Design and Construction 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 and constructed an electric snowmobile with 32 km (20 mi) range and acceleration comparable to a 75+ kW (100+ hp) internal-combustion-powered snowmobile. Starting with an Polaris IQ Fusion chassis, a direct-drive chaincase was engineered to couple a General Motors EV1 copper-bar rotor AC Induction electric motor to the stock track drive paddle. Eighty-four 28 V, 2.8 A-hr Lithium-Ion battery modules supplied by Milwaukee Tool compose a battery pack that stores 6.2 kW-hours of energy at a nominal voltage of 336 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 326 kg (717 lb). The vehicle, called the BuckEV, accelerates to 150 m (500 ft) in 6.9 seconds and has a top speed of 160 km/hr (99 mph) with a pass-by sound level of 58 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.

Table 1. BuckEV Design Goals

Parameter	Competition Goal	UW Goal	UW Achieved
Range	≥ 16 km (10 mi)	≥ 32 km (20 mi)	30 km (18.6 mi)
Top Speed (IC goal)	≥ 70 km/hr (45 mph)	≥ 140 km/hr (90 mph)	≥ 160 km/hr (99 mph)
Acceleration (150 m)	≤12 s	≤10 s	6.9 s
Emissions	Zero	Zero	Zero
Vehicle Weight		≤ 340 kg (750 lb)	326 kg (717 lb)
Drawbar Pull		≥ 250 kgf (550 lbf)	250 kgf (550 lbf)
Noise (IC)	≤ 78 dB	≤ 60 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 Competition (CSC) with the goal of encouraging the development of zero-emissions utility snowmobiles to support scientific research. A number of environmental research projects taking place at locations such as Summit Station (Greenland) and South Pole Station (Antarctica) involve sampling 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 are 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.

ELECTRIC ENERGY STORAGE REVIEW

When chemical potential energy (liquid fuels) can 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.

Currently, there are three families of battery chemistry either available for use in vehicular applications – lead acid absorbent glass mat (AGM), nickel metal hydride (NiMH) and lithium ion (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. Figure 1 graphically depicts the number of cells of each battery chemistry needed to produce 12 V. 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 [1].

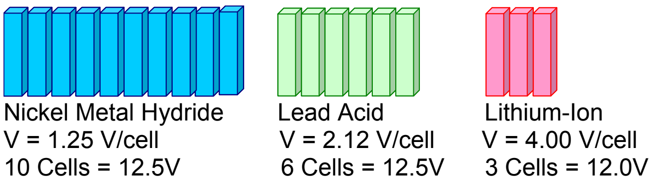

Figure 1 *Depiction of the number of cells needed for each battery chemistry to supply 12 volts, adapted from Dougherty [1].*

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 2. 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 lithium-ion and NiMH at all depths of discharge (Figure 2). NiMH and Lithium-ion batteries offer reasonable performance in all three criteria, with Lithium-ion having an advantage in energy density [2].

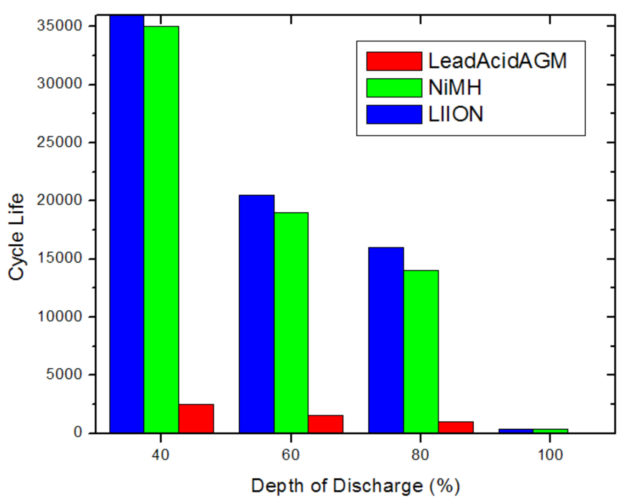

Figure 2 *Cycle life for each battery chemistry for various different state-of-charge swings, adapted from Dougherty [1].*

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.

