conditions (if yes, please describe issues and/or weather/road conditions as appropriate):

_____

_____

_____

7. End Mileage: _____
8. End Time: _____

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Appendix B: EV Maintenance Logs

EV-001

WO #	EQP #	PROBLEM DESCRIPTION	COMMENTS	DATE CLOSED	LBR HRS	MATERIAL COST
H660139	ET00001	SUPPLY PARTS ONLY	NO LABOR, PARTS ONLY. SUPPLIED CHOCK.	2/19/2011	0	23.99
H689424	ET00001	DRIVER'S DOOR DIFFICULT TO CLOSE AND LATCH.	REPLACED LATCH AND ADJUSTED STRIKER. PM SCHEDULE PERFORMED ONCE PER YEAR, NOT TIED TO HOUR METER.	12/28/2011	12	147.49
H695434	ET00001	STICKING THROTTLE PEDAL.	TROUBLESHOT THROTTLE ISSUES. FOUND NO ERROR CODES, NO BREAKS OR CROSSED WIRES IN HARNESS. TEST DROVE REPEATEDLY AND FOUND NO CONTINUING ISSUES. INSTALLED LED LIGHTS. RUNS ON MONTHLY/ANNUAL PM.	2/4/2012	18	283.57
H698858	ET00001	BATTERY CHARGER NEEDS REPROGRAMMING	PROGRAMMED BATTERY CHARGER AND THE SPARE ONE ALSO. REPLACED IN-DASH DISPLAY, DID NOT WORK, ORDERED NEW ONE. ACCELERATOR PEDAL SURGED WHEN PRESSED, REPLACED PEDAL ASSEMBLY, WORKS FINE.	2/24/2012	2	398
H701652	ET00001	PRE-SEASON CHECKS. [H1001]	COMPLETED PRE-SEASON CHECKS.	3/29/2012	24	3.15
H728173	ET00001	END GATE NEEDS 2-NEW BRACKETS. STRIKE ON DRIVER SIDE DOOR INOPERATIVE. CANOPY LID HYDRAULIC CYLINDER NEEDS REPLACED.	NO PARTS ZERO FILL. NEED TO FABRICATE STEEL TAIL GATE LATCHES FOR DURABILITY. MACHINE/ REPAIR TAIL GATE LATCH. WELDED ON GATE LATCHES. REMOVE LEAKING REAR LEFT SHOCK ABSORBER. REPLACED WITH SHOCK REMO	12/20/2012	4	0
H729719	ET00001	100 HR PM [05244]	PM JOB STEPS COMPLETED.	12/20/2012	1	0

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EV-002

WO #	EQP #	PROBLEM DESCRIPTION	COMMENTS	DATE CLOSED	LBR HRS	MATERIAL COST
H660138	ET00002	SUPPLY PARTS ONLY	PARTS ONLY. NO LABOR. SUPPLIED CHOCK.	2/21/2011	0	23.99
H661064	ET00002	DEFROST HOSE NOT ATTACHED UNDER DASH. BOLT THAT GOES INTO THE SUSPENSION ON RIGHT REAR SIDE IS LOOSE.	NO PARTS USED. REMOVED DASH TO REINSTALL DEFROST HOSES. TIGHTENED ALL BELTS ON REAR SUSPENSION.	3/1/2011	1.5	0
H691183	ET00002	REPLACE LIGHTS WITH LEDS. REPROGRAM BATTERY CHARGER.	NO PARTS USED. REPROGRAMMED BATTERY CHARGER. PM PERFORMED ANNUALLY, NOT TIED TO HOUR METER.	12/28/2011	10	0
H698859	ET00002	BATTERY CHARGER NEEDS REPROGRAMMING	NO PARTS USED. NO LABOR HOURS. WORK NOT PERFORMED BY VMF MECHANIC. REPROGRAMMED BATTERY CHARGER TO -25C.	2/24/2012	0	0
H701159	ET00002	PRE-SEASON SERVICE. [H1001] CHECK BATTERY. DRIVER'S SIDE DOOR NOT OPENING.	COMPLETED PRE-SEASON SERVICE. RE-SECURED RIGHT HAND SIDE MIRROR AND HEATER PLUG COVER. REPLACED LATCH CABLE ON DRIVER'S SIDE DOOR. REPOSITIONED LATCH CABLE ON BOTH DOORS TO PREVENT RUBBING ON WINDOW T	3/23/2012	10.5	0.29
H725323	ET00002	VEHICLE SUDDENLY STOPPED MOVING. POPPING SOUND HEARD BEFORE IT JUST STOPPED. MOTOR SOUNDS LIKE IT IS RUNNING BUT NO WHEELS ARE TURNING. AXLE?? SERVICE REQUEST SUBMITTED 17 JULY, 2012.	NO PARTS USED. DISASSEMBLED REAR END. FOUND SNAPPED SHAFT IN TRANSAXLE. NO PARTS, ZERO FILL. GAVE PART # TO MARK HUME. REASSEMBLED REAR END AND PUT ELECTRIC MOTOR IN CAB SO VEHICLE COULD BE MOVED. INSTALLED NEW GEAR/SHAFT ASSEMBLY IN TRANSAXLE AND REINSTALLED MOTOR AND AXLE IN VEHICLE. CONTROLLER THOWS ERROR CODE 37. REPLACED AC MOTOR CONTROLLER AND ERROR CODE IS GONE. PARTS BROUGHT DOWN BY KEN	2/14-15/2013	23	0

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Appendix C: Web Dashboard Plots

Vehicle 002 is shown first on the left. It was used considerably more than Vehicle 001. The McMurdo station manager was the primary user of Vehicle 001, while many people used Vehicle 002.

The order of the plots is the same as that presented on the website at http://antarctica.hemdata.com.

Charging	**Usage/Driving**
Average AC Energy In (http://antarctica.hemdata.com/vehicle/2/plotACEnergyInAvg/) AC Energy Per Charge Histogram (http://antarctica.hemdata.com/vehicle/2/plotWattsPerChargeCounts/) Charge Time Histogram (http://antarctica.hemdata.com/vehicle/2/plotChargeTimeCounts/) Charge Time vs. Month (http://antarctica.hemdata.com/vehicle/2/plotAverageChargeTimePerMonth/)	Daily Travel Time Histogram (http://antarctica.hemdata.com/vehicle/2/plotDrivingCounts/) Daily Number of Trips (http://antarctica.hemdata.com/vehicle/2/plotTripsPerDayCounts/) Use / Day vs. Month (http://antarctica.hemdata.com/vehicle/2/plotCounts/) Average Drive Cycle Energy Usage vs. Month (http://antarctica.hemdata.com/vehicle/2/plotDCEnergyOutAvg/)
Battery and Temperature	**Energy Usage and Efficiencies vs. Month**
Ambient Temperature / Month (http://antarctica.hemdata.com/mcMurdo) Battery Capacity vs. Temperature (http://antarctica.hemdata.com/vehicle/2/plotBatteryCapacity/) Battery Temperature Histogram (http://antarctica.hemdata.com/vehicle/2/plotBatteryTempCounts/) Battery Temperature / Month (http://antarctica.hemdata.com/vehicle/2/plotAverageTemperaturePerMonth/) Average Battery % Before Charge / Month (http://antarctica.hemdata.com/vehicle/2/plotAverageEndTripChargePerMonth/) Battery % Before Charge Histogram (http://antarctica.hemdata.com/vehicle/2/plotEndTripChargePercentCounts/)	Electrical Efficiencies (http://antarctica.hemdata.com/vehicle/2/plotEfficiency/) Average Energy / Day (http://antarctica.hemdata.com/vehicle/2/plotEnergyPerDay/) Energy / Mile (http://antarctica.hemdata.com/vehicle/2/plotEnergyPerMileOld/) Energy / Hour (http://antarctica.hemdata.com/vehicle/2/plotEnergyPerHour/)

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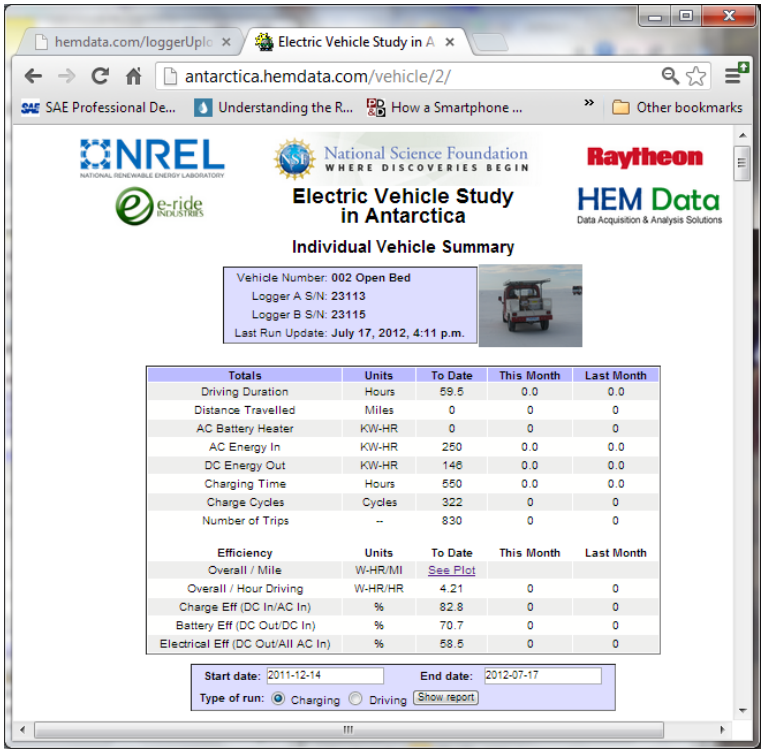
1.1.1 Summary Table

These data summarize each vehicle.

