Design of an affordable electric snowmobile — revisited

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ABSTRACT

The University Alaska Fairbanks Nanook EV team has converted another snowmobile to electric power. Our new machine has a 48 km (30 mi) range at 32 km/h (20 mi/h). Building on last year's success (winning Best Range with our original model), we started this project with a lighter chassis: a Ski-Doo Tundra 300F at 167 kg (370 lb), and a stronger motor, a NetGain WarP7 DC-series motor. The motor is connected directly to the sprocket shaft using two Gates Tri-power BX belts. The accumulator is configured to support 211 V using 396 Headway 10 A•h Lithium-ion cells, which utilize Lithium Iron Phosphate ($LiFePO_4$) chemistry. This 12.672 kW•h battery pack is the largest used in any electric snowmobile to date. The batteries are connected to a 249 V Logisystems motor controller to power the motor. The snowmobile is a respectable 295 kg (650 lb). It has a top speed of 80 km/h (50 mi/h) and it is pretty quiet at 54 dB. This snowmobile is poised to do very well in the competition. Table 1 summarizes our goals.

Table 1: UAF Goals for CSC 2010

Category	Challenge Record	UAF Goal	UAF Obtained
Range	29 km (18 mi)	48 km (30 mi)	>48 km (30 mi)
Weight	226 kg (498 lb)	317 kg (700 lbs)	<272 kg (650 lbs)
Drawbar Pull	2.56 kN (575 lbf)	2.67 kN (600 lbf)	>2.67 kN (600 lbf)
Noise*	65 dB	64 dB	<64 dB
MSRP	$14K	$12K	<$12K

* With studded track

INTRODUCTION

The National Science Foundation (NSF) supports research in polar regions, which are extremely sensitive areas that are highly impacted by pollution. In 2005 the Clean Snowmobile challenge added the additional category: "Zero-Emissions" in order to promote the use of vehicles which would not contaminate the fragile environments in these regions [1]. Also, it was important to avoid contaminating samples taken from these areas, as engine fumes could adversely affect the samples. Our team was also motivated to design an affordable electric snowmobile due to local high energy costs in Alaska. Gasoline is a precious commodity in rural villages across the state, many of which are not connected to a road system. The price of a gallon of gasoline can be in the $10 range. Fuel is shipped to Alaskan villages in the summer by barge when the rivers and other shipping lanes are ice free. In some areas, fuel needs to be flown in, increasing the price even more [2].

The Nanook EV team has focused on finding transportation solutions for rural Alaska that can help reduce villagers' energy consumption, but still maintain their traditional way of life. Electric vehicles have been a very promising solution when paired with locally generated renewable power. The team envisions clean, efficient electric vehicles used as primary local transportation, powered by renewable energy such as geothermal, wind and hydropower. These resources are abundant in rural Alaska but are currently under-utilized.

Our snowmobile is designed for the most practicality and performance that an electric sled can offer. At the same time, we strove to demonstrate that electric vehicles can be a viable option for certain applications. To accomplish this, a "better, faster, cheaper" design philosophy was adopted. The goal was to produce a system that had impressive performance, while still being affordable and easily obtainable by the general public. This is our second year in this competition, and we offer an improved vehicle that is lighter and more comfortable for the rider, along with additional modifications to the original chassis, all while maintaining a clean, flexible, and aesthetically pleasing design.

Snowmobiles are an indispensable means of winter transportation in rural Alaska. While these machines are primarily used for recreation in the rest of the country, here they are an important tool that makes life in remote villages possible. Snowmobiles are therefore an ideal candidate for electric conversion. The Nanook EV team has extensive experience in converting traditional vehicles to run on electric power. Members of the team have converted everything from cars and trucks to ATVs and lawn mowers [3].

Figure 1:U.S. Army Signal Corp dog team at Ladd Field, Fairbanks, AK.

DESIGN STRATEGY

The main design strategy was to convert the snowmobile to be most successful at the competition. This year's competition scoring is more in line with CH2M Hill Polar Services' desires. Currently, over 57% of the events relate directly to their needs. The acceleration event has been deleted and the objective handling event has been modified. Even though the acceleration event is gone, we still wanted a high power density battery for the straight-aways, which would benefit our machine on the objective handling track. As we expected, lithium battery prices have lowered from last year's levels by one-third, which fit in nicely with our light-weight inexpensive chassis. This keeps our overall cost low for our final Manufacturer's Suggested Retail Price (MSRP).