Table 2 Comparison of battery chemistries [3]

	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

Early work by SnoLectric demonstrated the advantages of higher voltage electrical systems [4]. 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.

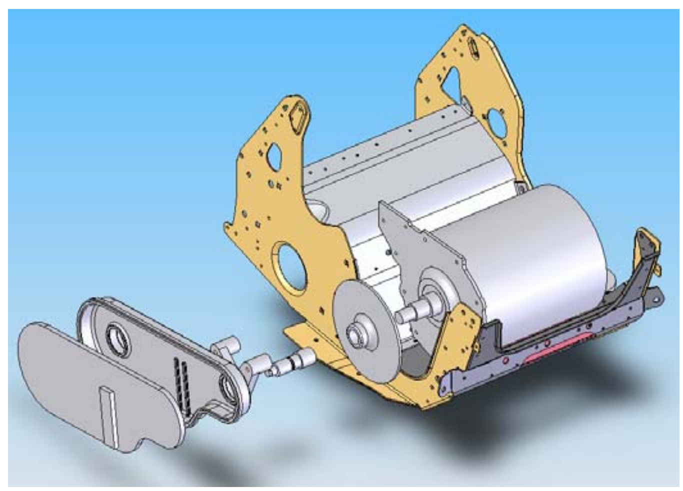

Figure 3 *Overview of the BuckEV drivetrain. The electric motor is coupled through the brake rotor into custom-designed chain-case.*

DRIVETRAIN

The electric drive system consists of a Delphi EV1 motor controlled by an Azure Dynamics DMOC445LC motor controller and powered by a battery pack consists of 588 lithium-ion cells supplied by Milwaukee Tool.

TRACTION MOTOR – Permanent magnet synchronous motors can 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. For this reason an AC induction motor was chosen for BuckEV. AC induction motors are the most robust type of electric motor design that still offers good efficiency.

__Figure 4__ Photograph of the Delphi EV1 copper-bar-rotor AC induction electric motor, with a peak power of 110 kW. The transaxle used in the GM EV1 was removed and replaced with a student-designed endplate (not shown).

The GM EV1 motor (Figure 4), developed by Delphi, features a copper bar rotor design which significantly reduces losses and increases power density. The motor's aluminum water-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 paddles by a custom-designed chaincase.

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 ranging from 20-40 Nm, as shown in Figure 5. 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, 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 which consumes relatively little total energy.

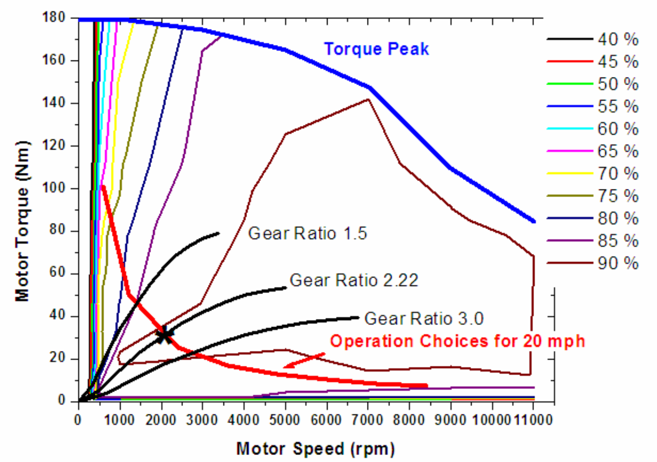

__Figure 5__ The EV1 motor operates above 90% efficiency over a wide torque/speed envelope. Road-load curves for several possible reduction ratios are shown, with the red constant-power line indicating the options for 32 km/hr (20 mph) operation. A reduction ratio of 2.22 was chosen to maximize efficiency at 20 mph, while still giving good acceleration and top speed.