Vehicle 002

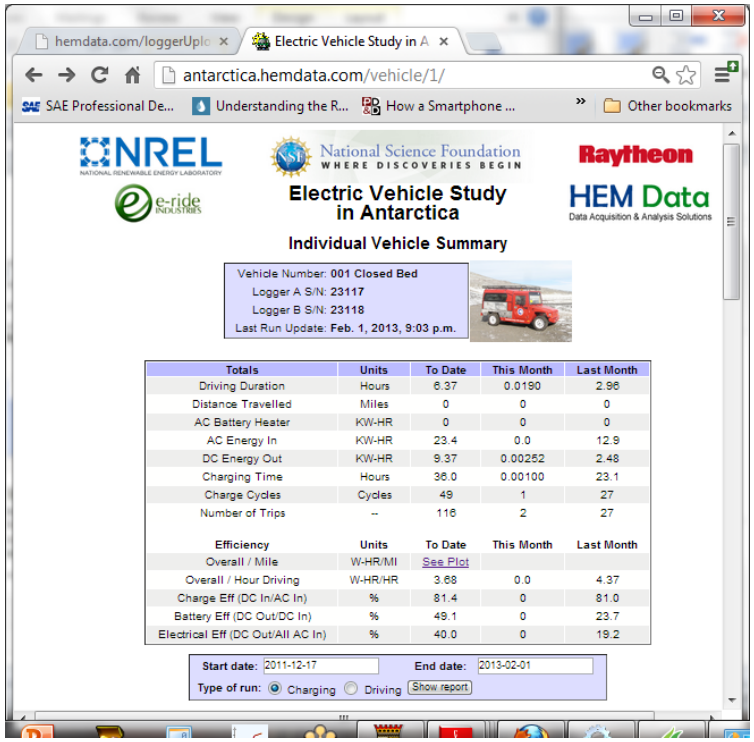


Totals	Units	To Date	This Month	Last Month
Driving Duration	Hours	59.5	0.0	0.0
Distance Travelled	Miles	0	0	0
AC Battery Heater	KW-HR	0	0	0
AC Energy In	KW-HR	250	0.0	0.0
DC Energy Out	KW-HR	146	0.0	0.0
Charging Time	Hours	550	0.0	0.0
Charge Cycles	Cycles	322	0	0
Number of Trips	--	830	0	0

Efficiency	Units	To Date	This Month	Last Month
Overall / Mile	W-HR/MI	See Plot		
Overall / Hour Driving	W-HR/HR	4.21	0	0
Charge Eff (DC In/AC In)	%	82.8	0	0
Battery Eff (DC Out/DC In)	%	70.7	0	0
Electrical Eff (DC Out/All AC In)	%	58.5	0	0

Vehicle 002 acquired 59.5 hours of driving through December 2012.
Energy/driving time is 4.2 Wh/hour of driving.
Charge efficiency is 83%.
Battery efficiency is 71%.
Electrical efficiency is 58%.

Vehicle 001



Totals	Units	To Date	This Month	Last Month
Driving Duration	Hours	6.37	0.0190	2.96
Distance Travelled	Miles	0	0	0
AC Battery Heater	KW-HR	0	0	0
AC Energy In	KW-HR	23.4	0.0	12.9
DC Energy Out	KW-HR	9.37	0.00252	2.48
Charging Time	Hours	36.0	0.00100	23.1
Charge Cycles	Cycles	49	1	27
Number of Trips	--	116	2	27

Efficiency	Units	To Date	This Month	Last Month
Overall / Mile	W-HR/MI	See Plot		
Overall / Hour Driving	W-HR/HR	3.68	0.0	4.37
Charge Eff (DC In/AC In)	%	81.4	0	81.0
Battery Eff (DC Out/DC In)	%	49.1	0	23.7
Electrical Eff (DC Out/All AC In)	%	40.0	0	19.2

Notice that only 6.37 hours were acquired on Vehicle 001. Vehicle 002 is the main source/vehicle for data. Comparisons to Vehicle 002 are made in this report.
Energy/driving time is 3.7 Wh/hour of driving.
Charge efficiency is 81%.
Battery efficiency is 49%. *The January 2013 data include 16 charges without a drive, causing this calculated inefficiency.*
Electrical efficiency is 40%.

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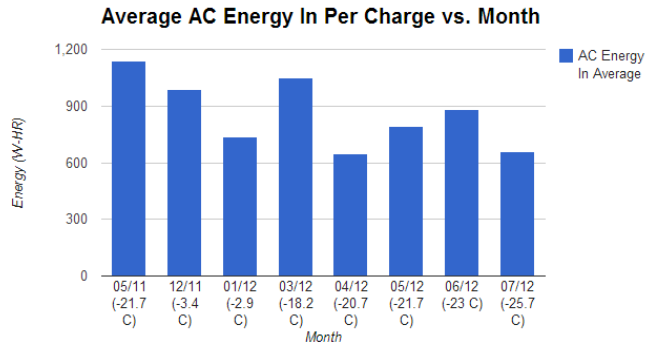
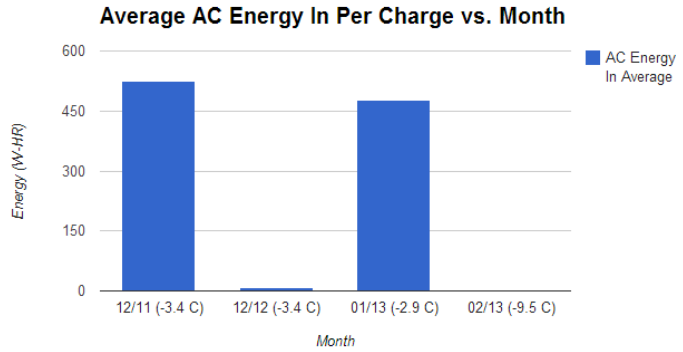
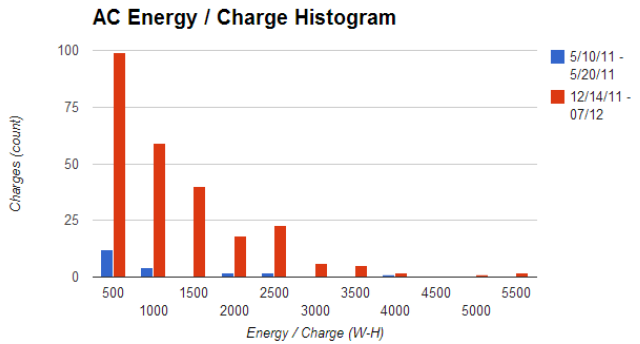
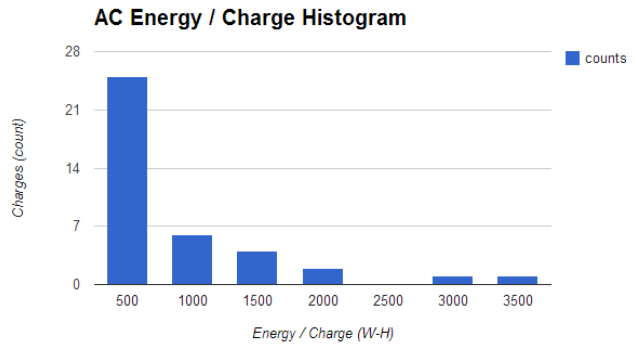
1.1.2 Charging Data

Vehicle 002	Vehicle 001
	
The average AC energy per charge is plotted vs. different months. Because the battery capacity is over 5,000 Wh, the graph shows that less than 25% capacity is typically used per day. The amount of AC energy in depends on the usage of the vehicle and heating of the batteries and cabin, so it can be quite variable from month to month. The range of values per month is 688–1,137 Wh.	Significantly less energy is being put into Vehicle 001. It is not clear whether this is because it is being charged more often or if the battery capacity is diminished.
	
The maximum battery capacity at 80°F is 6,745 Wh, and at 60°F it is 5,629 Wh. In the summer the batteries are typically warmed to 60°F (average), and up to a maximum of 80°F. The plot shows that the energy used between charges is less than 20% of the capacity in most instances. There have been some charges that were almost the entire capacity of the battery, but that seldom occurred. Battery temperature for winter averages 32°F. For both the warmer and cooler months, the frequency of AC charge energy decreased dramatically. See the plot of battery temperature / month at http://antarctica.hemdata.com/vehicle/2/plotAverageTemperaturePerMonth/.	The above plot has the same asymptotic shape as Vehicle 002, showing that the energy used between charges is less than 20% of the capacity in most instances.