Second, we had the incentive to keep the modification as simple as possible while using available and affordable parts. The parts needed to be low cost yet durable. Emphasis was added on using "off the shelf" components that are common to equipment such as electric forklifts and other electric vehicles. This not only would keep the MSRP low, but allow repeatability and ease for a pre-fabricated kit to be manufactured, so other users could enjoy and benefit from the use of an electric snowmobile. Although electric sleds have been emphasized in past competitions as tools for research purposes, our sled would also be ideal for the general public. Uses could include transportation to work in rural areas, checking trap-lines, subsistence hunting and fishing, and grooming ski and dog sled trails. Bottom line, we wanted a snowmobile that riders would want to use. Consumers are mostly interested in cost and range, and we feel we have achieved a snowmobile that meets those criteria.

Historically, it is interesting to note that dog mushing had been a common transportation choice in Alaska until the mid-1970s. Dog teams were used by the Postal Service in remote villages until the 1960s. The Army (Figure 1) and the National Park Service maintained sled dog teams for rescue missions or patrolling in remote areas. Denali National Park still employs a dog team today since motorized vehicles are not allowed in certain areas of the Park. With the advent of the snowmobile, Alaskans and other northern locales became enamored with this new machine; however, travel could be dangerous if the snowmobile broke down or ran out of fuel. An electric snowmobile offers a few different options. While the batteries may run out, the machine probably is not too far away from help. Also, the snowmobile could be equipped with an on-board emergency generator to provide enough power to limp home. But perhaps the most exciting option would for the machine to carry either a hydro or wind turbine that could be setup when the snowmobile was stationary. The use of portable solar panels was also considered, but solar is not a viable option for several reasons. Arctic regions enjoy little sunlight in the winter, and current solar panel technology is very inefficient and would require a trailer that is 12 m (40 ft) long to accommodate the number of panels required.

ENERGY STORAGE REVIEW

To attain sufficient range, we placed great importance on energy storage capacity. Batteries generally available for traction applications consist of metals such as Lead, Nickel and Lithium. Thomas Edison designed the first traction batteries using Nickel Iron (NiFe) [4]. His battery (and his electric car) was later replaced with Lead Acid batteries (PbA) in the early 20th century. The Nickel battery has evolved to such variants as the Nickel Cadmium (NiCd) and Nickel Metal Hydride (NiMH) battery. Using Nickel was an improvement over Lead, except for cost and safety to the end user. Both Lead and Nickel exhibit a poor Mass Energy Density of under 75 W·h/kg. However, when using the lightest metal available, Lithium batteries promised excellent Mass Energy Density. At first, a non-rechargeable Lithium Battery was developed and dubbed "Lithium Metal". When the first Lithium secondary cells were promoted, they were distinguished from non-rechargeable primary cells as "Lithium-Ion", or "Li-Ion." Today there are four types of Lithium rechargeable batteries in production and available for resale. They are: Lithium Cobalt ($LiCoO_2$), Lithium Manganese ($LiMn_2O_4$), Lithium Nickel ($LiMn_xNi_yCo_zO_2$), and Lithium Iron Phosphate ($LiFePO_4$). Table shows various cell attributes.

The main reason why $LiFePO_4$ is the best alternative to the commercially used cathode $LiCoO_2$ is its environmental benignity, its abundance, and the fact that it is less expensive than $LiCoO_2$. Additionally, the redox couple Fe^{+3}/Fe^{+2} is conveniently located at 3.45 V with respect to Li^{+1}/Li, and is compatible with many organic and polymer electrolytes. The successful commercialization of $LiFePO_4$ happened due to its high electrochemical performance, particularly in terms of reversible capacities. The initial problems of low electronic conductivity and low Li-ion diffusion rates have been improved significantly by co-synthesizing it with conductive sources, and making the particle size remains smaller, which resulted in diffusion path reduction [5].