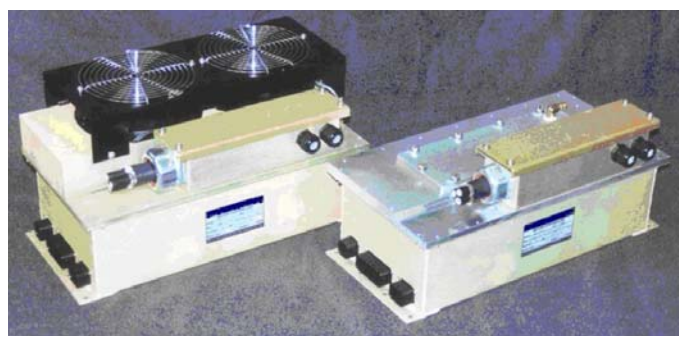

__Figure 6__ Photograph of Azure Dynamics DMOC445LC liquid-cooled 78 kW motor controller (right), alongside the air-cooled unit (left). The liquid-cooled controller offers the same power in a substantially smaller package.

MOTOR CONTROLLER – An Azure Dynamics DMOC445LC motor controller/inverter (Figure 6) 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 nominal battery input voltage of up to 336 V and can deliver 78 kW (105 hp) peak power and 46 kW (62 hp) continuous power at 312 V.

COUPLING – The coupling connecting the electric motor to the track drive paddles was analyzed using 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 multiplying 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 3, a chain drive type is the best overall selection.

Table 3 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 chaincase's center-to-center sprocket spacing was two inches shorter than necessary. A new chaincase was designed and constructed to transmit torque from the motor drive shaft to the vehicle's track drive shaft. To maximize performance and durability, the new chaincase was designed to use as many stock Polaris parts, including the chain tensioning system, bearings, and seals. The chaincase was CNC-machined out of aluminum and the cover out of a homopolymer acetal (Delrin™).

Because of the increased center spacing, a longer chain was required, and the 92P chain was replaced with a 104P. 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 chaincase 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.

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 84 Milwaukee Tool V28 battery modules. These units are intended for use in cordless tools and have been designed for high capacity at rapid discharge rates (40 A continuous). 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. The team has as good working relationship with Milwaukee Tool, having collaborated in the past on two electrical vehicle designs using Nickel Cadmium batteries [5,6].

Each module contains seven 4.0 V, 2.8 A-hr cylindrical cells connected in series. The pack is configured into seven parallel strings of twelve modules in series (84 cells per string), yielding a capacity of 19.6 A-hr at a nominal voltage of 336 V, capable of continuous discharge at 280 A (matching the current limit of the electric drive). Each module weighs 1.04 kg as manufactured and 0.97 kg after being modified for installation in the sled, leading to a total pack weight of 81.5 kg (180 lbs). Pack parameters are summarized in Table 4.

Table 4 Battery Pack Specification

Characteristic	Milwaukee Tool Li-Ion
Battery Mass	81.5 kg
Nominal Voltage	336 V
Capacity	19.6 A-hr
Energy	6590 W-hr
Power Density	1150 W/kg
Energy Density	80 W-hr/kg

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 7.

The battery pack was initially sized based on road-load predictions from the M.S. thesis of Auth [7] 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.