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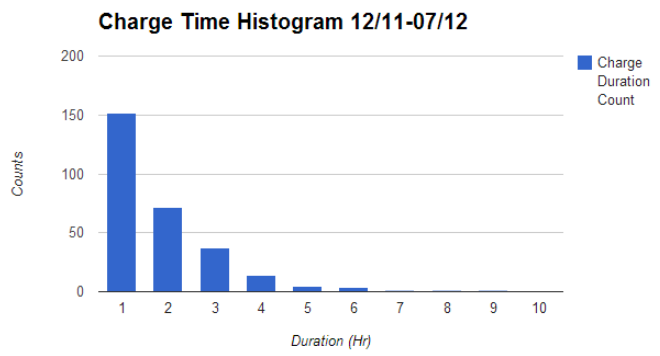
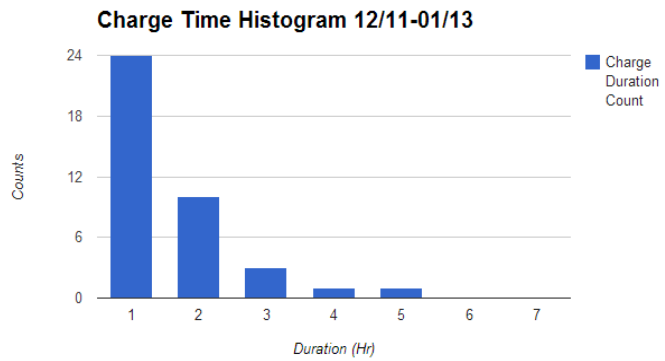
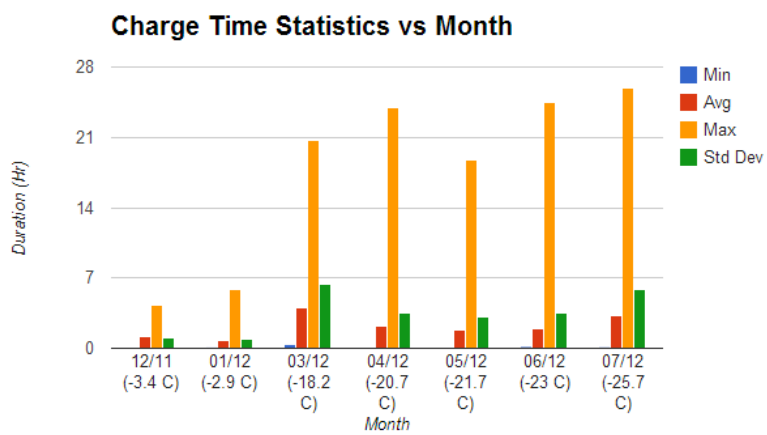
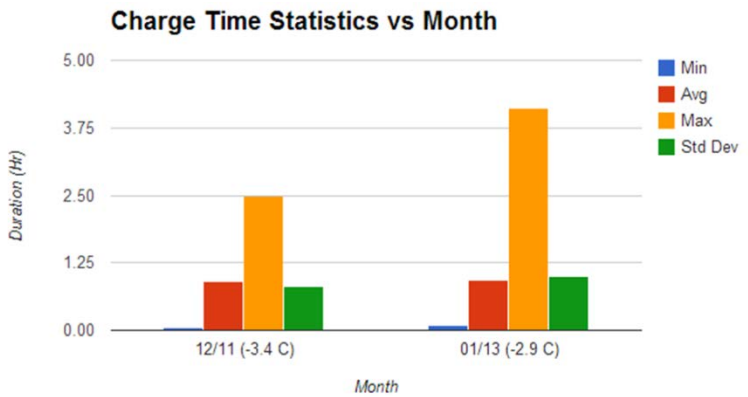




The time required to charge the battery for typical usage is less than 1 hour. For reference, a fully depleted battery takes 7 hours to charge. The plot shows the time for the actual charge, not the time plugged in.	Duration of charges is consistent between the two vehicles. Significantly less data exists for Vehicle 001.





The time required to charge the battery for typical usage is slightly more than 1 hour for most of the charges. For reference, a fully depleted battery takes 7 hours to charge.	Average charge time is slightly lower for Vehicle 001, but it was also used much less because it was driven mostly, if not solely, by the site manager, as described in Section 5.

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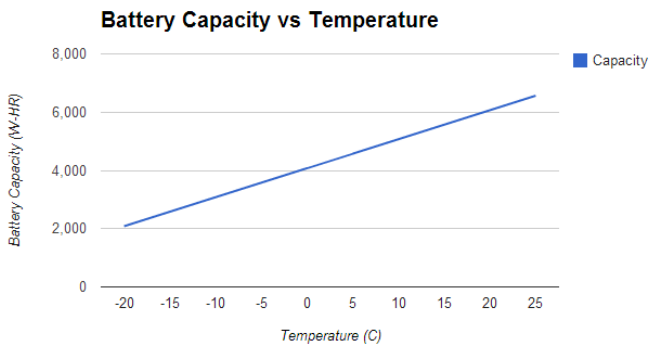
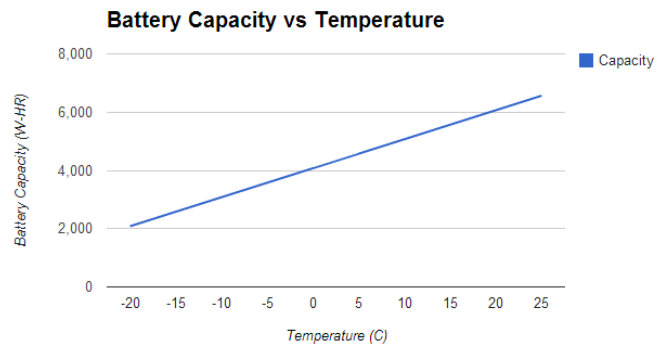
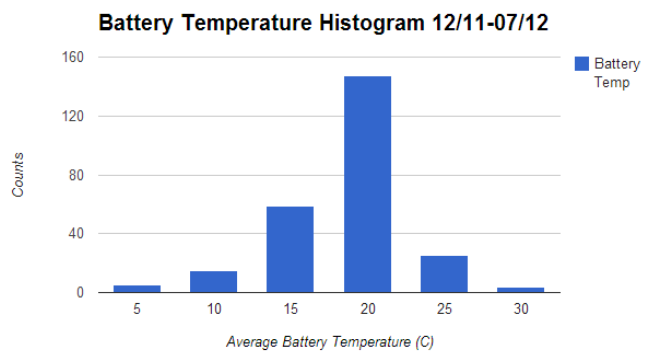
1.1.3 Battery and Temperature Data

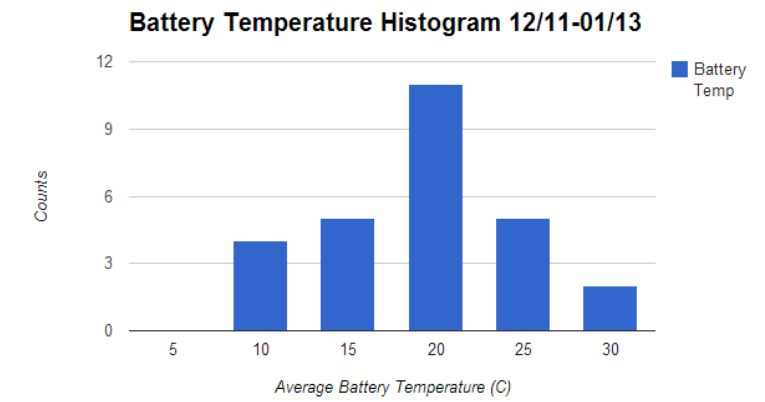




This plot regarding the temperature effect on battery capacity is based on information from the battery supplier. Because battery temperature is usually 15°C or higher, then the capacity should be 6,000 Wh or higher. Compare this to the Battery Temperature Histogram below. Occasionally the temperatures dropped below freezing, which can degrade the battery.

Battery capacity vs. temperature is the same for both vehicles because they have the same battery model.





During the warmer months, the battery heater kept the battery temperature close to 20°C. The battery temperature occasionally was at or below 10°C, but in most cases it was between 15°C and 20°C. The battery temperature is measured directly with a thermocouple.

The battery temperature profiles appear to be the same for each vehicle. Counts for Vehicle 001 are fewer because much less data were taken on Vehicle 001.