Our team (and likely anyone else on a budget) chose the $LiFePO_4$ for our electric snowmobile. Our primary reasons were safety and cost. These batteries are the least expensive Lithium batteries available. They are heavier, and have less energy density and power output than Lithium Cobalt, but they are inherently safer because of their lower relative Lithium content. The emphasis on designing a safer electric vehicle convinced our design team that the best choice for batteries is Lithium Iron Phosphate.

We installed 396 Headway cells. These batteries have a 3.2 V nominal voltage, making the total pack size 211.2 V. These cells are series and parallel connected. Every six cells are connected in parallel and then the battery pack contains 66 of these in a series connection. Increasing the battery voltage will make a more efficient vehicle [6]. Higher voltages allow a smaller amount of amperages, which produces less heat and less wasted energy.

Table 2: Battery Chemistry Examined

		Nickel		Lithium-ion		
Criteria	Lead Acid	NiCd	NiMH	$LiCoO_2$	$LiMn_xNi_yCo_zO_2$	$LiFePO_4$
Mass Energy Density (W·h/kg)	35	40	75	180	160	110
Volume Energy Density (W·h/L)	68	50	200	250	250	220
Power Density (W/g)	0.18	0.15	0.7	3	3	3
Cycle efficiency (% charge/discharge)	70	70	70	95	95	95
Self-discharge (%/month)	10	10	30	5	5	5
Cycle life (total cycles)	200	1000	500	500	500	2000
Current cost (US Dollar/W·h)	$0.05	$0.23	$0.47	$0.60	$0.60	$0.31
Nominal Voltage	2.1	1.2	1.2	3.7	3.7	3.2
BMS Required	No	No	No	Yes	Yes	No
Environmental	Poor	Bad	Good	Average	Average	Good
Cost based on cycle life x W·h of Lead	1	0.7	1.3	1.75	1.75	0.2

Note: Some values are averages

The batteries are protected using a Clean Power Auto MiniBMS Battery Management System (BMS), as shown in Figure 2. These BMS boards output both high voltage and low voltage warnings. Also, they protect the battery from overcharging by shunting the charging current across the board instead of the battery when the battery reaches 3.6 volts. The use of the BMS will provide a durable battery system that is capable of 3 000 cycles while only contributing a 20 % increase in cost for each battery.

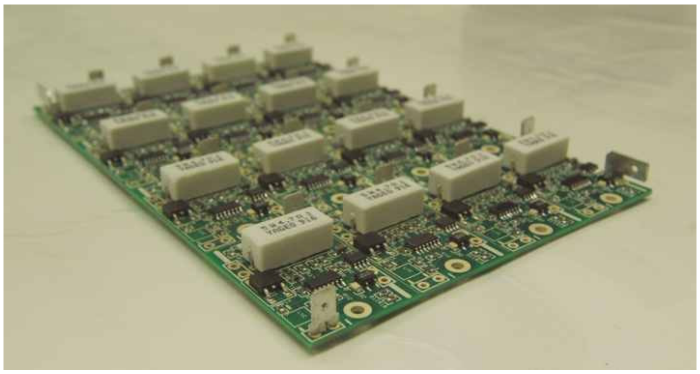

Figure 2: CleanPowerAuto MiniBMS array. The shunting resistors are the white rectangular blocks. This array can protect 16 batteries.

The batteries were confirmed to exhibit a low internal resistance during loading. Resistance values per battery are in the 0.001 Ω to 0.007 Ω range. Having a low internal resistance allows the snowmobile motor to draw more power. This is a huge improvement when compared to lead acid batteries. Charger efficiency is also increased because less energy is wasted in heat.

ENERGY STORAGE CONTAINERS

In order to safely house all the batteries necessary to meet the range goal, a robust energy storage containment system was designed and fabricated. The energy storage containers are constructed of 0.511 mm (24 Gauge) Aluminum. In order to provide electrical insulation and additional strength, the internal surfaces are faced with FR4 plastic. Two battery boxes were designed and fabricated using the tunnel as part of the box. One box was attached to the tunnel (the part of the frame that is directly above the track and supports the rear suspension components). This placement necessitated deletion of the gas tank. We kept the seat intact, mindful of rider comfort. The second box is set low into the engine compartment giving good center of mass for the overall sled. As with all the other components added, the location and construction of the energy storage containers contribute to the reproducibility and practicality of the design.