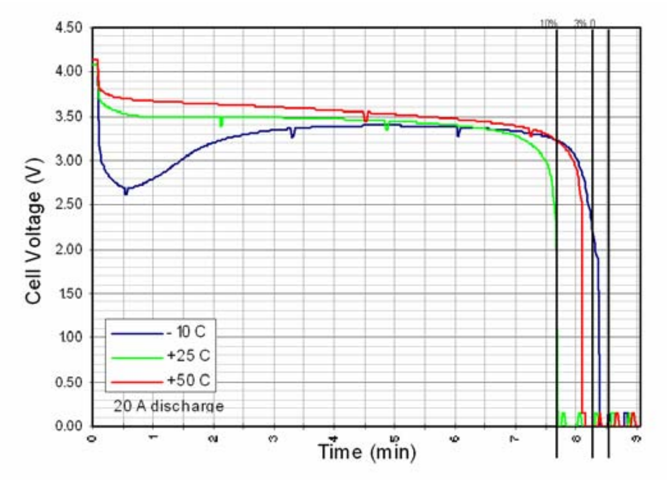

Figure 7 *The Milwaukee Tool V28 batteries demonstrate good performance down to -10°C in a 20 A discharge test. The cells initially show a 30% reduction of terminal voltage, but rapidly warm up to the point that full power is available. Note that low-temperature operation yields only about a 7% loss of energy capacity compared to 50°C operation (which is very detrimental to battery life) and actually offers slightly more energy than discharge at 25°C.*

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. However, this experience was limited to NiMH cells, so the parallel strings are each fused separately 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 production.

Safety, weight balance, center-of-gravity height, and serviceability were foremost in the design of the battery pack. The batteries were mounted in five individual units which can be easily removed and serviced separately from the sled. Two units (each containing 24 modules in two strings) were mounted in each of the side pods of the hood, while the fifth unit (containing 36 modules in three strings) was mounted under the fuel tank.

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 battery can be entirely isolated from the vehicle by disconnecting and capping two connectors, allowing vehicle service without high-voltage electrical hazards.

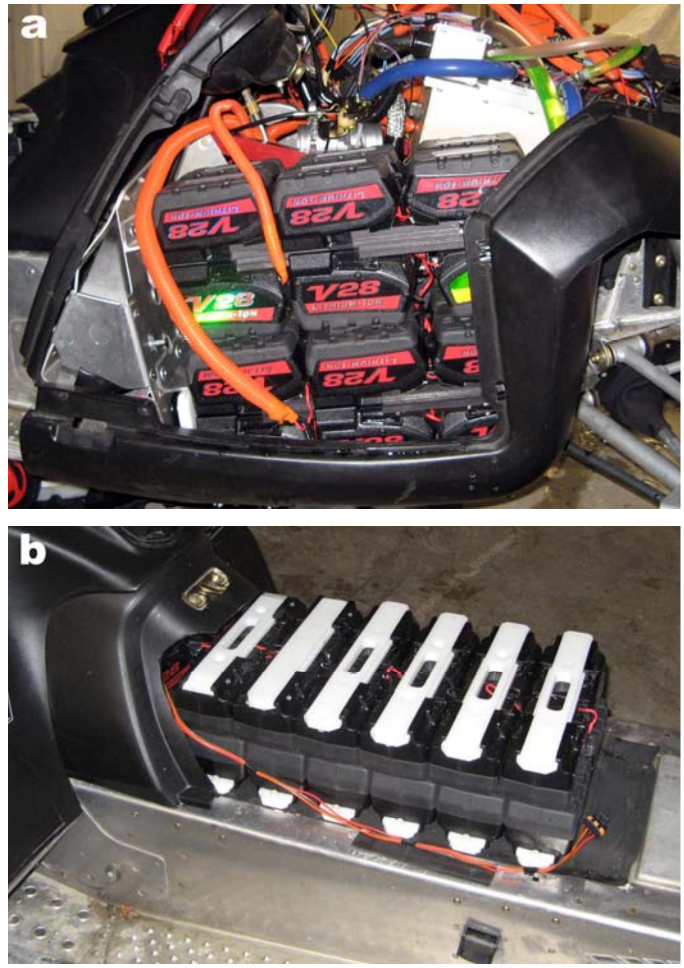

Figure 8 *The BuckEV's battery is split into three removable modules, one in each of the side pods of the hood (a) and the third under the seat (b). Electrical safety was a major factor in the design of the energy storage system, and the design ensures that no conductive surfaces are exposed.*

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%.