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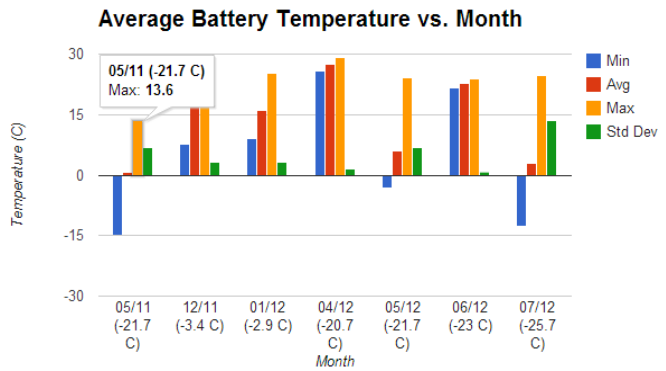	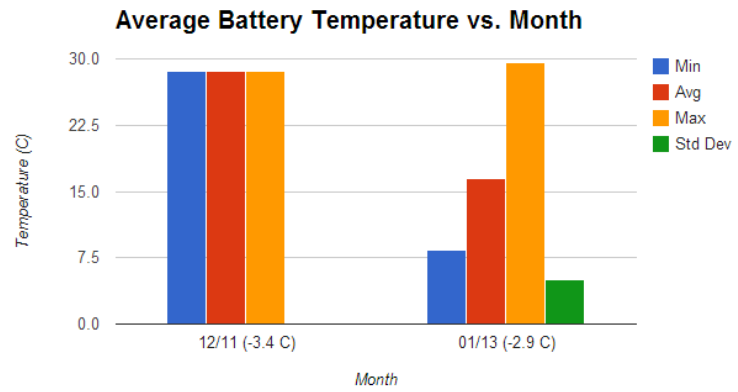
The average battery temperature is 16°C for warmer months of December through January. The lowest temperature was 7°C, and the highest was 29°C. The battery heater is designed to shut off above 27°C. The thermocouple reading of 29°C could be reading a couple degrees high, which is within tolerance of the measurement, or the heater could be shutting off at a higher temperature. The difference is likely due to the thermocouple accuracy. Importantly, the thermocouple appears to be providing reasonable temperature readings. Additional insulation should be considered because the heater is unable to keep the battery warm. A larger heater, however, will simply require more energy and will likely be counterproductive.	Data for Vehicle 001 show a consistent maximum, likely due to the heater. Minimum values are not as low because the data were only collected for warmer months.
For the colder months, the battery temperature is significantly colder—near freezing. This will significantly reduce the battery capacity from 6,187 Wh at 70°F (21.1°C) to 3,956 Wh at 30°F (-1.1°C), which is 64% of the 70°F capacity that is assumed to be 100% by the battery manufacturer. Batteries may have frozen in May 2011 and July 2012. In the warmer months, the temperature was less than 30°C (86°F).	

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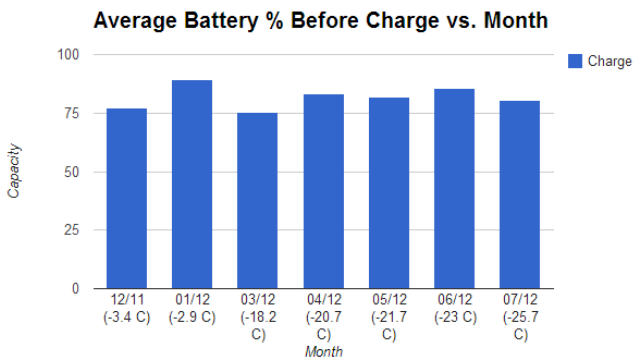
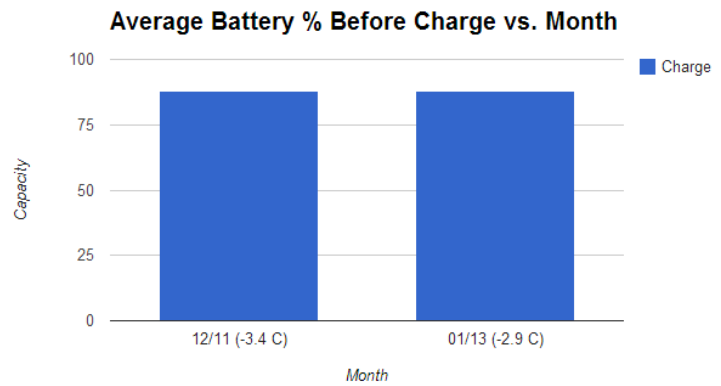
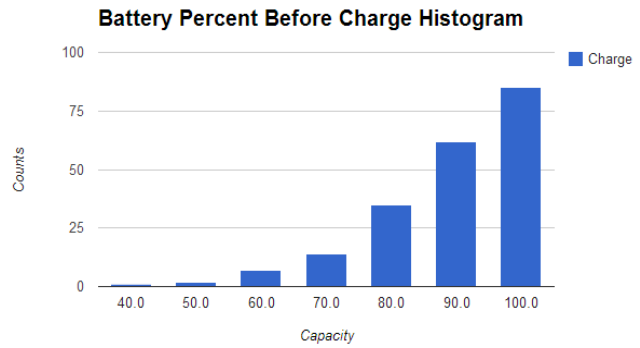
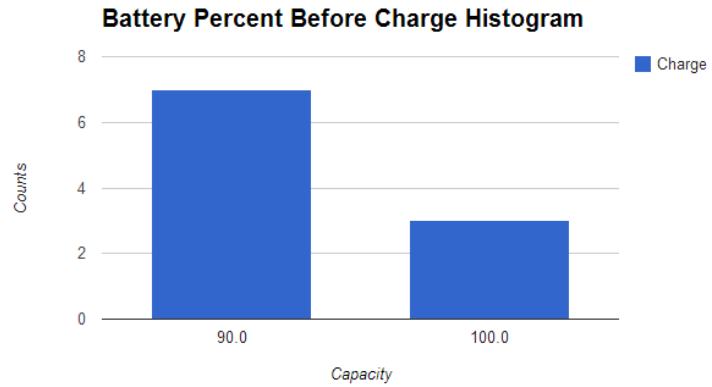
	
This plot shows that generally the battery is still well charged before it is recharged. The average capacity remaining was always 75% or higher, though this should be researched further to determine how often the battery should be recharged and the accuracy of these calculated percentages. The variation of capacity with temperature is taken into account. The plot shows that vehicles used more energy between charges in December than in January.	The results are consistent for both vehicles. This plot also shows that Vehicle 001 does not appear to be used as often as Vehicle 002.
	
This plot shows that in most cases the battery has a good deal of charge remaining at the start of recharging. The variation of capacity with temperature is taken into account based on Table 4. The plot also could be an indication that the battery capacity is declining, according to Figure 2.	The results are consistent for both vehicles.

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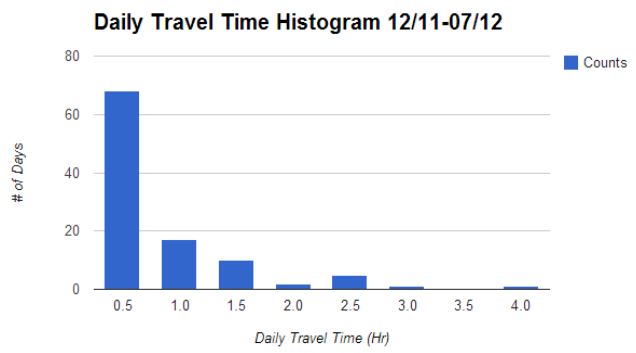
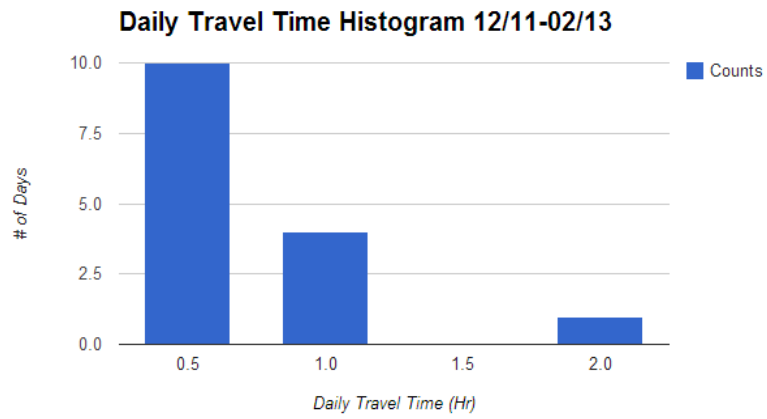
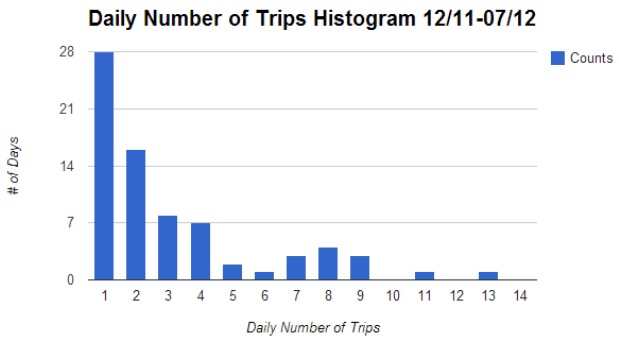
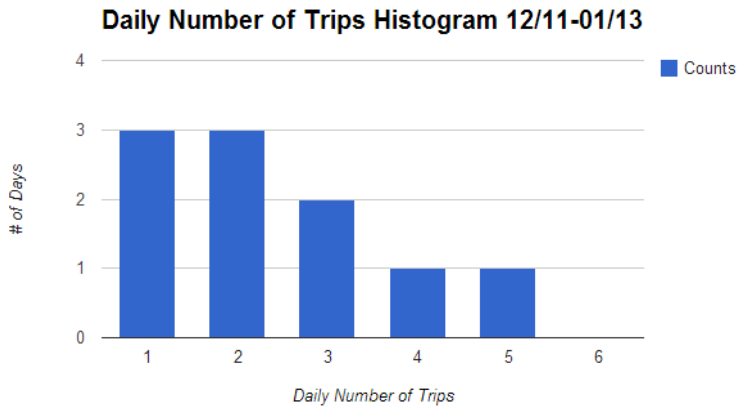
1.1.4 Usage/Driving

	
Most of the trips per day are relatively short in duration; the most frequent trip duration is less than 30 minutes. A trip is defined when the ignition is turned on and then turned off. This equates to the data file length/duration. Most of the trips were only a few minutes long because McMurdo work areas are fairly proximate to one another.	Daily trip duration is short for both vehicles.
	