Table 3: Belt Design Criteria

Option	Cost	Simplicity	Eff.	Noise
V-Belt	Low	Yes	Good	Quiet
Gates Polychain	High	No	Best	73 dB
Goodyear Eagle	High	No	Best	69 dB

DRIVE TRAIN

The gasoline engine is removed, along with the continuously variable transmission (CVT), the fuel tank, the muffler, and other associated parts. These are replaced with a Net Gain WarP7 DC series motor, a Logisystems Controllers 550 Amp 249 V Direct Current Controller, a 211.2 V battery system, and two Gates BX V-Belts.

Another way to increase the range of the design was to increase the drive train efficiency. The original CVT in the snowmobile was designed to keep the internal combustion engine operating at its optimal range. This however, is not an issue with an electric motor as a power source. Electric motors are capable of operating effectively at a much wider range of operating speeds. This property, combined with the ability of an electric motor to spin freely even when electrical power is not being supplied, allowed the use of a much more efficient direct drive system. Not removing the CVT can cause a decrease of performance by 20 %.

We did remove the chain case and jack shaft. Removal of the case now requires the snowmobile to have only two fluids: brake fluid and bearing grease. This makes a cleaner vehicle. It also reduces weight, and allows a simpler redesign.

With the chain case removed we had three choices for belts. These are Standard V-Belt, and two synchronous belts: Gates Polychain or a Goodyear Eagle Synchro belt (Table 3). The Synchronous belts afford a better efficiency of 98%, while the V-Belt slippage classified them with a 95 % rating. Synchronous belts also make 73 dB of noise whereas V-Belts are quiet. On the other hand, V-Belts cannot do as much power. In the end the design team went with the V-Belt for simplicity. We lost 3 percent efficiency by using the V-Belt; however, we can combat that by improving the motor efficiency. Thus, we installed Helwig-Carbon red-top brushes, increased the spring pressure by using Prestolite MT-42 springs, and used World Wide Bearings ceramic bearings. These design upgrades for the motor increased efficiency by 3 % and offset the losses of V-Belt usage.

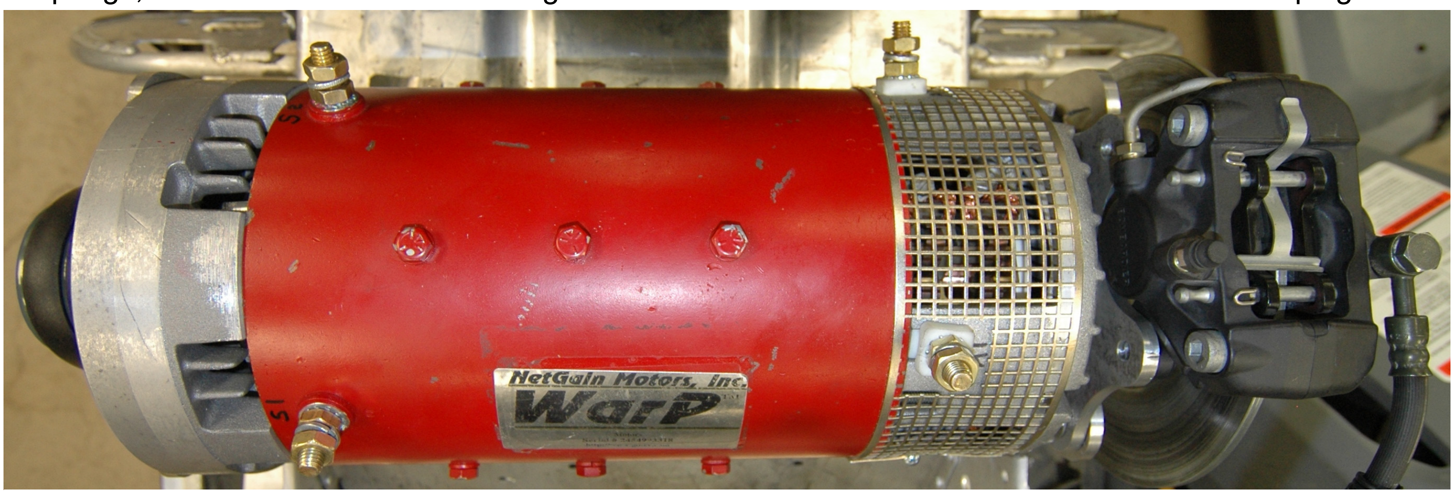

Figure 3: Picture of Warp7 motor used in the Ski-Doo Tundra 300F. With the double shafted motor the brake rotor was installed on Commutator End (CE) , left, and the pulley to the sprocket shaft was installed on the Drive End (DE), right.