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 to a rear-mounted heat-exchanger. 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 water-cooled, the entire hood is sealed, preventing intrusion of water or snow to improve reliability and ease of servicing.

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 per cell and an estimated battery heat capacity of 800 J/kg/°C [10], a peak temperature rate of increase of 13 K/minute 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 substantial cooling should take place due to loss of heat 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.

CHARGING SYSTEM – The sled is charged using a 6 kW off-board charger. The charger is powered by 230 VAC and is capable of charging at rates of up to 15 A at 400 V. The charger programmed to follows an algorithm recommended by the battery manufacturer. First the batteries are charged at a current of 2.5 A/string until the cells reach 4.25 V (357 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 75 minutes. The batteries are capable of rapid charging at up to 40 A/string, allowing full charge in approximately 20 minutes, but this would require a power connection of ~75A at 230VAC, which is not commonly available, and may reduce battery life.

HYBRID CONTROL

CONTROL HARDWARE - The BuckEV uses a MotoTron ECM-0555-080 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 the automotive environment. 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 seven 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 a 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 charge is conserved with this chemistry. 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 which relies not only on battery current integration, but also feedback from battery voltage, can provide more robust battery SOC calculations [8,9].

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 9. 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. 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.

Table 5 Variations in battery properties with temperature were characterized to improve estimation of SOC.

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 5. 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. Figure 12 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.

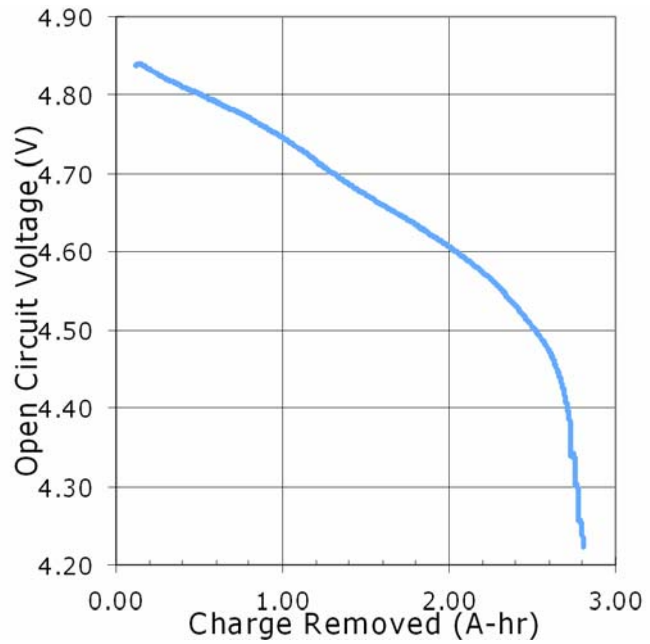

Figure 9 *The lithium-ion cells used in the Milwaukee Tool V28 batteries show linear open-circuit (no-load) terminal voltage vs. depth-of-discharge over much of their range. This allows easy estimation of battery state of charge (SOC) from terminal voltage at startup.*