The number of trips per day is quite variable, between 0 and 13. Number of trips equates to the number of trip files (non-charging files) generated.	Data regarding the number of trips are consistent for both vehicles.

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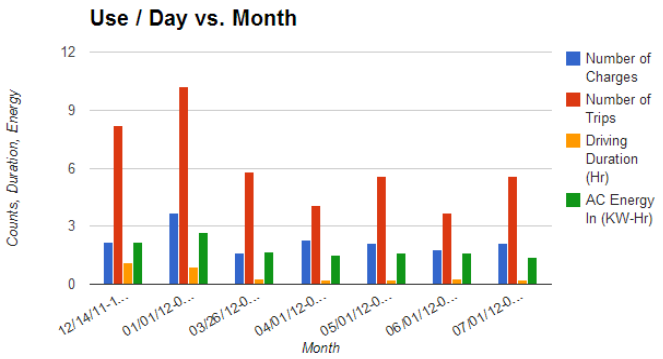
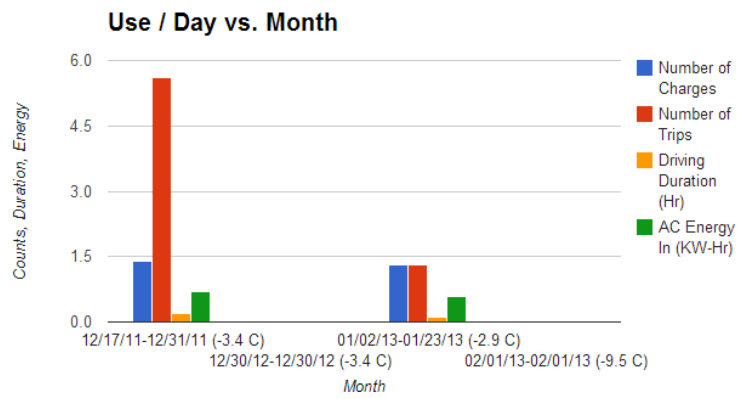
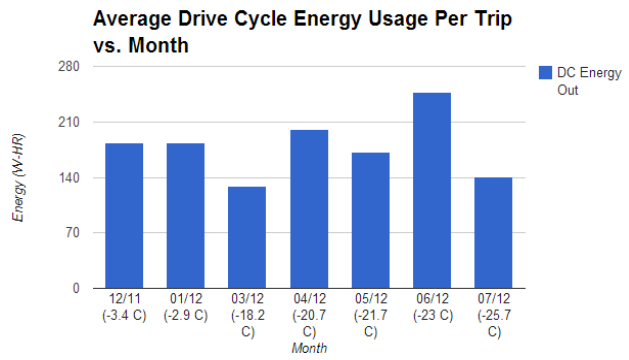
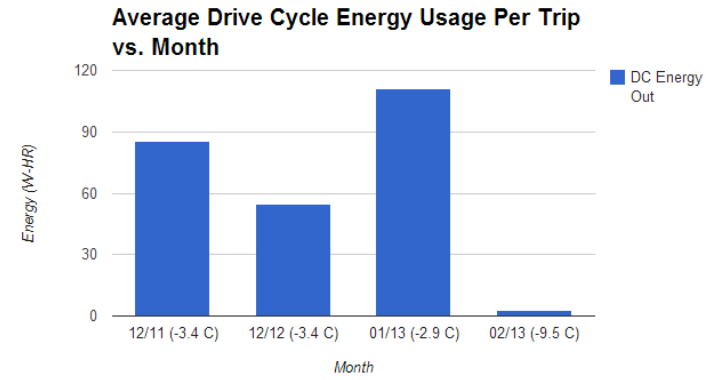




This plot shows that for the warmer months (December/January), the average number of daily trips was nine, while the number of charges was 2.8. For the colder months, the average daily trips dropped to five and the charges to two. The increase in AC energy consumed reflects the increased vehicle use in the warmer months.

Vehicle 001 was used less than Vehicle 002; however, the quantity of data is limited for Vehicle 001.





The average energy used per trip is less than 10%, likely because most of the trips were less than 30 minutes and often as short as 3 minutes. More average energy is used per trip when the ambient temperature is colder (627 Wh), as expected, due to the increased use of the DC 1,500 W cabin heater, lights, and a possible decrease in driveline efficiency stemming from increased friction.

Average energy used per trip is significantly lower for Vehicle 001. The station manager was the primary user of this vehicle, and his duty cycle is believed to be quite different from those using Vehicle 002.

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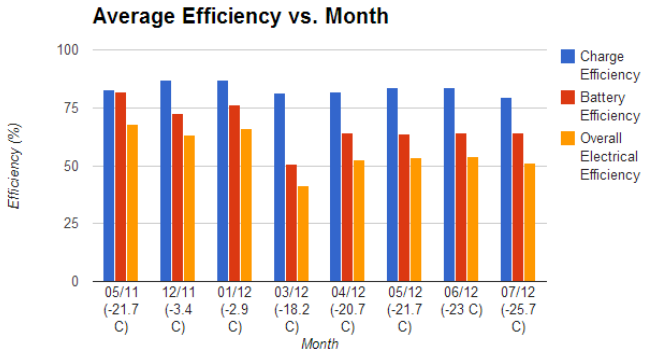
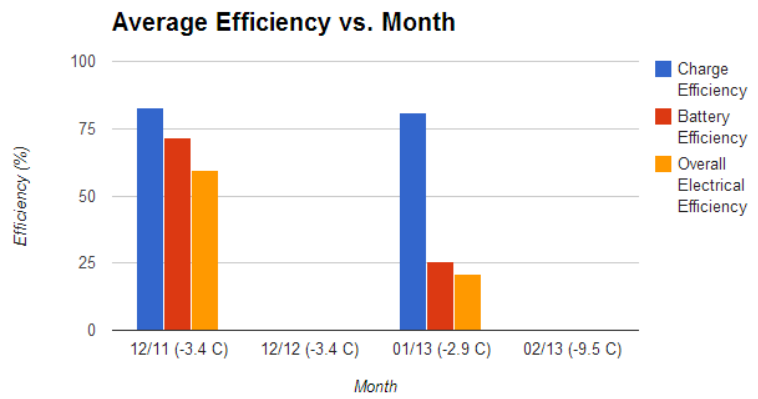
1.1.5 Energy Usage and Efficiencies vs. Month

	
The plot of the various electrical efficiencies show that: (1) for the warmer months, the charger efficiency is approximately 87%; and (2) the battery efficiency, which is the ratio of DC energy out divided by DC energy in, is approximately 75%. Multiplying these two efficiencies yields an overall electrical efficiency of approximately 65%. The efficiency of the driveline is not plotted here because it is not directly measured. It is included in the Wh/mile calculation.	The efficiencies for December 2011 are consistent with Vehicle 002. For January 2013, the battery and overall efficiencies are significantly lower for Vehicle 001. The collected data show that there were 16 charges before a trip was taken. There was much more energy in that energy out, resulting in a lower efficiency.
For the winter months, the ratio of AC energy in to DC energy in dropped from 86% to 83%, probably due to heating the cabin and to a lesser extent the decrease in the charger's efficiency. The same AC plug is used for charging the battery or heating the cab. When the DC in current is 0, but the AC current is non-zero, the cabin is being heated. The cabin heater is 1,500 W, so the AC current is 12.5A. e-ride Industries previously measured the charger efficiency to be 95% under 70°F conditions. The charger manufacturer specified the charger to work to -30°C but notes some degradation in performance is possible.	
The DC out to DC in (battery efficiency) decreased from 75% to an average of 62% when the temperature decreased (March–July 2012). May 2011 may be higher because the battery was new and possibly because only a small sample of 10 days was used for this calculation. For reference, e-ride has measured the battery efficiency at near-optimal conditions to be 89%.	