Another factor that we considered in regard to belt usage is that synchronous belts require good alignment; without it you could end up with bits of rubber on the frozen tundra, especially in arctic temperatures, when rubber tends to crack and break. Not a good thing for a zero-emissions vehicle.

The design utilizes a standard industrial V-Belt system for increased efficiency over the stock CVT. By using a conventional V-Belt, it was possible to stay true to the low cost, easily reproducible design strategy. Using Gates Design Flex Pro software [7], the minimum pulley diameter and belt type was chosen. The BX type belt was selected due to its performance at higher rev/min service, which could be reached at the vehicle's top speed. This belt can safely handle only half of the total motor output horsepower, so our application uses two belts. In order to maximize range at speeds needed for the competition, sheaves which would allow the motor to operate at its most efficient speed were chosen. The ratio of the sheaves allow for 2 100 rev/min of the motor while traveling at 32 km/h (20 mi/h). This ratio puts the motor at its most efficient operating point, but still allows for higher speeds.

MOTOR

In making the motor selection we wanted the most reliable motor available. In keeping with our underlying design methodology, a DC motor will give more power per dollar then an AC motor. AC motor setups typically cost at least four times

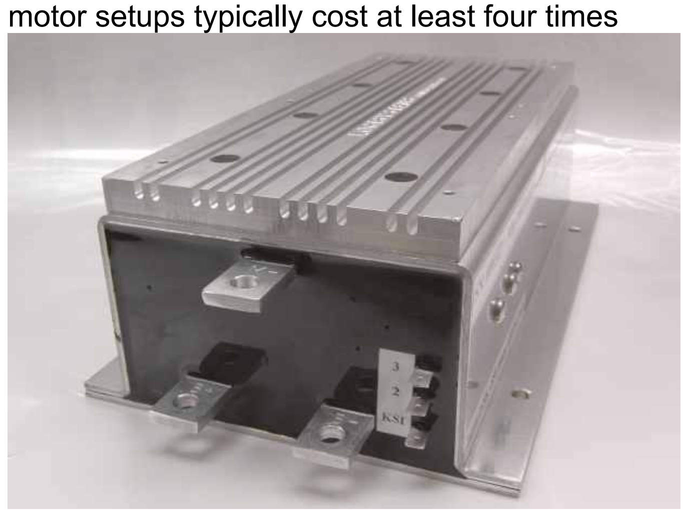

Figure 5: This is the DC brushed motor controller from Logisystems Controllers. It is manufactured in Odessa, TX and can do 137 kW continuous power. The three large connectors connect to the battery pack and motor. The three small connectors are for the variable resistor and the key switch.

more than DC. NetGain Motors designs DC motors which are manufactured by Warfield Electric especially for the Electric Vehicle industry.

We chose a NetGain WarP7" motor (Figure 3). It has a 181 mm (7.125 in) diameter and is 425 mm (16.75 in) wide. Thus, it fits nicely on the width of the tunnel. It weighs 45.5 kg (100.5 lb) and delivers a continuous power of 15.47 kW (21.75 hp). Additionally, the motor has the largest shaft diameter of 28.575 mm (1.125 in) in this size case. The lamination size is 16% larger than a 203.2 mm (8 in) diameter motor. Advanced timing is easily set with pre-drilled holes. We did advance time the motor to gain about 2 % efficiency.

The motor also exceeds "H" class insulation and can do 7 200 rev/min at 120 V and 400 A for five minutes. With our emphasis for the design to be the best at the 32 km/h (20 mi/h) range event, the motor will produce 47 N·m (35 lb-f) of torque, and 2 100 rev/min using 48 V and 230 A. We performed the multiplication of the voltage and the amperage to arrive at a power of 11 kW for this motor at that setting. This produces a mechanical power of 8.9 kW and is a sufficient amount of power for the range event based on the last two years of the Clean Snowmobile Challenge results.