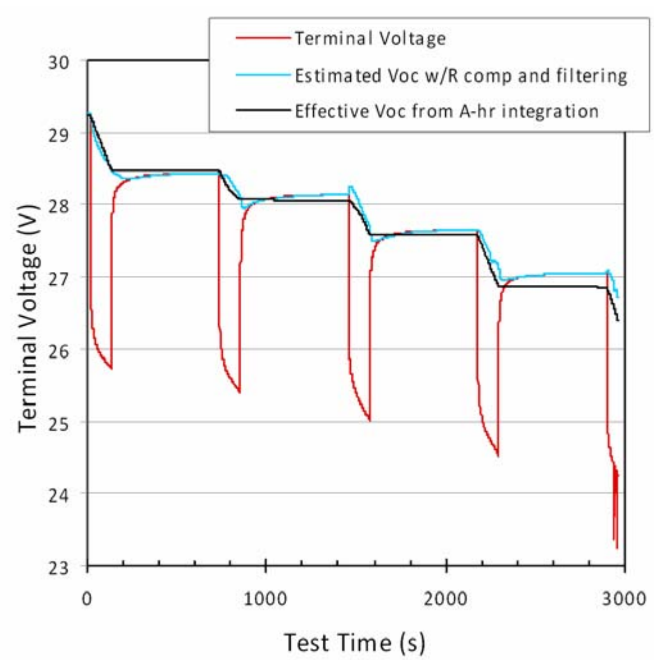

Figure 10 *Battery terminal voltage (red) drops enormously under load, complicating SOC estimation during varying current draws. Resistance compensation with filtering (sky blue) allows improved estimation of the effective open-circuit voltage (black), even during conditions of rapid and varying discharge.*

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, 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. A Bender RCM475LY Ground Fault Monitor continuously monitors this isolation – detecting unintentional connections between the DC and AC high-voltage busses and the chassis – and sounds an audible alarm if leakage current in excess of 10 mA is detected. 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.

CHASSIS AND HANDLING

The BuckEV is based on a 2006 Polaris Fusion IQ chassis (Figure 11). 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 24 battery modules (Figure 8a), 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 36 battery modules (Figure 8b) 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.

Figure 11 *The IQ Fusion chassis provides excellent handling for all types of rider over a variety of terrain.*

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 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 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 for an eight-hour workday.

With the electrical drivetrain, mechanical noise from the chaincase 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 [11]. 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 and 600 Hz and the chain case at 1350 and 2700 Hz. Consequently, mechanical noise reduction on the BuckEV has been focused on the chaincase and drive paddles. As described earlier, the newly-designed chaincase is fully sealed with an oil bath to minimize chain noise and has a polymer cover to dampen emitted noise.

To reduce track noise, a drive paddle noise dampener, invented and developed by team members in 2004 [12], was installed on the front arm of the rear suspension. This drive paddle sound dampener isolates 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.

PERFORMANCE

The full complement of batteries was not yet installed at the time of acceleration testing, so full acceleration performance could not be tested. With a partial battery pack consisting of three out of seven strings, the electric drive must be limited to a peak power of 28.75 kW (39 hp) and a peak battery current of 120 A. Acceleration from a stop to (150 m) 500 ft required 11.8 s with a peak speed of 72 km/hr (45 mph), slightly better than the competition goal of 12.0 s (which has never been met by an electric sled). This testing was performed on loose powder (the only surface available, aside from sheet ice) and traction was the limiting factor for nearly the entire run. With the full seven-string battery installed and the power and torque limits increased to their design values of 78 kW and 180 Nm, it is expected that the acceleration time will improve to 6.9 s.

RANGE

MODELING AND PREDICTIONS – Analysis based on the road-load model by Auth [7] predicts 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 battery pack, this corresponds to a current of 14 A, so the 19.6 A-hr pack would last 1.4 hours and allow a range of 45 km (28 mi). This road-load figure and the resulting range are believed to be optimistic. Initial testing showed a current consumption of 20 A at 32 km/hr (20 mph), suggesting a battery pack with ~20 A-hr capacity to 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 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, low enough that high-power capacity derating is unnecessary and nearly full capacity should be available.

This analysis, shown in Figure 12, predicts 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. The authors believe that a peak range of 40-44 km (25-27 mi) will be achieved at speeds of 16-24 km/hr (10-15 mph), and a maximum range of 32-34 km (20-21 mi) will be achieved at a speed of 32 km/hr (20 mph). Due to the limited accuracy of these measurements, the authors believe the tolerance of these range figures should on the order of 20%. Operation off-trail and especially in deep snow causes enormous reductions in range, although higher speeds mitigate the losses somewhat, since the sled is able to float above the snow.