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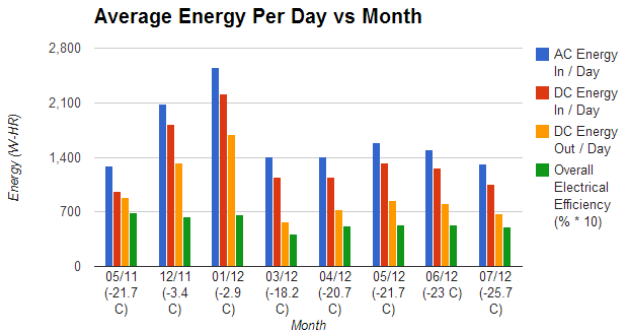
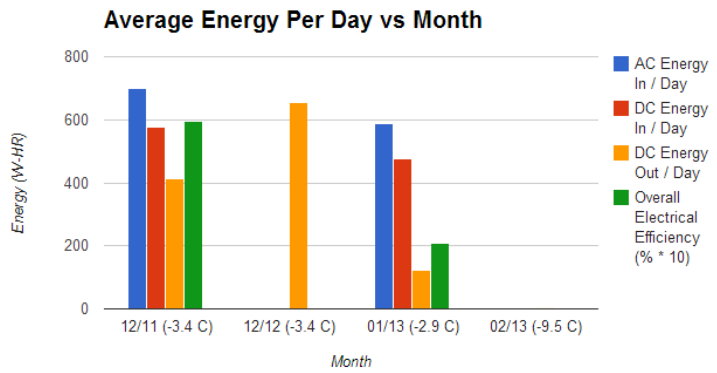
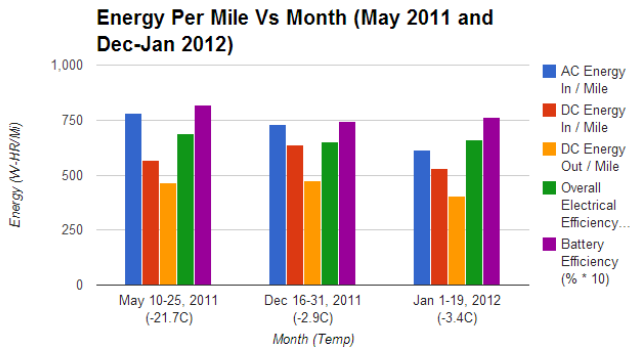
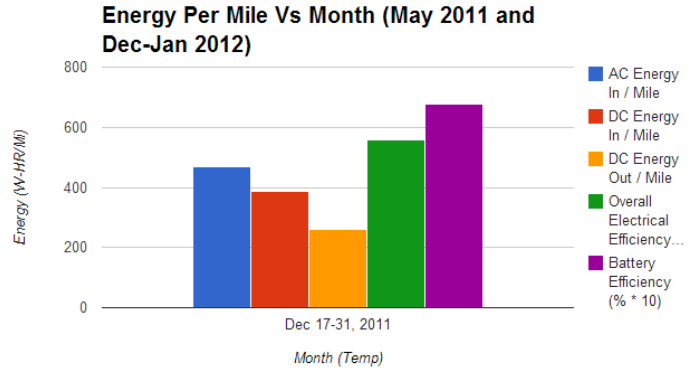
	
The average energy used per day is less than half of the battery capacity, so it appears that there is a good match between the battery capacity and the duty cycle of the vehicle. Fewer trips are taken in the cold months, likely because there are fewer workers at McMurdo, so the vehicles may be driven less often and the average use per day is less.	Significantly less energy is used per day by Vehicle 001. The decreased use should be investigated.
	
In the warmer months of December and January, the DC energy out per mile is approximately 390 Wh. For reference, the battery manufacturer's estimate is 250 Wh, not including the drive efficiency or DC cabin heater, so the calculated results appear reasonable. Looking at the data for the cold month of May, the DC energy out per mile increases to almost 465 Wh (a 19% increase from 390 Wh for warmer months). The colder temperatures could cause the driveline to be less efficient, and more likely, the lights and DC cabin heater are used more often, resulting in increased energy use.	The battery efficiency appears to be about the same for both vehicles: 67% for Vehicle 001 and 75% for Vehicle 002. The electrical efficiency is significantly lower for Vehicle 001, at 55.8%. The three values that are per mile all appear to be lower for Vehicle 001; that is, the AC energy per mile (468), DC energy in per mile (387),and DC energy out per mile (261). These per-mile values would tend to indicate that Vehicle 001 is more efficient, yet the calculated efficiencies indicate it is less efficient, so this needs to be investigated. One reason that the energy per mile is better is that the duty cycle may be less with fewer steep hills. This is congruent with the understanding that the vehicle is used primarily by the station manager.

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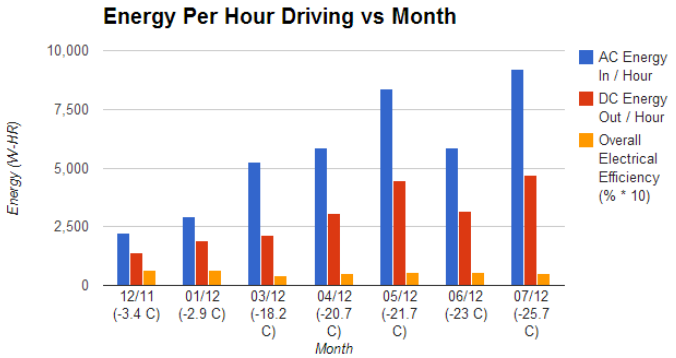
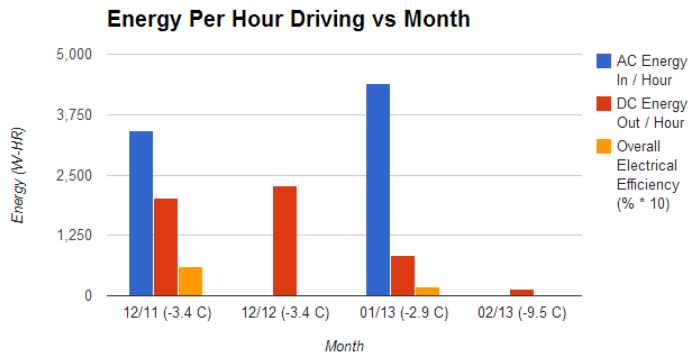
Looking at the AC energy in per mile, it is 608 Wh for the warmer months of December 2011 through January 2012, and then jumps to 782 Wh for the cold month of May, probably due to the increased use of the AC and DC cabin heater. Looking at the overall electrical efficiency, it was 65% for the warmer months and 69% for colder months due to the battery efficiency being higher in the cold months. See the electrical efficiency plot for more information. The energy per mile is also affected by the drivetrain, lights, and DC cabin heater.	
	
This plot shows the energy usage in Wh divided by the number of vehicle driving hours. In the warmer months the overall electrical efficiency was about 65%. For the colder months it averaged 53% (April–July 2012). In March 2012, the efficiency was only 41%. This could be related to data for this month documenting the longest average charging time. The energy used per hour increased as the temperature decreased, as expected, due to heating. June 2012 is a slight outlier, but vehicle usage was limited this month compared to other months.	DC energy out is 2,031 Wh, 2,270 Wh, and 836 Wh. Electrical efficiency is 59% and 19%.