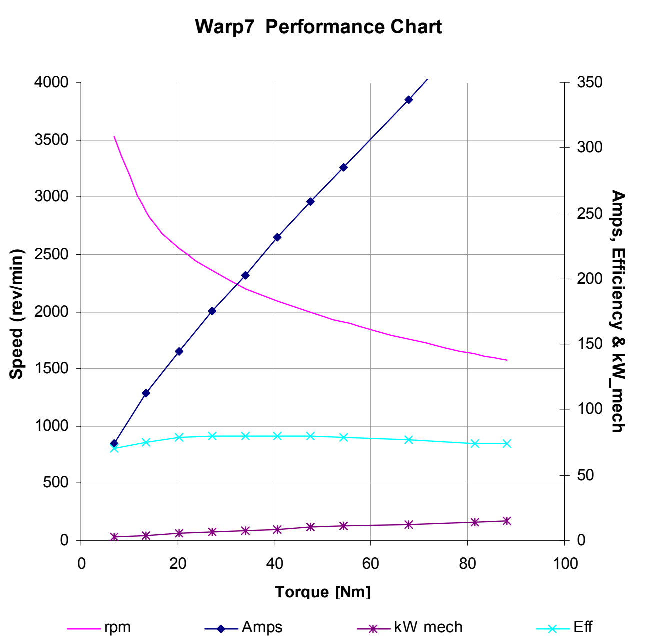

Figure 4: Torque-speed characteristics of the Warp7. Data was taken at 48 V and the load was varied from 6 N•m to 88 N•m. At each increment the motor speed (rev/min) and amperage were noted. Mechanical Power (kW) was calculated, and so was motor efficiency.

CONTROLLER

We are using a Logisystems Controller 120/196 which is rated for 249 V and 550 A continuously (Figure 5). This is a serious controller capable of doing 137 kW continuously. It is a DC controller designed for brushed DC motors. It comes with 0-5 kΩ input from the throttle, and exhibits a 0.25 V drop on a 200 V input. Thus, it is 99 % efficient, except when the temperature exceeds 73°C, which will not occur in our design since we will only be using about 10 percent of its capacity. This controller runs the motor with a Pulse Width Modulated at 14 kHz. It weighs 4.35 kg (9.5 lb) and is rated for -40°C (which occurs frequently in Alaska). It has come preset from the factory to allow effective acceleration.

COUPLER

We wished to remove as much rotating mass as possible in our electric snowmobile. The chain case was removed, and a 66 mm (2.6 in) Outside Diameter (OD) pulley was attached to the motor, and a 165 mm (6.5 in) OD pulley was attached to sprocket shaft (Figure 6). The gear ratio was found by determining the speed at which the track driver would have to turn in order to travel at 32 km/h (20 mi/h). Using the 203 mm (8 in) sprocket shaft, we calculated the circumference to be 638 mm (25 in) and then running the motor at 2 100 rev/min and then reducing that speed by 0.4 to 840 rev/min, the snowmobile will run at 32 km/h (20 mi/h). Using the motor curves in Figure 4 we found 2 100 rpm requires approximately 230 A at 48 V which is 11 kW.

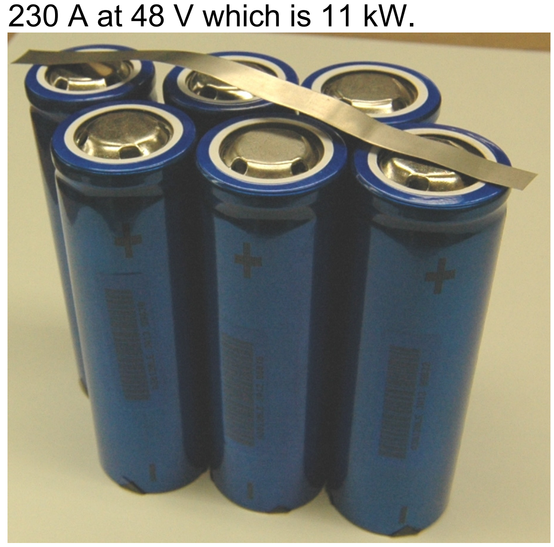

Figure 7: Each blue cylinder is a Headway 38120 10 A·h cell. Here are six of them ready to be connected with a Nickel Strip.

