Refinement of a High-Efficiency Electric Drivetrain for a Zero-Emissions Snowmobile

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ABSTRACT

The University of Wisconsin – Madison Clean Snowmobile team has designed, constructed and now refined an electric snowmobile with 40 km (24 mi) range and acceleration comparable to a 75 kW (100 hp) internal-combustion-powered snowmobile. Starting with a Polaris IQ Fusion chassis, a direct-drive chain-case was engineered to couple a General Motors EV1 copper-bar rotor AC induction electric motor to the track drive shaft. The battery pack uses 104 28 V, 2.8 A-hr Lithium-Ion battery modules supplied by Milwaukee Tool to store 8.2 kW-hr of energy at a nominal voltage of 364 V. Power is transmitted to the electric motor via an Azure Dynamics DMOC445LLC motor controller. All of the components fit within the original sled envelope, leading to a vehicle with conventional appearance and a total mass of 313 kg (690 lb). The vehicle, dubbed the BuckEV, accelerates to 150 m (500 ft) in 6.9 seconds and has a top speed of 122 km/hr (76 mph) with a pass-by sound level of 55 dB. This sporty electric sled surpasses all of NSF design goals (Table 1) for use in its arctic studies in addition to appealing to snowmobile enthusiasts. It was proven through two months at Summit Camp, Greenland, in support of environmental research projects, and has currently been operated for 800 km (500 mi) without failure.

Table 1. BuckEV Design Goals

Parameter	Competition Goal	UW '08 Achieved	UW '09 Goal
Range	≥ 16 km (10 mi)	31.5 km (19.6 mi)	≥ 40 km (24 mi)
Top Speed	≥ 70 km/hr (45 mph)	122 km/hr (76 mph)	≥ 160 km/hr (99 mph)
Acceleration (150 m)	≤12 s	8.3 s	≤7 s
Vehicle Weight		313 kg (691 lb)	≤ 313 kg (690 lb)
Drawbar Pull		206 kgf (254 lbf)	≥ 250 kgf (550 lbf)
Noise	≤ 78 dB	55 dB	≤ 60 dB

INTRODUCTION

In 2004, the Society of Automotive Engineers (SAE), in partnership with the National Science Foundation (NSF), created an additional event in the Clean Snowmobile Challenge (CSC) with the goal of encouraging the development of zero-emissions utility snowmobiles to support scientific research. A number of environmental research efforts taking place at locations such as Summit Station (Greenland) and South Pole Station (Antarctica) involve sampling the air and snow for global atmospheric pollutants which occur in levels of parts per billion. Visiting or even approaching these sites with conventional snowmobiles or more generally any internal-combustion powered vehicle can significantly contaminate the measurements. The Summit Station research facility has extensive areas in which vehicular traffic is prohibited due to concerns about contamination from emissions. Zero-emission transportation for personnel and equipment would ease the operation of distant satellite camp facilities and improve access to areas previously accessible only by foot.

In 2008, the University of Wisconsin – Madison Clean Snowmobile Team developed a snow machine, dubbed the BuckEV, which won the 2008 competition. After testing of the vehicle in Greenland during the summer of 2008, Alaska in the fall of 2008, and Wisconsin in the winter, we have made further refinements and here present our second generation design of the BuckEV for the 2009 CSC.

SUMMIT STATION FIELD TRIAL

After winning the 2008 SAE CSC zero-emissions category, the BuckEV was invited to Summit Camp, Greenland for evaluation. Summit Camp is a remote scientific research station situated at the top of the Greenland Ice Sheet. The highest point north of the Arctic Circle, Summit sits atop nearly two miles of ice and is 400 km (250 mi) from the nearest land or water. Conditions there are very inhospitable, with winter temperatures dropping to –60°C (–76°F) and summer daily high temperatures consistently below freezing.

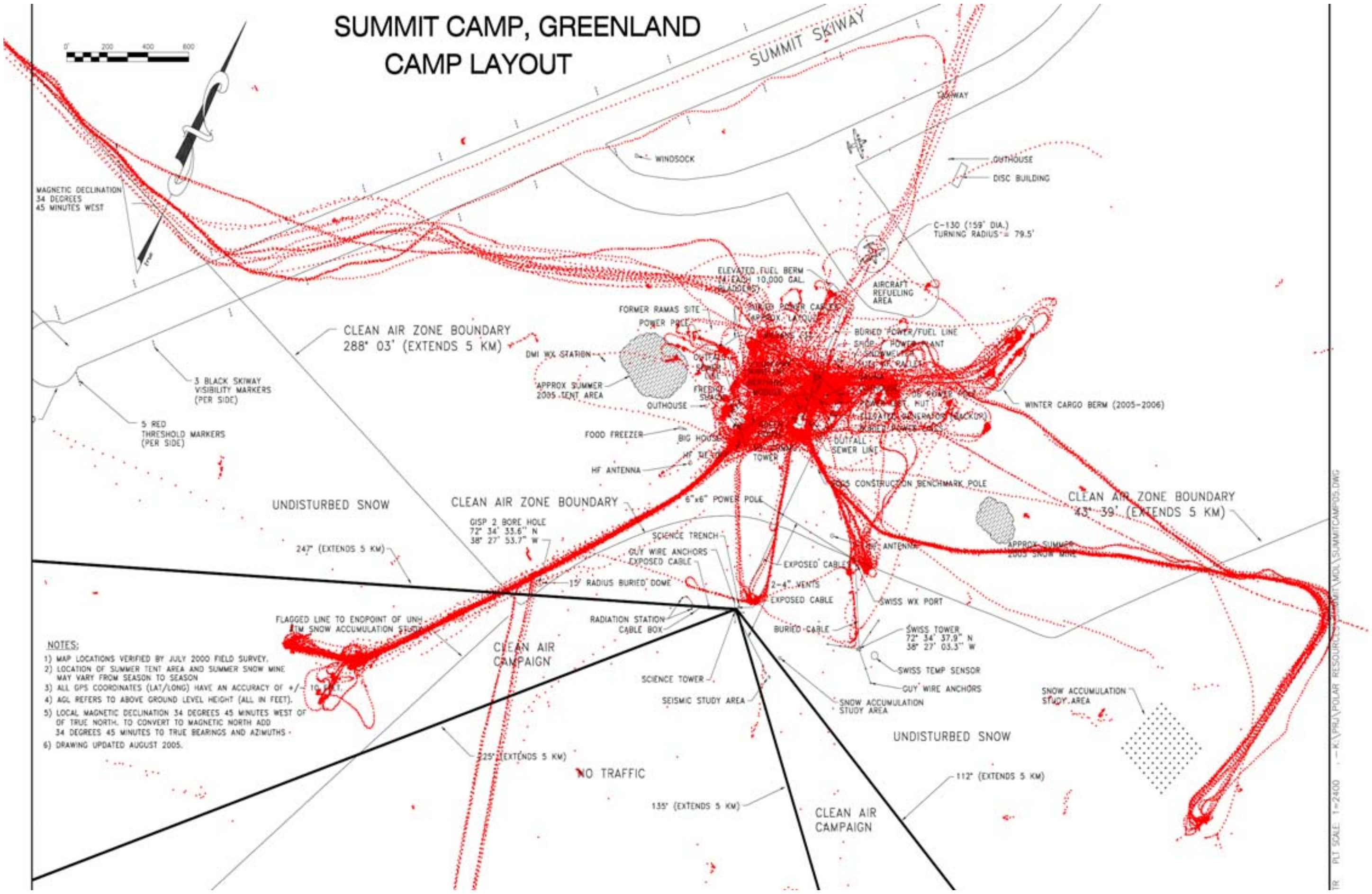

Figure 1 *A custom-designed data-logging system was installed on the BuckEV during its stay at Summit Camp, Greenland. In additional to all vehicle parameters, it recorded position at 1 s intervals, allowing analysis of vehicle usage patterns. Here, tracks from the entire stay are overlaid onto a map of the camp facilities (Spurious points and one-way tracks are due to temporary loss of GPS signal). The main camp personnel and cargo handling buildings are in the center, with the "Satellite Camp" to the southwest, and "clean" areas surrounding the camp on all sides except the north [1]. The tracks passing off the map all extend several kilometers away from camp*

Figure 2 *The BuckEV spent two months at Summit Camp, Greenland, being used on a daily basis to support climate research projects, hauling personnel and equipment 341 km (212 mi).*

Built in 1989, Summit Camp (Figure 1) is a now a permanently occupied science facility, inhabited by up to 50 staff and researchers in the summer, and maintained by a small crew of 5-10 personnel in the winter. Access to camp has historically been only via aircraft, so all personnel, equipment, food, fuel, and housing must be flown in (though the first overland traverse to the camp occurred during the BuckEV's stay).

The vehicle was flown up to Greenland on a ski-equipped LC-130 Hercules cargo plane operated by the New York Air National Guard (Figure 2). The journey required seven-hour flight from Stratton Air Force Base in Scotia, New York to Kangerlussuaq, an international airport on the coast of Greenland, followed by a two-hour flight and a landing on the snow at Summit.