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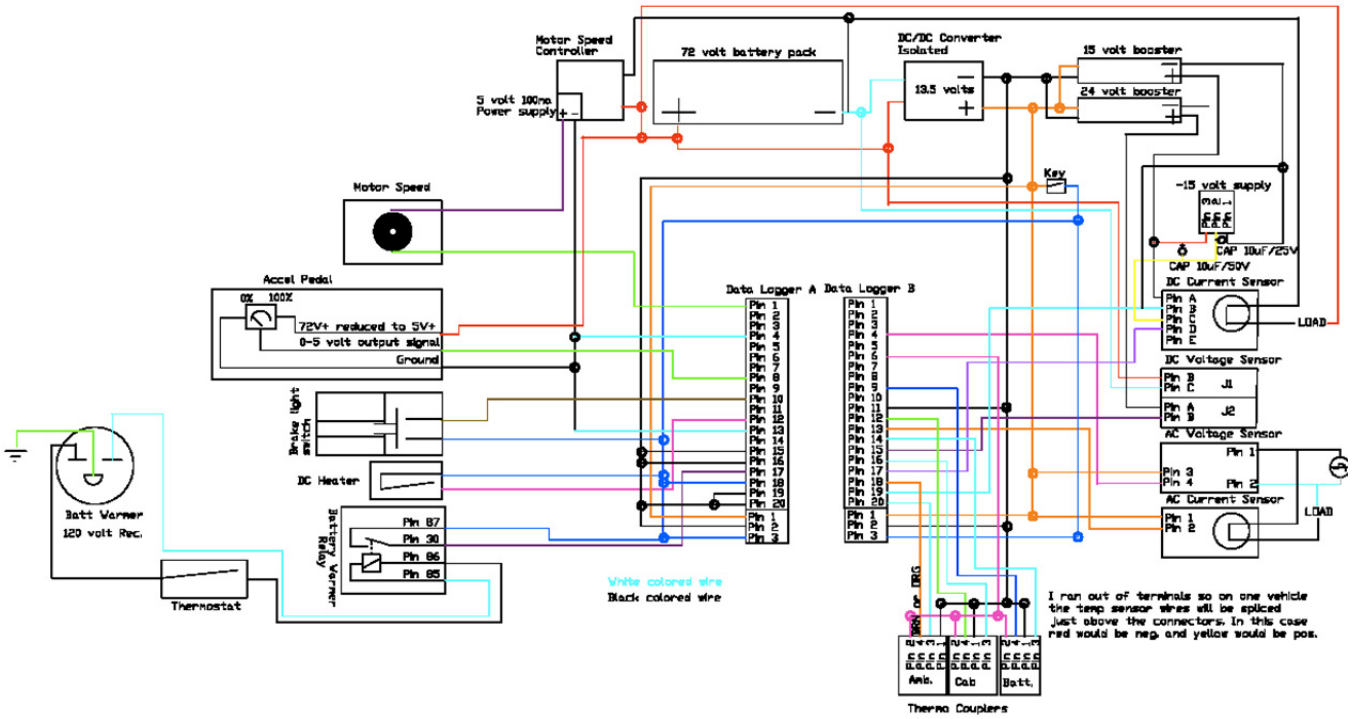
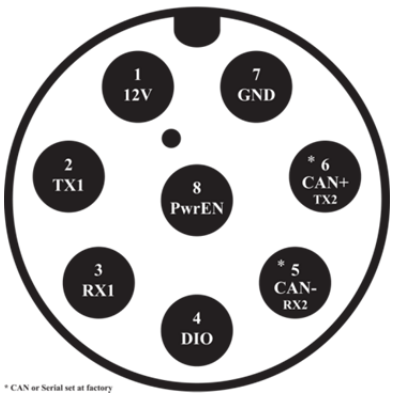
Appendix D: Wiring Diagram of Sensors Inputs to Loggers Used in EVs

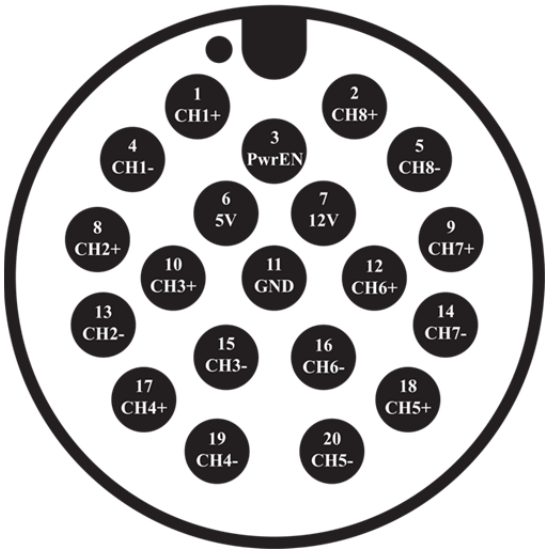


Male Connectors on the Logger

DAQ Module 3.0 8-pin connector pinout



DAQ Module 3.0 20-pin connector pinout



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Appendix E: AC and DC Voltage and Current Sensors Used in EVs

AC Sensors for the Electrical System Logger

Description	Sensor Model	Price	Temp. Range	Conditioning / Comments
AC Charge Voltage				0–110 V_{AC}. 12 V power required. Measurement range is 0–5 V.
American Aerospace Controls	108X-130	$216.00	-20°C to +70°C	**Average RMS AC Voltage Transmitter** 0–130 V_{AC} input, 4-20 mA DC output. No voltage supply required. Storage range is -55°C to +85°C. Industrial grade; output 0–5 V_{DC}; accuracy 0.5%FS; response 300 m-sec; powered by input; frequency 57–63 Hz (400 Hz available); temperature –20°C to +70°C; metal case; barrier screw terminals or optional connector; WT 10 oz. (284 grams). **http://www.a-a-c.com/ac-voltage-transducers.asp**
AC Charge Current				0 to 15 amps. 13 amps for 3 hours is the maximum. 15 V supply required.
American Aerospace Controls	1070-15	$306.00	-30°C to 60°C	**Average RMS AC Current Transmitter** 0–15 A RMS responding output 4–20 mA. 12 V to 32 V_{DC} supply voltage required. Accuracy 0.25%FS; two wire loop power +12 to +32 V_{DC}; frequency 20–2 KHz; response 300 m-sec; temp -40°C to +85°C; aperture 3/4 inch; plastic case; barrier screw, connector or sub-d terminations; WT 6 oz. (170 grams). http://www.a-a-c.com/ac-current-transducers.asp

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DC Sensors for the Electrical System Logger Used in EVs

Description	Sensor Model	Price	Temp Range	Requirements / Sensor Details
DC Voltage				Range 0–100 V. Nominally 72 V with 95 V during charging. Could measure directly or with a sensor. 12 V power required. Measurement range is 0–5 V.
American Aerospace Controls	S657-150		-40°C to +85°C	**DC Voltage Transducer** Requires 24 V power. 0–150 V input. 4-20 mA output. Rail transit grade; output 4–20 mA_{DC} proportional to (±) input absolute value; accuracy 1%FS over temp; isolation 5 KV; response 5 m-sec; power +22 to +26 V_{DC}; temperature –40° to +85°C; plastic case; connector and mating connectors included; WT 24 oz. (681 grams). http://www.a-a-c.com/dc-voltage-current-detectors.asp
DC Current				Range -125–600 amps.
American Aerospace Controls	943-600		-55°C to +85°C	**DC Current Transducer** Requires power of both ±15 V_{DC}. ±600 A input with ±5 V output. Use -1.25 V to +5 V range. Mil grade; output 0 to ±5 V; accuracy 0.5%FS; power ±15 V_{DC}; frequency DC-100 KHz; response 1m-sec; temperature –55°C to +85°C; aperture 1+3/8 inch dia; metal case; barrier or connector terminations WT 24 oz. (681 grams). Need to search website by number 943.

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Appendix F: Sample Data Files from EV Evaluation

The following section shows plots from select files that confirm the accuracy of the data collected.

Battery Capacity

For reference, to fully charge an e-ride Industries EV battery pack would take almost 6,000 Wh, but at the Antarctica temperatures to which the vehicles are subject, the battery capacity is believed to be reduced to roughly 64% (4,000 Wh). Table 3 in this report displays the drop in battery capacity/energy needed to charge batteries at lower temperatures. In the study vehicles, the typical large DC in values recorded have been, for example, 3,006, and 2,247. Many of the other values are 200 or less, showing that: (1) many trips are quite short in duration, (2) charges are short, or (3) no trips were taken but the ignition was on. It appears the values collected fall within or just below the normal range. A plot of the 2,953 Wh AC charging (2,247 Wh DC) is shown in Figure 29.

Discharge Cycle / Regen

Figure 30 is an expanded view of the driving (discharge) cycle. The regen energy for this trip was 1.6 Wh, which is a small amount. The efficiency of the battery absorbing this energy and the efficiency of sending it out of the battery also should be considered in any future research and reporting. Given the likely low efficiency and the low regen value of the EVs that are the subject of this report, it is believed that regen is not worth considering in calculations in this report (i.e., consider the increased efficiency of a Prius, for example, which has much higher regen).[11]

Remaining Parameters

Figure 31 shows the parameters addressed in this report, both acquired via the data logger and calculated from data collected. Moving left to right, the plots are: AC voltage and current; DC voltage and current; and ambient, cabin, and battery temperatures. These are measured parameters.

The calculated parameters moving left to right across the plots are: DC current in, AC power in, DC power in, charger efficiency, AC energy in, DC energy in, SOC intermediate, and SOC final.

The digital meter displays include: acquisition time, average ambient temperature, average battery temperature, number of data samples, total AC energy in, total DC energy in, charge efficiency, and total DC energy out of the battery.

The plots were generated using HEM Data's SnapMaster software. It reads the data files and quickly generates the calculated results and plots of the data. The SnapMaster instrument used for the analysis is named RPL_ANT5.INS.

[11] For reference, combined efficiency for a 2004 model year Toyota Prius (hybrid electric vehicle) is believed to be approximately 37%.