MOTOR MOUNT

One obvious component deletion was the internal combustion engine. This deletion created a major design challenge: to develop an electric motor integration system. To maintain drive train efficiency, we designed a mounting system for the motor that integrates belt tensioning. The system design does not require the use of a tensioner or idler pulley, thus increasing both efficiency and belt life. It is very similar to an automotive alternator V-Belt tensioning apparatus. The motor pivots about an axis to lengthen or shorten the distance between the two pulleys. The mount is constructed from 6061-T6 aluminum for long term durability -- as well as for its availability -- which is important to practicality and reproducibility. In order to produce a design for the mount, we had to determine the loads that the motor would produce. We accomplished this by examining the targeted performance for the snowmobile, and using those targets to identify the forces to be developed by the motor. After including the weight of the motor itself and doing an analysis for impact loading caused by bumps in the trail, we then included a safety factor, and were able to find the expected loads on the motor mount using static analysis. Once this was done, we were able to go about designing the mount.

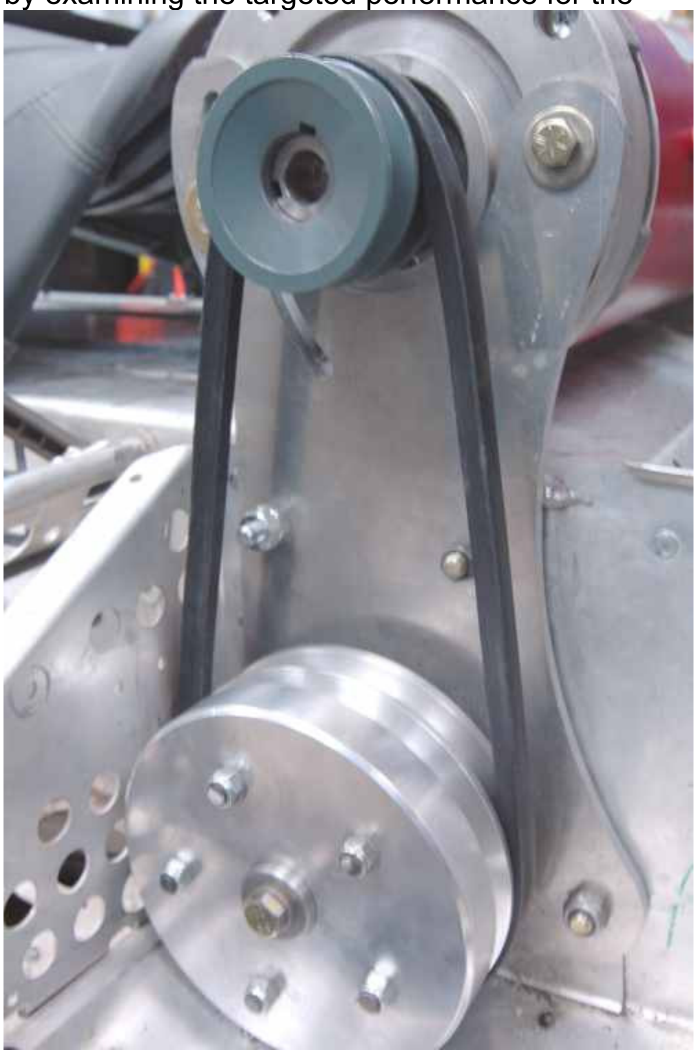

Figure 6: Two double groove pulleys are used to transmit the power from the motor to the sprocket shaft. Also pictured is the motor mount which is mounted on both sides of the tunnel.

Each component must be able to safely handle both the weight of the motor and the drive forces that the motor produces. In order to ensure that each component is up to the task, the Finite Element Analysis suite COSMOS (which includes the design program SolidWorks) was utilized. With this program, the stress distributions within the parts and with the expected loads could be calculated. Due to the accelerated timeline of the project, these results were only used to ensure that an adequate safety factor was present. Generous safety factors were allowed since the means to test the parts to failure (in order to confirm the COSMOS results) were unavailable. The material of choice for the components was aluminum; it is both lightweight and easy to work with, while still being strong enough to handle the load. Costs were kept low by keeping precision machining to a minimum. When mating the motor to the chassis, modifications of the snowmobile were kept to a minimum. Existing bolt holes were used when possible. The motor was mounted at the original location of the fuel tank and oil supply. The reasoning behind this was that the batteries and the motor have similar densities, and because of the cylindrical battery size, they would fit more compactly in the original engine compartment. The design allows for a very strong, easy to use, and low cost solution to integrating the electric motor into the snowmobile.