The sled went into service at Summit on June 3, 2008, and was immediately tasked with transporting personnel and equipment to some of the remote facilities surrounding the camp. To avoid polluting the site and tainting measurements, a "Clean Snow Zone" has been designated in certain areas around camp, in which operation of all engine-powered vehicles is prohibited. The sanctity of this zone is so vital that a GPS track of every trip into the area (even on foot) is recorded, to ensure that critical measurements will never again be made on or near any traveled path. Tracks for the entire summer are shown in Figure 1. In the past, personnel and equipment have been transported by human power, using cross-country skis and wooden Nansen sleds. The high altitude (3000 m/10,000 ft) and cold conditions (temperatures last July ranged from -30°C to -7°C (-20°F to +20°F) make this challenging –transportation has always been a major limitation on what can be achieved there.

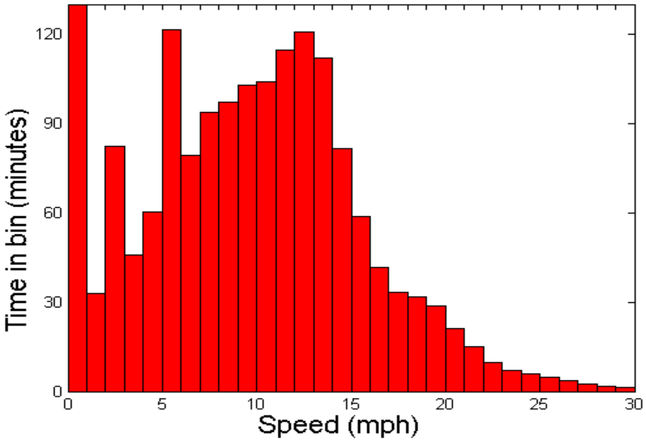

Figure 3 *Although the BuckEV is capable of speeds in excess of 100 km/hr (65 mph), it was primarily operated at low speeds, between 8-16 km/hr (5-15 mph), during its stay in Greenland. A histogram of time spent at each speed shows that the most common operational speeds were 5-6 mph and 13-14 mph.*

Initial experiences in Greenland show that our '08 vehicle could tow a 1500 lb payload five to ten miles before needing to be recharged. The loaded range is substantially lower than that measured in the competition range event, typically by a factor of 2-3, depending on conditions and load, suggesting that a minimum unloaded range of 20-30 miles is necessary to reliably achieve a ten mile useable range.

Every aspect of vehicle operation was recorded by an on-board data-logger and these results were studied alongside a trip log maintained by camp staff.

Due to the layout of the camp (Figure 1) and needs of the researcher, trips are primarily short in distance. The most common trip is between the Big House (the main personnel building) or the Balloon Barn (a cargo handling facility), and the Satellite Camp, a one-way distance of 1.1 km (0.7 mi). During a ten-day period in July that was studied extensively, of 72 trips during which the sled moved more than 0.03 km (1/10 mile), 47 were over 0.3 km (0.5 mi), 14 were over 0.6 km (1 mi), 6 were over 1.2 km (2 mi), and 3 were over 1.8 km (3 km).

In total, the vehicle traveled 341 km (212 mi) during the 57 days it was operational at Summit in the '08 summer season, an average of 6.0 km (3.7 mi) per day. The sled was in motion for 25.9 hours, with an average speed of 13 km/hr (8 mph). A histogram showing the typical usage speeds is in Figure 3.

Figure 4 *Photo of the BuckEV attached to the sled used to pull scientific equipment to remote testing locations near the NSF's Summit Station in Greenland.*

The need for longer trips is limited but unavoidable. In the summer of '08, long trips were mainly related to a Differential Optical Absorption Spectroscopy experiment that required the installation, relocation, and retrieval of retroreflector arrays mounted on poles 2.4 km (1.5 mi) and 4.8 km (3.0 mi) from camp. The infrequent need for low trips into the Clean Air Zone might, however, be related to the previous lack a vehicle that could support such experiments, so this may change in the future.

DESIGN OVERVIEW AND RATIONALE

Due to the differences between NSF design goals and the design criteria rewarded by the SAE CSC scoring, any design is necessary a compromise. We have summarized the design emphasis of the NSF and CSC in Table 2. The NSF values utility, with a primary emphasis on range and towing capacity (Figure 4) and little interest in recreational/performance characteristics like acceleration and handling. The CSC scoring puts far more emphasis on sportiness, with an additional major emphasis on noise. While cost is a nearly overwhelming design criterion for the NSF, the impact of cost on CSC competition scores is negligible. The UW team has chosen to focus primarily on design parameters where the NSF and CSC goals overlap.

Table 2. Design Rationale

Parameter	NSF Emphasis	CSC Emphasis	UW Emphasis
Range	Primary	Secondary (100)	Primary
Towing Capacity	Primary	Secondary (100)	Primary
Weight	Secondary	Secondary (100)	Secondary
Handling	Minor (safety only)	Secondary (125)	Secondary
Acceleration	None	Minor (50)	Primary
Noise	None	Primary (300)	Secondary
Cost	Primary	Minor (50)	Secondary

ELECTRIC ENERGY STORAGE REVIEW

When chemical potential energy sources (liquid fuels) may not be used in personal mobility applications, electric energy storage has become the preferred alternative due to its flexible packaging, easy control and low noise, vibration and harshness (NVH). This has spurred extensive research and development from government and battery manufacturers. Although significant advances have been made in the electric vehicle battery robustness and efficiency, further developments will be crucial in defining the ultimate range of electric vehicles.

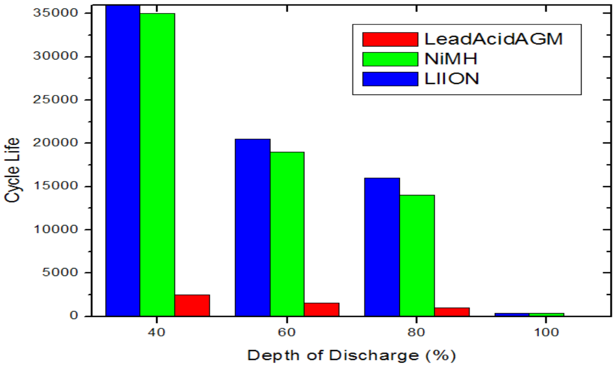

Figure 5 *Cycle life for each battery chemistry for various different state-of-charge swings, adapted from Dougherty [1].*

Currently, there are three families of battery chemistry either available for use in vehicular applications – lead acid absorbent glass mat (Pb-acid AGM), nickel metal hydride (NiMH) and lithium ion (Li-Ion, though actually a nickel-cobalt chemistry). Because each battery utilizes a different electrochemical potential difference, the number of individual cells needed to provide a specific terminal voltage varies. Three NiMH cells or two Pb-acid cells are typically required to obtain the same potential as one Li-Ion cell [2]. Reduced cell count leads to improved reliability, reduced cost, and simplified packing and interconnection. Currently, the price of nickel is increasing with the increasing demand for batteries in vehicular and other applications. Ultimately, the lithium-ion technology will reduce nickel usage by a factor of three.

There are three main characteristics demanded for batteries in electric vehicles – specific power, specific energy, and cycle life for deep discharge. While tradeoffs can be made in battery design to emphasize a particular characteristic at the expense of others, general trends exist, as shown in Table 3. Lead acid batteries are superior under conditions of high power demand, but have poor specific energy (especially on a mass basis) and extremely poor cycle life compared to both Li-Ion and NiMH at all depths of discharge (Figure 5). NiMH and Li-Ion batteries offer reasonable performance in all three criteria, with Li-Ion having an advantage in energy density [3].

Table 3 Comparison of battery chemistries [4]

	Lead Acid	NiMH	Lithium Ion
Mass Energy Density (Wh/kg)	30-40	40-120	100-180
Volume Energy Density (Wh/L)	60-75	140-400	200-300
Power Density W/kg	180	300-1000	1000-5000
Cycle efficiency (% charge/discharge)	70-92%	65-80%	95-99%
Self-discharge (%/month)	3-20	~30%	5-10%
Cycle life (total cycles)	500-800	500-1000	500-15000
Current cost ($/Wh)	0.15-0.30	0.30-0.60	0.50-2.50

As utility snowmobiles are intended to be operated for an hour or more at a relatively constant level, all of these battery chemistries provide adequate power density and energy density is the limiting factor. Since both weight and space are limited, energy density is crucial in both a gravimetric and volumetric basis.

Early work by SnoLectric demonstrated the advantages of higher voltage electrical systems [5]. Increased voltage allows more powerful, more efficient, and smaller motors, controllers, and wiring.

Lithium-Ion batteries also offer the additional benefit of maintaining most of their capacity at low temperatures, whereas lead acid and NiMH performance is substantially reduced at temperatures below 0° C.