To consider the realism of these range predictions, this data was compared to analyses from other teams in previous years. From a power standpoint, to propel the BuckEV at 32 km/hr (20 mph) requires approximately 20 A at 325 V, corresponding 6.5 kW (8.7 hp). This is substantially lower than the approximately 13 kW (17 hp) reported by Utah State in their 2007 tech paper [13], a figure based on drag 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).

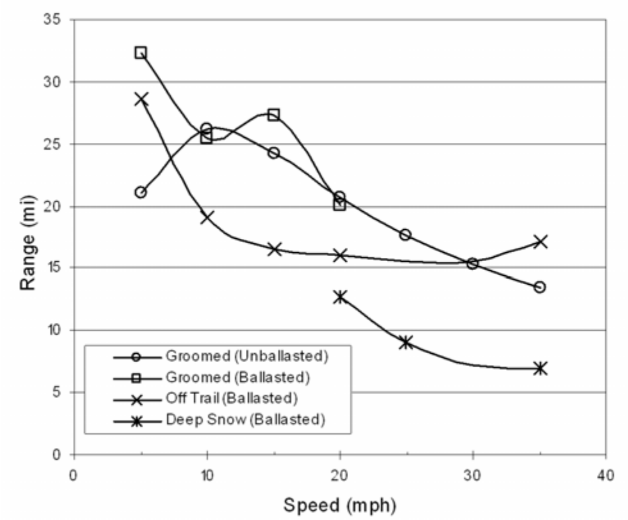

Figure 12 *Predicted range at various speeds based on current measurements and 97% depth-of-discharge of the battery pack. Testing was performed with a reduced battery pack and the vehicle was ballasted to simulate its final weight.*

Considering energy storage, the BuckEV has a battery capacity of 6.59 kW-hr, twice the size of the 3.24 kW-hr pack in the McGill sled last year [14] and 80% the size of the 7.92 kW-hr pack in the Utah sled [13]. Both the McGill and Utah sled were able to complete the ten-mile range event last year, but were not tested to exhaustion. McGill reported a typical vehicle range outside the competition of 9.0 – 9.5 mi [14] while Utah predicted a range of 8.5 mi but did not report data from testing [13]. The McGill sled used a CVT to transmit power from the motor to the track, leading to a 20% efficiency loss [7], 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 [16], predicting a range of 20.4 km (12.7 mi) for BuckEV.

TESTING - The finished vehicle, with the full battery pack installed, was tested for range. 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 is believed that better snow conditions for the competition range event and in Greenland will impart a 10-20% reduction in road load, improving fuel economy proportionally. This would improve range at 27.7 – 30.2 km (17.2 – 18.8 mi), within 10% of the team's goal of 30 km (20 mi).

TOWING CAPACITY

Given a sufficiently powerful drivetrain, towing capacity is limited by traction and ultimately limited by vehicle weight. In the 2007 competition, the only two teams earning more than 25% of the drawbar pull test points were the two heaviest sleds, both weighing over 360 kg (800 lbs). Both sleds weighing less than 300 kg (660 lb) performed poorly, with towing capacities less than 225 kg (500 lb). 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 use of track studs is another alternative to improve traction, but experience by team members' experience suggests a 10-20% increase in energy consumption for steady-state cruising with studded tracks, an enormous price to pay. This will be quantified prior to competition and reported in the oral presentation.

If traction can maintained, the drivetrain installed in the sled can provide approximately 275 kgf (650 lbf) of pull on the hitch up to a speed of 56 km/hr (35 mph). 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 pulling capacity 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.

SUMMARY

The University of Wisconsin team has 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 exceeds all performance goals of the CSC and NSF and comes 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.

Reliability, serviceability, and safety was 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 chaincase 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 ensures system operation in a manner which will not endanger the rider or permit electrical subsystem 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 for safe transportation of personnel and equipment in extreme climates and conditions.

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