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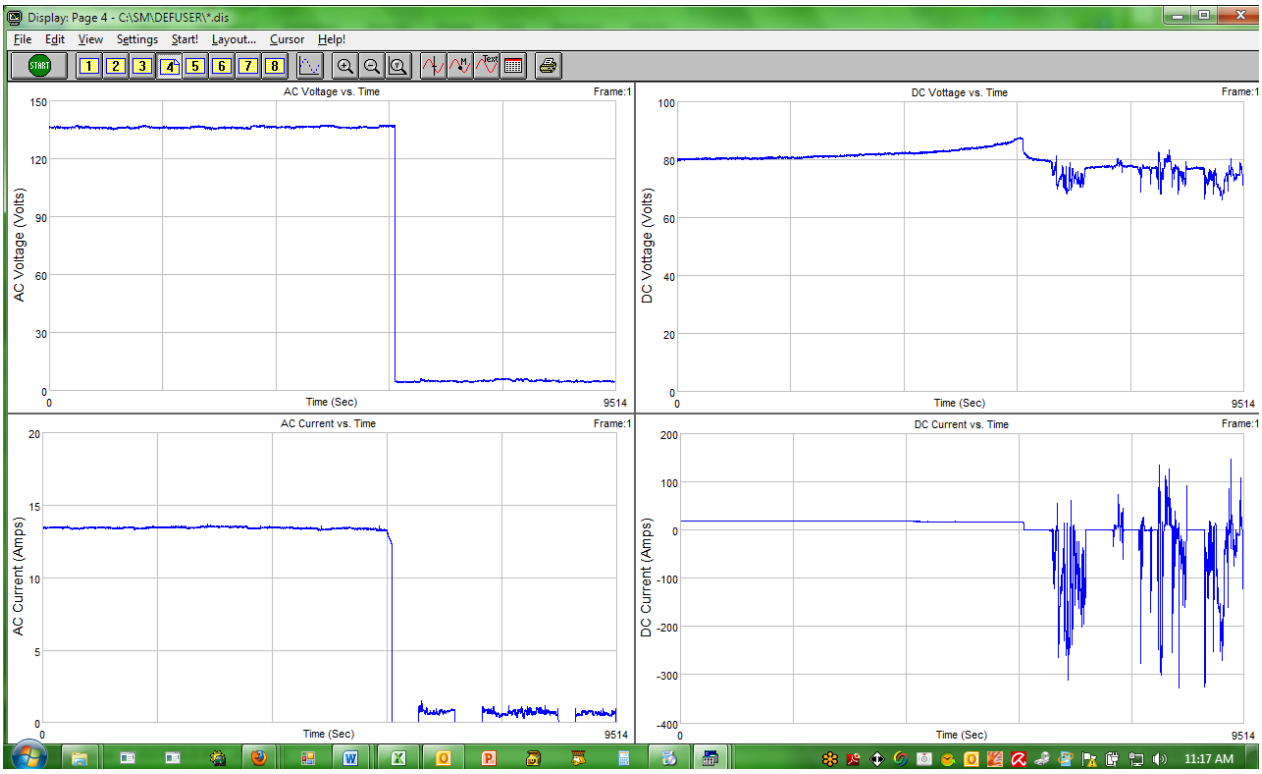

Figure 29. Charging is occurring during the first three-fifths of the time period.

Driving is occurring in the last two-fifths of the time period. Notice that for DC current, when the value is positive, regen is occurring.

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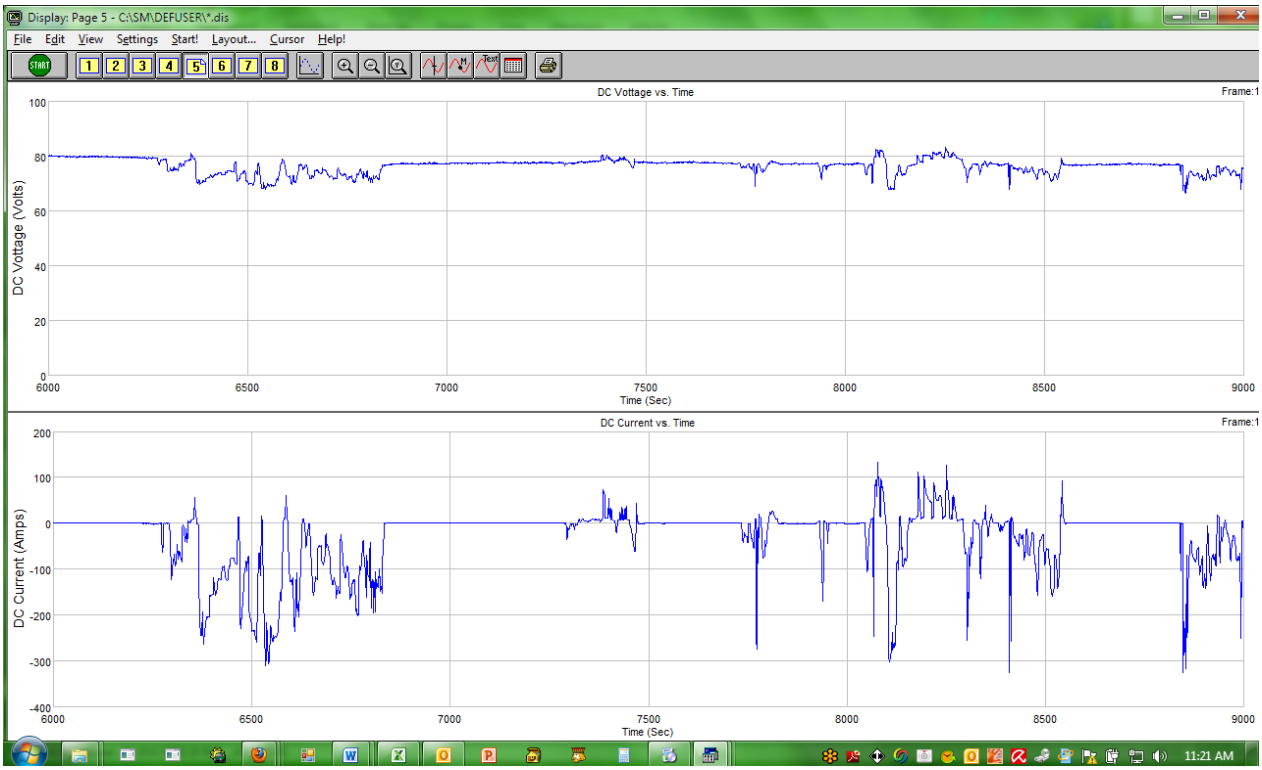

Figure 30. Expanded view of a driving cycle.

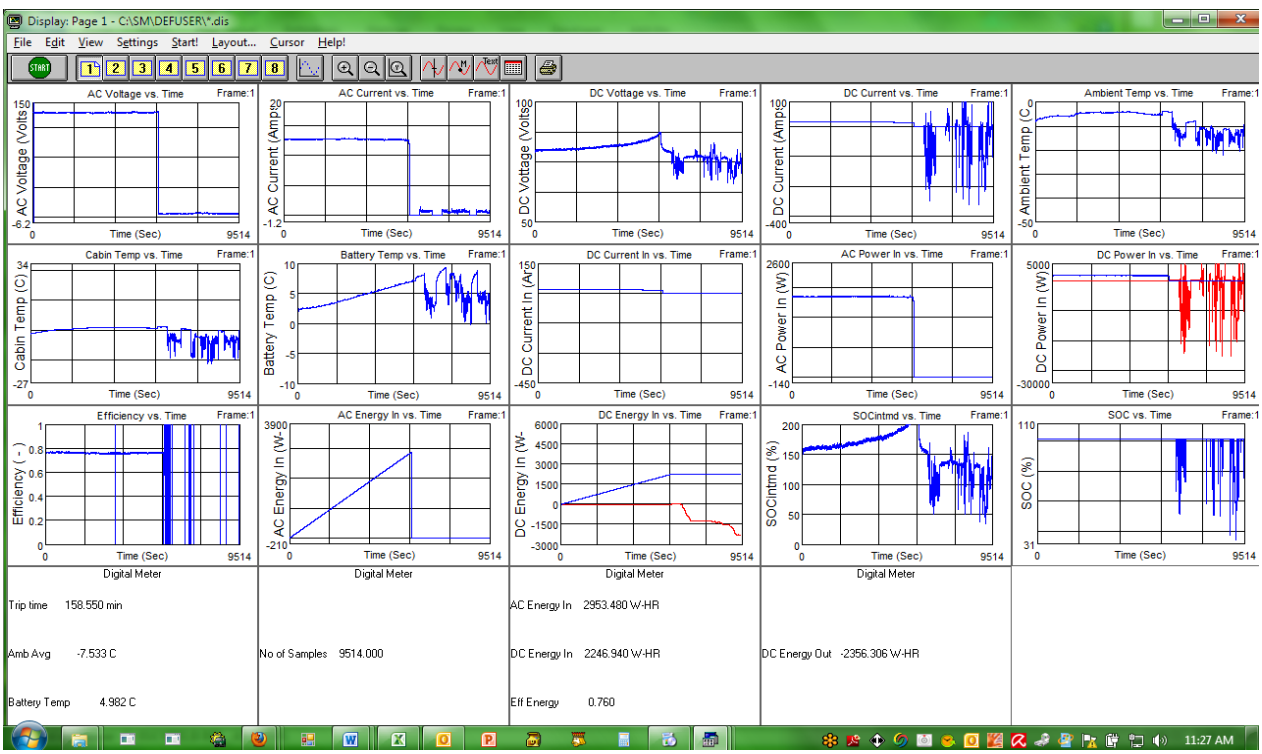

Figure 31. All parameters, both acquired and calculated.

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