However, it is crucial to remember that all of these electrochemical energy storage technologies have gravimetric energy densities measured in the tens or hundreds of W-hr/kg, while gasoline can store on the order of 13,000 W-hr/kg, a factor of 50-400 more, though typically only 1/3 of this energy can be extracted effectively. This order of magnitude difference in energy storage capabilities means that it is currently impossible to build a practically sized electric snowmobile with range comparable to a conventional engine-powered one.

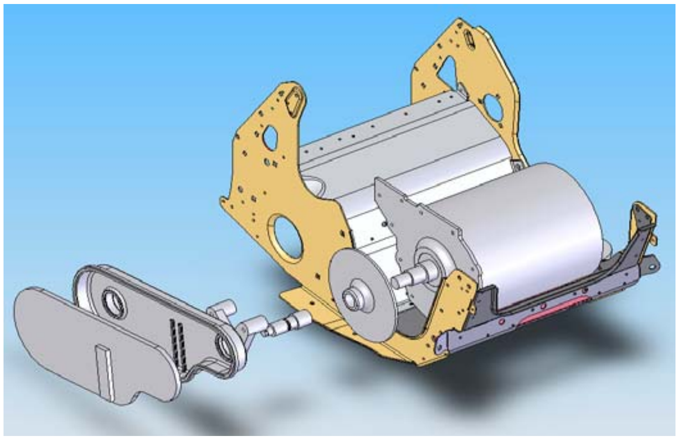

Figure 6 *Overview of the BuckEV drivetrain. The electric motor is coupled through the brake rotor into custom-designed direct-drive chain-case.*

DRIVETRAIN

The electric drive system (Figure 6) consists of a Delphi EV1 motor controlled by an Azure Dynamics DMOC445LC motor controller and powered by a battery pack consisting of 728 lithium-ion cells supplied by Milwaukee Tool. As the predominant practice in the automotive industry is to use 240-400 V systems light duty applications, production electric drive components are reasonably priced and available from a variety of manufacturers.

TRACTION MOTOR – Permanent magnet (PM) synchronous motors offer the highest energy conversion efficiency which would lead to the longest range for a pure electric vehicle; however cost of rare earth magnets necessary to get high power density can be prohibitive. Also, the control system must take care to avoid demagnetizing the magnets, rendering the motor useless. DC motors, while simple to design and manufacture, offer the lowest efficiency of motor technologies and have poor reliability. AC induction motors are rugged, inexpensive, and still offer efficiency close to that of PM systems. For this reason an AC induction motor was chosen for BuckEV.

The GM EV1 motor (Figure 7), an AC induction machine developed by Delphi, features a copper bar rotor design that significantly reduces losses and increases power density. The motor's aluminum liquid-cooling jacket allows the motor to produce 100kW peak power and 37 kW continuous power. This will provide adequate power for cruising while still giving plenty of performance. The electric motor is transversely mounted in front of the tunnel and is coupled to the track drive paddles by a custom-designed chain-case.

The high torque and wide speed range over which efficient constant power operation is possible allows this motor to be used in a direct-driven configuration, without a continuously variable transmission (CVT). The motor was geared to operate at 2500 rpm at 32 km/hr (20 mph), a speed at which it is more than 90% efficient for torques from 20-40 Nm, as shown in Figure 8. While a CVT would allow the motor to operate efficiently over a wider range of speeds, CVTs have peak efficiency of approximately 80%, entirely eliminating any advantage. Due to the wide torque/speed envelope in which the motor operates at high efficiency (Figure 8), even a perfectly efficient variable-ratio transmission would only offer major improvements in overall efficiency during low speed acceleration, a portion of the driving cycle that consumes relatively little total energy.

MOTOR CONTROLLER – An Azure Dynamics DMOC445LC motor controller/inverter has been tuned specifically for operation with Wisconsin's EV1 motor. The DMOC is a liquid-cooled vector drive inverter and is equipped with a Controller Area Network (CAN) bus for interfacing with the vehicle controller. The inverter is 96-98% efficient, weighs 10.6 kg, and is rated for operation down to -40° C. The unit is rated for a battery input voltage of up to 400 V and can deliver 78 kW (105 hp) peak power and 46 kW (62 hp) continuous power at 312 V. While it does support regenerative braking, there is little energy to be recovered this way in a utility snow machine, due to the high drag/inertia ratio and typical steady-state operation, so this feature is not used. Unfortunately, the overall power and speed rating of this controller are less than the motor ratings (78 kW instead of 100 kW and 10,000 rpm vs. 12,000 rpm), limiting maximum power and speed. We are currently investigating the use of a prototype controller for 2010 that is better matched to our motor.

Figure 7 *Photograph of the Delphi EV1 copper-bar-rotor AC induction electric motor, with a peak power of 100 kW. The transaxle used in the GM EV1 was removed and replaced with a student-designed endplate (not shown).*

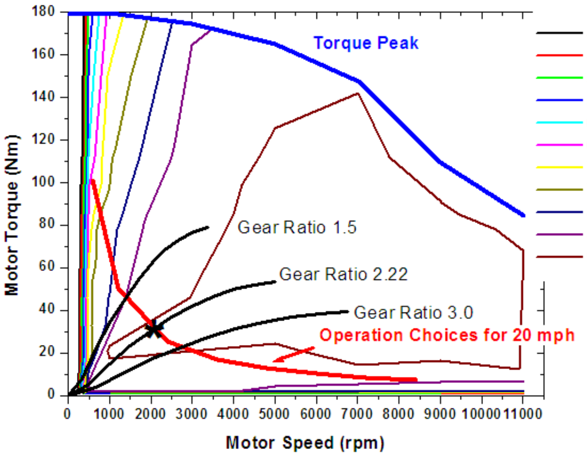

Figure 8 *The EV1 motor operates above 90% efficiency over a wide torque/speed envelope. Road-load curves for several possible reduction ratios are shown in black, with the red constant-power line indicating the options for 32 km/hr (20 mph) operation. A reduction ratio of 2.22 was chosen to maximize efficiency at this speed while still giving good acceleration and top speed.*

COUPLING – The coupling connecting the electric motor to the track drive paddles was analyzed for '08 using a component selection matrix. The three types of couplings considered were a belt, chain, and gear drive. The criteria used to determine the best overall coupling were cost, strength, simplicity, and reliability. Simplicity was determined to be the most important criterion, with a weighting factor of 1.5. This criterion was stressed over the others due to the fact that the system must be implemented in a shortened development cycle. Based on the selection matrix seen in Table 4, a chain drive type is the best overall selection.

Table 4 Component selection matrix for motor coupling

	Cost (x1)	Strength (x1)	Simplicity (x1.5)	Reliability (x1)	**Factor Sum**	
Belt	7	6	8	4	**6.5**	🟨
Chain	7	9	6	8	**7.5**	🟩
Gear	4	10	4	9	**6.5**	🟨

With the electric motor mounted in the location of the conventional two-stroke engine, the stock chain-case's center-to-center sprocket spacing was two inches shorter than necessary. A new chain-case was designed and constructed to transmit torque from the motor drive shaft to the vehicle's track drive shaft using a 92P chain instead of the stock 104P chain. To maximize performance and durability, the new chain-case was designed to use as many stock Polaris parts, including the chain tensioning system, bearings, and seals. The chain-case was CNC-machined out of aluminum and the cover out of a homopolymer acetal (Delrin™). This chain-case has currently been operated for 800 km (500 mi), including operation in regimes where large shock loads are common (riding with passengers, towing trailer sleds, and jumping), without any failure, signs of wear, or oil loss.

The goals of the competition necessitate maximizing efficiency during the trail ride, at speeds of approximately 32 km/hr (20 mph). Based on road load predictions and motor torque/speed efficiency curves, the optimal gear ratio was just over 2:1. With a 40T sprocket on the track drive and an 18T sprocket on the motor, motor speeds of 2400 rpm are seen at 32 km/hr (20 mph), yielding near-peak efficiency without compromising low-speed torque or top speed. The chain-case is splash-lubricated with synthetic ATF to reduce frictional losses at all temperatures and is vented through a filter to eliminate emissions due to fluid evaporation, making this a true zero-emissions vehicle.

Based on conversations with belt industry representatives at the '08 competition, an alternative drive coupling is currently under developement, using a prototype belt and sheaves being developed by Gates Rubber and cooperatively tested by our team (Figure 9). This system has been fabricated, installed on a sled, and is currently in initial stages of testing. Further development of this vehicle was delayed after competition rule changes precluded entering a new sled this year, but development of this drivetrain will continue after competition and we anticipate using it in our 2010 vehicle. It should lead to substantial weight reduction and allow for the elimination the chain case oil bath (currently the only petrochemical used in the sled).

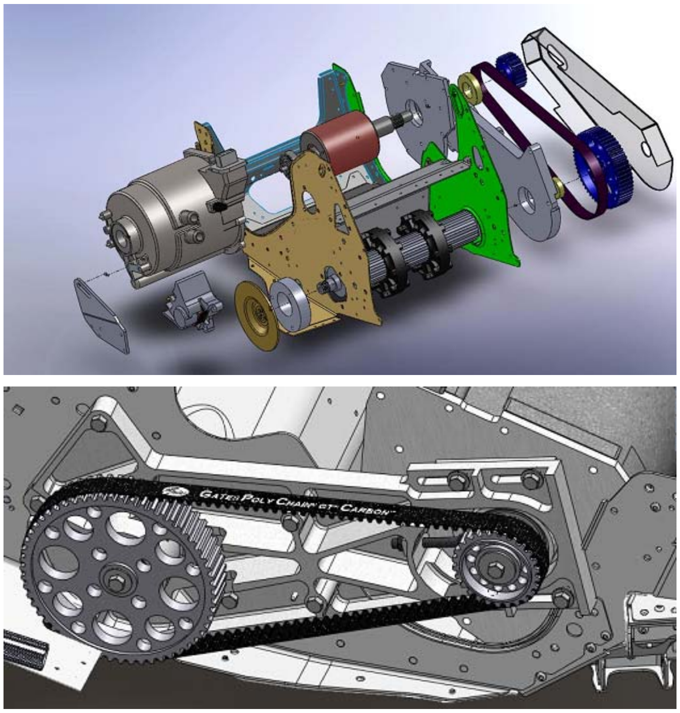

Figure 9 *An alternative drive coupling using a prototype composite belt was developed in collaboration with Gates Corporation. FEA shows that it should be adequate for 110 kW (120 kW) with motor speeds up to 12,000 rpm. This system is planned for use in our 2010 sled.*

Another improvement made to the drivetrain to enhance efficiency was to machine the driveshaft paddles into true circles. The team purchased a hollow, light weight driveshaft to reduce weight. Like most mass-produced track drives, this one had plastic molded drive paddles that had not been machined. This molding process does not create a very uniform shape, which can cause a snowmobile's track to change tension while moving. This effect of cycling track tension over each revolution reduces efficiency and increases noise and wear. To reduce these effects, the driveshaft was machined on a lathe to make both drive paddles symmetrical and perfectly round.

BATTERY – The BuckEV snowmobile uses an energy storage system consisting 104 Milwaukee Tool V28 battery modules, up from 84 modules used in '08. These units are intended for use in cordless tools and have been designed for high capacity at rapid discharge rates. The cells are rated for a minimum of 150 cycles at a 90% depth-of-discharge and can be discharged up to 97% without risk of damage.

The Milwaukee Tool battery modules were chosen due to their high peak power, high energy density, and capability for continuous discharge at high rates without risk of overheating or damage. These cells were readily available, as they are used in a mass-produced commercial product, and the team has as good working relationship with Milwaukee Tool, having collaborated in the past on two hybrid-electric vehicle projects [6,7].

Each module contains seven 4.0 V, 2.8 A-hr cylindrical cells connected in series. The pack is configured into eight parallel strings of thirteen modules in series (91 cells per string), yielding a capacity of 22.4 A-hr at a nominal voltage of 364 V, capable of continuous discharge at 320 A (exceeding the 280 A capacity of our electric drive). The increase in pack size (from seven to eight strings and 84 to 91 cells per string) leads to a 24% increase in energy storage capacity and a 5% improvement in battery pack resistance. The increased voltage allows the motor controller to operate more efficiently, leading to a 6% reduction in overall losses at low speeds and a 14% reduction at maximum power.

Each module weighs 1.04 kg as manufactured and 0.74 kg after being modified for installation in the sled. The second generation BuckEV uses a new battery packaging method (Figure 10b) that offers significant weight savings over the first generation design (Figure 10a). In the previous design, 84 modules were used with only minor modifications to the original plastic packaging. The new design eliminates this original packaging entirely, saving 0.23 kg (0.51 lb) per module, for a mass reduction of 19.3 kg (42.5 lb). The original plastic packages in the old design also required a complex mounting system with multiple machined plastic slides to capture each module and aluminum mounting brackets to support the slides. The second generation battery packaging method here eliminates these complex mounts, saving an additional 7.4 kg (16.3 lb). This redesign led to a nearly 1/3 reduction in per-unit battery system mass, allowing a larger pack with lower overall weight. Pack parameters are summarized in Table 5.

The cells maintain full performance down to temperatures of +10° C and have been tested by the manufacturer down to –20° C. Reduced power delivery performance is seen when cold, but very cold cells will rapidly heat up due to increased internal resistance, and 90% of normal power is available within 105 s of start-up (at 20 A discharge), as shown in Figure 11.

In 2008, the battery pack was initially sized based on road-load predictions from the M.S. thesis of Auth [8] and refined based on power-consumption measurements made using a prototype implementation with a smaller battery pack and the sled ballasted to its expected final weight.

The 2008 vehicle, though it nearly doubled the competition range goal, did not meet our design goals, and during the summer in Greenland, proved to have marginally adequate range, with the ability to perform some desired long trips limited by load and snow conditions. The battery energy storage capacity was increased by 24% this year in order to be more competitive at the CSC and improve confidence in the vehicle's ability to make 16 km (10 mi) round-trips into the Clean Snow Zone at Summit.

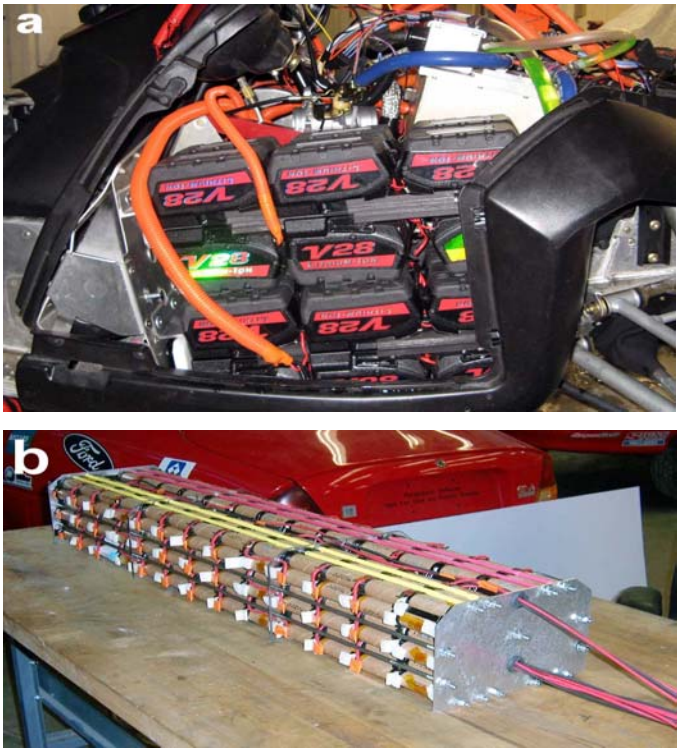

Figure 10 *(a) Shows the side pod batteries in the '08 design and (b) shows the under-seat battery unit in the '09 design. The BuckEV's battery was redesigned for 2009, eliminating nearly 26.7 kg (58.9 lb) of packaging and mounting hardware. Repackaging of the side pod batteries is currently in progress. Electrical safety was a major factor in the design of the energy storage system, and the design ensures that no conductive surfaces are exposed during operation or service.*

Table 5 Battery Pack Specification

Characteristic	Milwaukee Tool V28 Li-Ion
Battery Mass (w/packaging)	84.1 kg (185 lb)
Nominal Voltage	364 V (+8%)
Capacity	22.4 A-hr (+14%)
Energy	8153 W-hr (+24%)
Power Density	1220 W/kg
Energy Density	96 W-hr/kg (+20%)

Previous experience with a variety of multi-string battery packs show that recirculating currents between parallel strings are typically not a concern during discharge and may only be a problem during abnormal charging conditions. Though this experience had been limited to NiMH cells, it appears to apply to Li-Ion as well based on experiences from the previous year. The parallel strings are internally fused (mid-string) for safety and, in this prototype vehicle, monitored using individual per-string current and temperature sensors. These sensors have demonstrated that the strings remain balanced after cycling and would not be necessary in a production vehicle. The prototype vehicle also contains connectors allowing charging of individual battery strings to rebalance the battery pack, though this capability should not be necessary in a production vehicle.

Safety, weight balance, center-of-gravity height, and serviceability were foremost in the design of the battery pack. The batteries were mounted in three individual units that can be easily removed and serviced separately from the sled. One unit (containing 13 modules in one string) was mounted in each of the side pods under hood, while the third unit (containing 78 modules in six strings) was mounted under the fuel tank cover and seat.

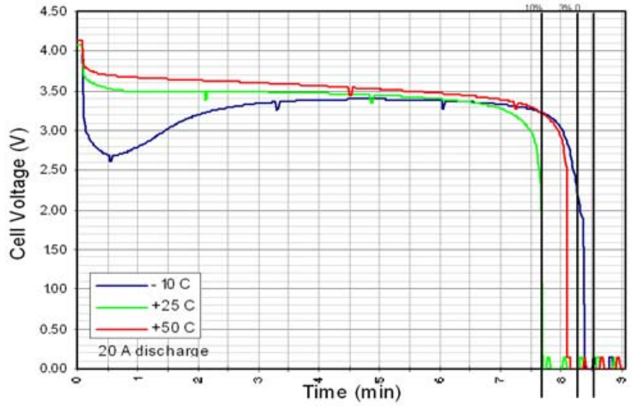

Figure 11 *The Milwaukee Tool V28 batteries demonstrate good performance down to -10℃ in a 20 A discharge test.*

The cells initially show a 30% reduction of terminal voltage, but rapidly warm up to the point that full power is available. Note that low-temperature operation yields only about a 7% loss of energy capacity compared to 50°C operation (which is very detrimental to battery life) and actually offers slightly more total energy than discharge at 25°C.

The battery packs have no exposed conductive surfaces and are safe from the standpoint of a “finger test” (requiring that a human finger be unable to come into contact with any live parts during normal operation or routine servicing) as well as a “drop test” (meaning that the electrical system is protected against hazards from a dropped tool or bolt). Note that the vehicle has not been evaluated by UL or VDE for formal compliance with these tests, but rather satisfies the tests as described in the high-voltage safety standards of the Department of Energy FutureTruck competition. The batteries can be trivially disconnected from the drive (isolating them electrically) or even removed entirely to permit vehicle service without high-voltage electrical hazards or to comply with shipping regulations.

AUXILIARY ELECTRICAL SYSTEM – A conventional 12V electrical system is required to operate the lights, hand warmers, coolant pump, and vehicle controllers. A Powersonic 12 V, 5 A-hr sealed lead-acid battery (1.69 kg) buffers power demands and a Solectria 750 W DC/DC converter (3.00 kg) charges the 12V system from the high voltage pack. This power converter offers ≥95% efficiency and uses nearly zero power when not in operation. The vehicle can operated for more than one hour after failure of either of these components.

To reduce parasitic electrical losses, all incandescent miniature light bulbs have been replaced with high-efficiency LEDs, saving 30 W of continuous power (0.5% range improvement per hour of operation) and improving reliability (there is no filament to burn out). During daytime operating conditions, solely the LED running lights can be used, saving an additional 100 W (1.5% additional range improvement per hour of operation). Together these modifications improve range by approximately 0.6 km (0.4 mi) at 32 km/hr. For operator comfort, the conventional passive electrical hand-warmers were retained – their operation requires up to additional 65 W, reducing range by approximately 1%.

Because the 12V system is supplied by the large high-voltage battery, the vehicle can service as a source of power for external devices. The headlights can be operated for more than three days as an auxiliary light source, and a plug is available to plug in a 120VAC inverter, allowing up to 750W continuous power (for over ten hours) and 1500 W of peak power, enough to run many AC power tools. This may eliminate the need for a gas-powered generator in some remote applications.

COOLING SYSTEM – The motor and controller have a closed-loop liquid cooling system with a 60/40 mixture of ethylene-glycol and distilled water, for freeze protection down to -56° C (-69° F). The coolant is circulated using a Bosch electric water pump through the side rails and a heat exchanger mounted at the front of the tunnel. The pump flows up to 15 L/min and requires 18 W, but is typically run at a reduced rate according to system temperature and drivetrain power output. As the electric drive is liquid-cooled, the entire hood is sealed, preventing intrusion of water or snow to improve reliability and ease of servicing. Experience from the previous design showed that the cooling system is more than adequate, with a peak power-electronics temperature of 25.4°C seen during a ten-day period of study. As the power electronics permit temperatures up to 80°C, the cooling system was substantially downsized by removing the rear heat exchanger, saving 3.1 kg (6.9 lb) over the ’08 design.

The batteries have extremely low internal resistance, leading to very low levels of heating. The battery supplier has advised the team that the batteries can be continuously discharged at 40 A without overheating. Thermal analysis of the pack shows that, based on a measured cell resistance of 15 mΩ and an estimated battery heat capacity of 800 J/kg/°C [9], a peak temperature rate of increase of 13 K/min will be seen at a maximum continuous discharge rate of 280 A. As this rate of discharge will completely exhausted the pack in approximately 4 minutes, peak temperature rise of 55 K will be seen. Since the batteries are rated for a maximum operating temperature of 70°C, vehicle operation is typically expected at temperatures below 10°C, and some heat will be lost to the surroundings, it is not anticipated that battery cooling will be required during vehicle operation or charging. However, thermistors in each string sense of battery temperature, allowing the controller to derate power if necessary for battery protection. During a ten-day period of study in Greenland, observed battery temperatures ranged between -20°C and +17°C.

CHARGING SYSTEM – The sled is typically charged using an on-board Brusa NLG513 3.3 kW charger. The charger runs off 120-240 VAC (a set of cords are provided with plugs for most common outlets) and is capable of charging at rates of up to 12.5 A. The charger is controlled via CAN by the main vehicle controller – when the vehicle is plugged in, the system powers up automatically, detects the state-of-charge, and initiates charging if necessary, following an algorithm recommended by the battery manufacturer.

First the batteries are charged at a current of up to 2.5 A/string until the cells reach 4.25 V (387 V overall). Constant-voltage charging then continues at 4.25 V/cell until current drops to 50 mA per string. This leads to a full charge in approximately 120 minutes. This charger can parallel with up to two off-board Brusa chargers in a master/slave configuration to permit rapid charging in 40 min when 208V/3φ power is available.

An off-board 6 kW charger is also available to enable rapid charging in 75 minutes. The batteries are capable of rapid charging at up to 40 A/string, allowing a full charge in approximately 20 minutes, but this would require a 240V/100A power connection, which is not commonly available, and may reduce battery life.

VEHICLE CONTROL SYSTEM

CONTROL HARDWARE - The BuckEV uses a MotoTron ECM-0555-080-0312M Powertrain Control Module (PCM) embedded controller specifically designed for automotive applications. The PCM, which utilizes software developed by MotoTron, is hermetically sealed and suitable for rugged environments. Its operational ratings allow temperatures from -40˚C to 130˚C, high acceleration and vibration (direct engine mounting in marine racing applications is permitted), and indefinite submersion in 3 m of water. It has 15 analog inputs, 6 digital inputs, 20 low side driver (LSD) power outputs capable of PWM (pulse-width-modulation, a technique for variable power output), 8 logic level outputs and dual CAN 2.0B interfaces.

Every control system connector has been specified for automotive, marine, or military applications. Rugged and waterproof components were used where appropriate.

Vehicle controller inputs include accelerator position sensor, brake switch, stop switch, reverse switch, cruise control switches, auxiliary system voltage, cruise control switch, and battery temperature and current sensors (each of the eight strings is sampled once per second through analog multiplexers). Feedback from the Azure Motor Controller over the CAN link yields battery voltage, vehicle (motor) speed, motor and controller temperature, actual torque and current, and any drivetrain faults.

The vehicle controller commands a torque command and optionally a target speed (for cruise control) to the Azure motor controller over the CAN link. It also controls the speedometer, a torque indicator, dash indicator and warning lights, and the variable-speed coolant pump, and operates an electrical system monitoring gauge (MotoTron MiniView) over a serial link.

CONTROL SOFTWARE – The control strategy was developed using the MotoHawk development system, which allows for rapid control prototyping using MATLAB Simulink. This allows for easy simulation of control algorithms and thorough bench-testing using “software in the loop” testing techniques. The use of MATLAB Simulink to develop controls software, as opposed to traditional techniques using C code or assembly, allows for better insight into the properties of the physical system and eases the development of better controls algorithms.

BATTERY STATE OF CHARGE ESTIMATION – The battery state-of-charge (SOC) must be known at all times to allow for maximum range while preventing damage to the batteries due to excessive discharge. With Li-Ion batteries, battery SOC can be calculated very accurately by integrating current to get amp-hours, as the chemistry conserves charge. Unfortunately, this method is very sensitive to offset and gain errors in the current measurement, which can be common over the wide range of operating temperatures seen in a snowmobile. A system that relies not only on battery current integration, but also feedback from battery voltage, can provide more robust battery SOC calculations [10,11].

For the batteries used in BuckEV, tests were performed to determine the relationship of battery voltage to battery SOC as shown in the discharge tests in Figure 12. The nearly linear relationship over most of the curve allows for easy battery SOC calculation based on voltage. Furthermore, the rapid deterioration of battery voltage as zero SOC is approached helps ensure that the battery is not excessively discharged when using battery voltage for SOC calculation. For this reason a system was developed that utilizes the effective open circuit voltage of the battery.

The open circuit voltage of the battery can be trivially measured (directly at the battery terminals) when the battery is not being used, however when current is being drawn from the batteries, potential swings due to internal resistance affect the terminal voltage (Figure 13). Due to battery chemistry, the resistance is not necessarily constant. This phenomenon can be characterized as an equivalent circuit model with a temperature-dependent series resistance, $R(T)$, and a temperature-dependent series RC element with resistance $R_{transient}(T)$ and time constant τ, where T is battery temperature.

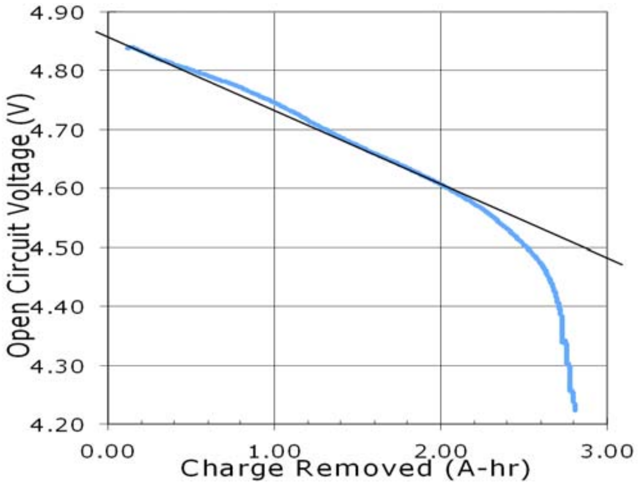

Figure 12 *The lithium-ion cells used in the Milwaukee Tool V28 batteries show linear open-circuit (no-load) terminal voltage vs. depth-of-discharge over much of their range. This allows easy estimation of battery state of charge (SOC) from terminal voltage at startup.*

Table 6 Battery properties vs. temperature

Temperature	R_{total} (Ω)	R (Ω)	$R_{transient}$(Ω)	τ (ms)
–10 °C	0.500	0.338	0.162	25
+25 °C	0.186	0.133	0.038	24
+50 °C	0.135	0.108	0.023	24

Based on testing, the battery resistance and time constants were determined as shown in Table 6. The internal resistance of the battery has significant temperature dependence, increasing by a factor of 2.5 when the battery is cold. As battery temperature is already monitored by the vehicle controller, this feedback can be incorporated into the SOC estimation algorithm. In practice, estimates of internal resistances can be continually updated within the control algorithm, based on knowledge of voltage, current, and battery temperature. Figure 13 shows the output of this estimator applied to battery testing performed by the Wisconsin team. It is clear that the terminal voltage varies widely during loading, but, after accounting for the effects of internal resistance, the estimated open-circuit voltage closely tracks the predicted voltage based on current-time integration.

The control system continuously estimates battery SOC during vehicle operation, allowing prediction of a "distance to empty" at the current speed, which is displayed on the Mototron MiniView multifunction gauge. At a point where 10% of energy is remaining, an indicator is illuminated on the dashboard, further warning the driver that the battery is nearly exhausted. At 3% remaining energy, the maximum depth-of-discharge permitted by the manufacturer, the drive is disabled and the vehicle shuts down to avoid damage to the batteries.

VEHICLE SAFETY AND DIAGNOSTIC CAPABILTIES – The Mototron system has a sophisticated fault detection mechanism to ensure safety and diagnose vehicle malfunction. Every input is continuously range-checked to detect failed or disconnected sensors. Continuous CAN communications between the vehicle and motor controller is necessary for operation of the electric drive (shutdown automatically occurs within 50 ms of a communication loss), and a multitude of temperature sensors ensures that temperature thresholds are not exceeded. Faults are signaled to the operator using flash codes on the "Check Engine" dashboard indicator, and sensor values and internal control strategy variables can be examined at any time using a Mototron MiniView multifunction gauge. The snowmobile's dashboard temperature indicator warns the driver if performance is being reduced due to low or high temperatures.

For more extensive diagnostic capabilities, a laptop can be connected to serial ports on each controller, allowing simple monitoring and modification of inputs and control strategy variable, adjustment of calibrations, or even reflashing the controllers with new programs. With an available network connection, this diagnostic process can be performed by off-site personnel over the internet.

For electrical safety, the high voltage bus is entirely isolated from the chassis and auxiliary electrical system. This isolation is continuously monitored using a Bender RCM475LY Ground Fault Monitor. If an unintentional connection between the DC or AC high-voltage busses and the chassis permitting leakage current in excess of 10 mA is detected, an audible alarm is sounded, the electric drive is shut off, and all vehicle lights are flashed continuously to warn the operator. This improves safety by warning of hazards caused by improper servicing or physical damage to the battery. The emergency stop button and tether disable all outputs from the controller and physically interrupt power to the main high-voltage contactors, disabling the electric drive.

The multiple battery strings introduce complexity, but also offer an advantage in redundancy, as a single-cell failure within the battery will generally only knock out only 1/8 of the battery capacity – the failed string is automatically identified by the controller so it can be disconnected by the operator and the vehicle can be safely ridden back to base.

The vehicle has an on-board data acquisition system which logs every aspect of its operation once per second. Recorded fields include time, position (via GPS), speed, user inputs, commanded and actual torque, battery voltage and per-string current, estimated battery stage of charge, battery, motor, and inverter temperature, cruise control state, and charging system state. During last summer's stay in Greenland, these logs were downloaded by Summit Camp staff every two weeks and sent to team members in Wisconsin, allowing continual fine-tuning of the control strategy. This data has aided the team in refining the vehicle design for this year's competition.

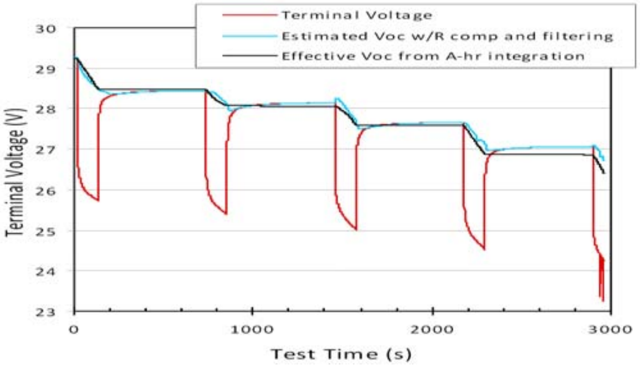

Figure 13 *Battery terminal voltage (red) drops enormously under load, complicating SOC estimation during varying current draws. Resistance compensation with filtering (sky blue) allows improved estimation of the effective open-circuit voltage (black), even during conditions of rapid and varying discharge.*

CHASSIS AND HANDLING

The BuckEV is based on a 2006 Polaris Fusion IQ chassis. The chassis allows for easy access to the entire engine bay through the hood and two removable side panels. The side panels open up to two large bays well-suited for mounting batteries. Each bay holds 12 modules, keeping transverse weight distribution balanced and the center of gravity low. The chassis also has a long fuel tank extending well underneath the seat. Modification to the fuel tank allowed space for 78 battery modules (Figure 10b) with no change in exterior appearance or reduction in seat padding. With a substantial portion of the batteries mounted over the track and the rest mounted at the extreme aft of the hood compartment, good longitudinal weight distribution is maintained, providing a balance between handling and economy.

An important consideration in choosing the chassis was to maximize usability for a variety of different riders at the research stations. The Fusion IQ chassis is designed to be comfortable for almost any rider. The Polaris Rider Select system allows the handlebar position to be selected from seven different settings ranging over 15 cm (6 in) of arc and 2.5 cm (1 in) of height. This enables optimal rider position and control for users with differing heights. The IQ seat is 15 cm (6 in) higher than traditional Polaris seats, giving a more ergonomic rider position. Its contours allow the rider to move forward for better control over rough terrain or sit further aft for maximum comfort.

The rear suspension offers 30 cm (12 in) of vertical travel, preventing bottoming out over rough terrain. The new independent front A-arm suspension has 25 cm (10 in) of travel to provide better control over rough terrain. The front springs and rear springs were replaced with higher rate components and the rear suspension was adjusted to maintain stock ride height.

For rider protection and to prevent slipping, the chassis has wide running boards with an integrated traction surface. Finally, the IQ chassis is equipped with Accu-Track 2 skis, featuring an extra-deep keel and dual carbide runners, to maximize control and turning ability over hard pack and icy surfaces.

NOISE REDUCTION

Noise reduction was prioritized below range and performance, as research-related snowmobile operations tend to be take place in isolated locations (without neighbors), be low in volume (minimizing impact on wildlife), and are conducted by researchers who tend to be interested solely in utility and little concerned with other factors. Furthermore, noise from electrical sleds is typically minimal.

Sound testing of the BuckEV prior to the '08 competition showed noise levels at 58-60 dB at 48 km/hr (30 mph) and 54-57 dB at 24 km/hr (15 mph), based on the peak of the A-weighted fast response measurements during a pass-by at 15.2 m (50 ft) on each side. These levels correspond to normal spoken conversation and are not disruptive to bystanders. Sound level measured at the ear of the occupant was 76 dB, quieter than the standard for an IC-powered snowmobile measured at 15.2 m (50 ft), and well below the OSHA standard [12] for an eight-hour workday.

With the electrical drivetrain, mechanical noise from the chain-case and track is more evident and steps were taken to reduce sound emission from the BuckEV. Spectral sound analysis had previously been conducted on an IC-engine powered snowmobile to determine the major sources of sound emission [13]. The sources of the three major peaks were determined by calculating the first and second order contributions of several snowmobile components at 72 km/hr (45 mi). Major noise peaks are the track/paddle interface at 300 Hz and 600 Hz and the chain case at 1350 Hz and 2700 Hz. Consequently, mechanical noise reduction on the BuckEV has been focused on the chain-case and drive paddles. As described earlier, the newly designed chain-case is fully sealed with an oil bath to minimize chain noise and has a polymer cover to dampen emitted noise.

Due to the competition scoring's major emphasis on noise, a drive paddle noise dampener, invented and developed by team members in 2004 [14], was installed on the front arm of the rear suspension. This dampener contains and attenuates the sound produced by the drive paddles contacting the drive lugs on the track. Previously testing shows that this dampener entirely eliminates the drive paddle sound power at 300 Hz and its harmonics. At the 2008 CSC, the BuckEV had measured noise levels of 55 dB according to the competition test procedure, the best of all entrants, and also yielded the best subjective noise evaluation.

PERFORMANCE

In the 2008 competition, the sled required 8.34 s to accelerate from a stop to 150 m (500 ft). The acceleration test took place on extremely hard-packed snow and traction was the limiting factor. Traction studs, added to improve towing performance, have substantially improved traction, leading to a predicted acceleration time of 6.9 s, assuming test conditions are similar to last year. Test data from the Greenland field trial shows that the fastest sustained acceleration was 20-50 mph during a 3 s period with full torque command, but that operator demands for maximum torque were exceedingly rare.

RANGE

ROAD LOAD ANALYSIS – The battery was initially designed in 2008 based on the road-load model by Auth [8], which predicted power demands of 4.6 kW (6.2 hp) at 32 km/hr (20 mph). With the battery at a mean voltage of 320 V, this corresponded to a current of 14 A, so the 19.6 A-hr pack used in 2008 should have lasted 1.4 hours and allowed a range of 45 km (28 mi). This road-load figure and the resulting range were believed to be optimistic, as initial testing showed a current consumption of 20 A at 32 km/hr (20 mph), suggesting a battery pack with ~20 A-hr capacity would travel 32 km (20 mi) at 32 km/hr (20 mph).

Road-load testing was performed with a partial battery pack as soon as the 2008 vehicle could be made operational. The vehicle was tested at a weight approximately 45 kg (100 lbs) below its final weight as well as in a ballasted configuration that approximates its finished weight with a 90 kg (200 lb) rider. Battery current was recorded (including auxiliary loads) at speeds in 8 km/hr (5 mph) increments from 8 km/hr (5 mph) to 56 km/hr (35 mph). The useful pack capacity was estimated to be 19.0 A-hr, corresponding to the maximum 97% depth-of-discharge recommended by the manufacturer. Typical per-string currents were below 6 A at these speeds, low enough that high-current capacity derating is unnecessary and nearly full capacity should be available.

This analysis, shown in Figure 14, predicted that efficiency is highest at relatively low speeds, below 25 km/hr (15 mph). The predictions at very low speed (8 km/hr, 5 mph) are considered to be unreliable due to difficulty in maintaining precise speed control and large fluctuations in load and non-linear track behavior at very low track speeds.

RANGE PREDICTIONS – In 2008, the authors hoped that a peak range of 40-44 km (25-27 mi) would be achieved at speeds of 16-24 km/hr (10-15 mph), and a maximum range of 32-34 km (20-21 mi) would be achieved at a speed of 32 km/hr (20 mph), with a 20% margin of error. The 2008 CSC results reflect 29.0 km (18.0 mi) range (at 20 mph), though the odometer (which had previously been calibrated against GPS) showed a 31.5 km (19.6 mi) range, a 9% difference. In either case, this is well within the 20 mi ± 20% prediction in the 2008 design paper.

The snow condition for the competition range event was highly packed powder (optimal for minimizing road load), the vehicle started in a heated garage, and the vehicle was operated by a small individual with no cargo, so real-world range is known to be lower. Operation off-trail and especially in deep snow causes enormous reductions in range, although higher speeds mitigate the losses somewhat, since the sled can then float above the snow. Figure 14 summarizes the range estimates from all the different experiments based on the '08 battery.

Considering the increased pack capacity and improved system efficiency, the authors predict a range of 40 km (24.3 mi) on the endurance event, assuming similar snow conditions as last year.

COMPETITIVE ANALYSIS – These range predictions were compared to analyses from other teams in previous years. Propelling the BuckEV at 32 km/hr (20 mph) requires approximately 6.5 kW (8.7 hp). This is substantially lower than the 13 kW (17 hp) reported by Utah State in their 2007 tech paper [15], a figure based on drag force tests. As their vehicle was presumably tested at a mass of 566 kg (1249 lb, 1049 lb sled at competition plus 200 lb estimated for rider) and our vehicle as tested was approximately 331 kg (730 lb, 570 lb sled plus 160 lb rider) and rolling resistance is assumed to vary approximately linearly with mass, adjusting their figure by a scale factor of 0.58 yields a predicted rolling resistance for BuckEV of 7.5 kW (10 hp), a figure about 15% higher than measured. With this more pessimistic figure for rolling resistance, the BuckEV's range would be reduced by 15-20%, dropping it to approximately 27 km (17 mi).

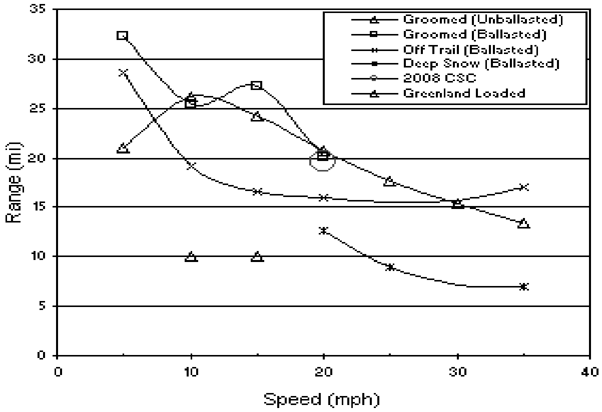

Figure 14 *Predicted range for the '08 design at various speeds. Initial testing performed with a reduced battery pack and the vehicle was ballasted to simulate its final weight. The 20 mi range based on the 2008 CSC Range event, and the 10 mi range prediction is based on towing a loaded sled in Greenland.*

Considering energy storage, the BuckEV has a 6.59 kW-hr battery, twice the 3.24 kW-hr pack in the ’07 McGill sled [16] and 80% the size of the 7.92 kW-hr pack in the ’07 Utah sled [17]. Both the McGill and Utah sled were able to complete the ten-mile range event in ‘07, but were not tested to exhaustion. McGill reported a typical vehicle range outside the competition of 9.0 – 9.5 mi [18] while Utah predicted a range of 8.5 mi but did not report data test data [17]. The McGill sled used a CVT to transmit power from the motor to the track, leading to a 20% efficiency loss [8], so it is reasonable to believe that the direct-driven BuckEV vehicle could achieve more than double its range. The 20% larger Utah pack was for a vehicle with an estimated operating weight 44% higher and a motor with 6% lower efficiency [19], predicting a range of 20.4 km (12.7 mi) for BuckEV. In 2008, South Dakota used a 9.6 kW-hr Li-Ion battery and an 85% efficient motor coupled through an 80% efficient CVT (at their target motor speed) on a 770 lb sled [20]. The lower efficiency of their drivetrain should yield available energy comparable to our ’08 sled, predicting a 16 mi range, twice the 7.9 mi they actually achieved. This suggests that motor and clutch efficiency were reduced due to operating at higher motor speeds than desired, further emphasizing the disadvantages of DC motors and conventional clutches.

TESTING – Prior to the ’08 competition, a full range test with the full battery was performed on the finished 2008 vehicle. The vehicle traveled 22.0 km (13.7 mi, measured by odometer calibrated against GPS) on an 1.0 km (0.6 mi) oval course at a target speed of 32 km/hr (20 mph) before reaching the predetermined stopping criteria of 15% estimated remaining battery capacity. If the test had been continued to the 97% depth-of-discharge, the expected distance would have been 25.2 km (15.6 mi). Snow conditions for the test were 20 cm (8 in) of snow, consisting of 15 cm (6 in) of loose unconsolidated powder atop 5 cm (2 in) of densely packed snow. The sled had to break trail during the first lap, requiring a measured power consumption of 10 kW, but then followed in its tracks, for a power consumption of 6 kW, increasing gradually to 7 kW. The increased power consumption towards the end is attributed to the sled sinking deeper into the snow, to the point that the front suspension was dragging in loose snow. At the completion of the test, the measured depth of the ski tracks was 8 cm (3 in) and the depth of the drive track was 10 cm (4 in). It was believed that better snow conditions for the competition range event would impart a 10-20% reduction in road load, improving fuel economy proportionally and yielding a predicted “range [of] 27.7 – 30.2 km (17.2 – 18.8 mi)” [15], exactly bracketing the official range achieved at that competition.

Testing in Greenland showed that towing a trailer sled leads to enormous increases in road load and thus substantially decreases in range. The loaded range is a factor of 2-3 lower than the range measured in the competition range event, suggesting that a minimum unloaded range of 20-30 miles is necessary to reliably achieve a ten mile useful range (Figure 15, Figure 16, and Figure 17).

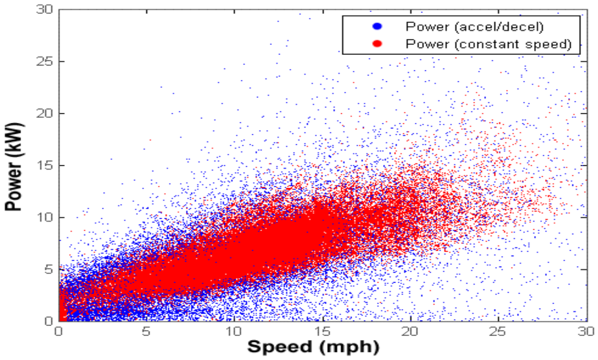

Figure 15 *This road load plot shows power vs. speed (for both steady state conditions and during acceleration) for the entire summer ’08 season in Greenland.*

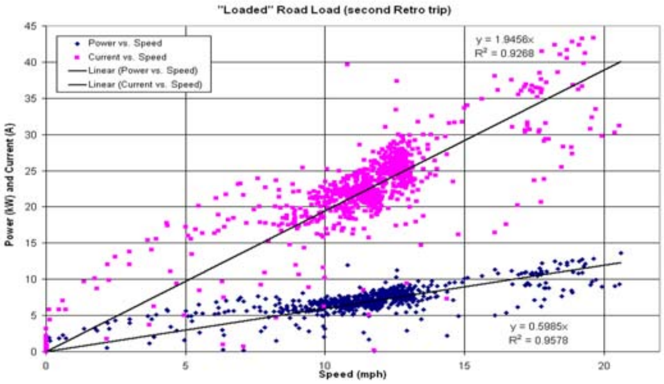

Figure 16 *Plotting power and current against speed during periods of steady-state operation yields a road load curve. This data was taken during a 5 km (3 mi) trip, with an operator and one passenger on the vehicle and towing a trailer sled with 100 kg (220 lb) of equipment and two additional passengers, with ambient temperatures of –15℃ (+5℉), on two inches of loosely consolidated snow atop a 3 km (1.9 mi) thick heavily packed base. Under these conditions, a range of 16 km (10 mi) can be achieved.*

TOWING CAPACITY

Given a sufficiently powerful drivetrain, towing capacity is limited by traction and ultimately vehicle weight. In the 2008 competition, the towing event scores were ordered by weight, with the heaviest sled winning and the lightest sled coming in last. Increasing sled weight is clearly undesirable as it negatively impacts every other aspect of performance, including range, acceleration, load capacity, and handling. While ballast can be temporarily added to a lighter sled to improve traction for towing, a heavier sled always must suffer the consequences of its increased weight. The competition scoring similarly penalizes heavy sleds. The combined points received from the Drawbar and Weight events in the 2008 competition (excluding Clarkson, as motor controller issues prevented their sled from achieving full torque) are ordered from lightest (most points) to heaviest (fewest points).

Theoretical modeling predicted that drivetrain and gearing used last year would achieve 275 kgf (650 lbf) of pull on the hitch up to a speed of 56 km/hr (35 mph), assuming that traction could be maintained. The drawbar pull procedure proscribed by the competition rules yielded a maximum force of 206 kgf (455 lbf) on a hard-packed snow surface. The electric drivetrain's linear and smooth torque deliver delivery allowed the operator to precisely modulate track slippage for maximum traction, but towing was ultimately limited by the track spinning.

Two ways to improve pull force without increasing vehicle weight are to shift the weight balance aft and to increase the effective coefficient of friction between the track and snow. To shift more weight onto the track, we have added three battery strings to the back of the sled and removed two from the front, effectively moving 30 kg of weight from the skis to the track. This should improve our weight distribution (with a 200 lb rider) from 57% on the track ('08) to 66% of the weight on the track, increasing normal forces between the track and the snow.

Traction studs (Woody's Golddigger 60°-carbide Traction Master 1.175" in a 96-stud configuration) will be installed on the track to further improve traction. Studs have been shown to double the tractive force between a track and a "Scraped/Hard-packed/Icy Roads" [21]. On an appropriate surface, the use of studs will permit a much higher static tractive effort compared to the normal force, substantially improving towing capacity without an increase in weight.

It is important that a reasonable towing capacity be maintained as speed is increased. In the 2007 competition, the winning sled produced a maximum pull of 385 kgf (850 lbf) at 6.4 km/hr (4 mph). However, since that sled used a DC brushless electric motor with a CVT, their maximum tractive effort will fall precipitously at higher speeds due to the loss of gear reduction in the CVT as well as field weakening of the electric motor. The direct-driven AC-induction drivetrain used in BucKEV will maintain full torque and towing capacity up to a practically usable towing speed. The NSF has indicated that a reasonable towing capacity should be available at speeds up to 25-40 km/hr (15-25 mph).

COST

While cost is always a factor in vehicle design, it is not a major factor in competition scoring. The "MSRP" event, which is based on a crude and unrealistic calculation of vehicle cost, counts for only 50 points, less than every other applicable event. The vehicle with the highest "cost" can lose at most 50 points relative to the other teams, regardless of the actual cost difference, even though increased spending permits significantly larger point gains in other events (e.g. range, acceleration, and handling). Thus, cost was not a primary consideration in this design, as it would be if the vehicle were designed with a commercial mindset. As this scoring system encourages unreasonably high spending, cost remained a significant design consideration in light of our team's limited budget, the needs of other student vehicle projects, and the hope of building such vehicles for the NSF in the future. Though vehicle cost is a major criterion for the NSF, the arbitrary "MSRP" procedure specified by the rules does not yield a cost estimate that does not come anywhere close to the actual cost of building either a one-off prototype (which is much higher) or full-scale production vehicles (which would be much lower).

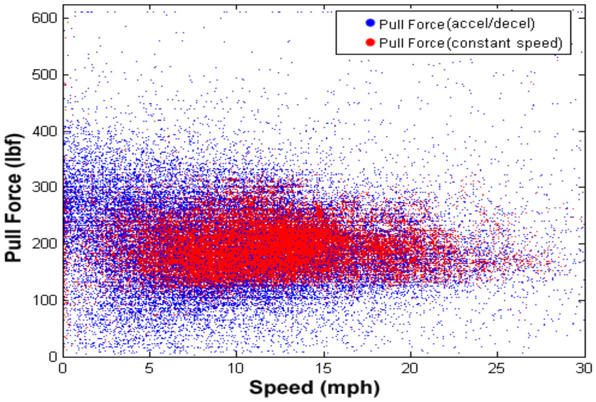

Figure 17 *Tractive effort is plotted against speed for the full Greenland dataset. Data points where speed is constant are plotted in red, while points of acceleration/slowing are plotted in blue. This shows that a steady-state tractive force of approximately 130 lbf is required to move the sled and rider (independently of speed, between 5-15 mph), with towed sleds causing an additional 100-150 of drag.*

Many systems used in the vehicle are prototypes or produced in small numbers and have correspondingly high prices, but would be relatively inexpensive if mass-produced. Batteries will unavoidably be a major component of vehicle cost, as the only currently available battery technology suitable for polar use in these applications is lithium-ion, which is necessarily expensive. It is important to remember that all polar operations are expensive. The NSF has indicated that round-trip transportation of a snow machine between New York and Summit costs over $23,000 (based on summer 2008 prices from the Air National Guard 109th Airlift Wing), a substantial fraction of the $29,220.35 MSRP calculated for our vehicle in the 2008 competition scoring.

SUMMARY

In 2008, the University of Wisconsin team leveraged ten years of experience building hybrid-electric and pure-electric vehicles to build a world-class electric snowmobile in a single season. The snowmobile exceeded all performance goals of the CSC and NSF and was successful in its first season in Greenland. The design was refined this year to build a second-generation that improves performance in nearly every measured respect, coming close to the design performance goals set by the Wisconsin team.

Extensive modeling of snowmobile dynamics was performed prior to establishing the design to optimize component selection and maximize performance. Solid modeling of all major components prior to fabrication allowed a rapid design cycle and enabled all parts to fit together the first time. Substantial effort was also put into designing a new motor controller, battery system, and belt drive for the 2010 competition – construction of this vehicle has already begun and will continue immediately after the 2009 competition ends.

Reliability, serviceability, and safety were considered foremost in the design of BuckEV. The vehicle is modular and all major components, including the batteries, control system and high-voltage wiring, motor controller, motor, and chain-case can be removed individually, without requiring complete disassembly of the vehicle.

The operator interface is identical to that of a conventional IC-powered sled and a rider can easily and safely use the BuckEV without any additional training. The control system continuously monitors battery charge and the health of all internal systems and, to the greatest extent possible, ensures system operation in a manner that will not endanger the rider or cause vehicle damage.

We believe this vehicle to be a prototype of a tool the research community has sought to simplify polar operations. It is well suited and has proven itself for safe transportation of personnel and equipment in extreme climates and conditions.

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