Table 4: Battery Pack Comparisons

	HeadWay 38120	**Change from TS-90**
Battery Mass	125 kg (275 lb)	24%
Nominal Voltage	211 V	211%
Capacity	60 A·h	-33%
Energy	12.6 kW·h	41%
Energy Density	100 W·h/kg	4%
Power Density	5 W/g	66%
Power Density (pulse)	10 W/g	n/a

BATTERY SELECTION

The snowmobile uses an energy storage system consisting of 396 Headway $LiFePO_4$ cells. These cells were designed for Electric Vehicles. Each cell is 10 A·h, and can allow a 50 A·h drain or 100 A·h at pulse.

We selected these cells because their rapid discharge rates were twice as high as the Thunder Sky TS-90 batteries we utilized last year. Lithium Iron Phosphate batteries were chosen due to their low cost and for their number of cycles.

These batteries allow 2000 cycles when discharged at 80 % in each cycle. If the batteries are completely drained by 100 % the batteries' performance will deteriorate to 1 500 cycles. This deterioration is due to the fading of Lithium Iron Phosphate chemistry by 0.03 % per charge. In Figure 9 you can see life cycle performance at various discharge cycles.

After extensive battery research, we decided to use the cells manufactured by Headway. They were affordable and many Electric Vehicle enthusiasts/hobbyists are currently using them with good results [3]. There are currently many manufacturers of Lithium cells so our decision was extremely difficult and time intensive as we weighed our options.

Our pack consists of six cells grouped in parallel making a 3.2 Volt 60 A·h battery (Figure 7). Sixty-six of these batteries are assembled in each series making a nominal 211.2 V pack at 60 A·h. This pack is capable of producing 63 kW at 5 C-Rate. However, the battery output this for about 750 s (Figure 8).

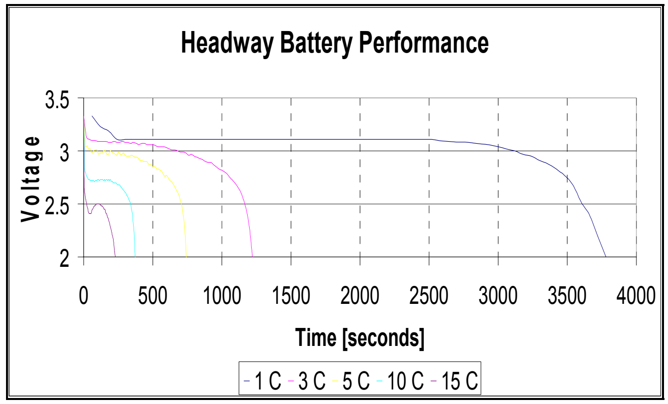

Figure 8: Discharge curves under different loads.

In comparison to last year's machine [8], we increased the energy storage by 41 % by going from 8.991 kW·h to 12.672 kW·h. Not only did we increase the energy capacity, we increased the voltage by a whopping 211 %. This will make the motor and controller run at lower amperages while being more efficient. Although our battery went from 90 A·h to 60 A·h for a 33 % loss, the higher voltage is more important and more beneficial. However, the weight of the pack increased by 24 % to 125 kg (275 lb) (Table 4). Ultimately, to achieve our goal of having the best range, we required a larger battery pack. The University of Wisconsin Madison (UWM) team used a 7.5 kW·h battery pack last year [9], and according to the SAE CSC forums they expected to increase their pack size from 336 V to 400 V. This would be a 20 % increase and give them a 9 kW·h battery pack. Keeping this in mind, our design team wanted a larger pack -- which we achieved, but also added an additional 25 kg (55 lb) to our snowmobile. That is a 24 % heavier battery pack then last year. Obviously this will hurt our team's performance in the weight category; however it will be an advantage with other events like the drawbar pull.

Lithium Iron Phosphate batteries behave well in cold temperatures. In real life situations, the batteries would not remain cold for long as they

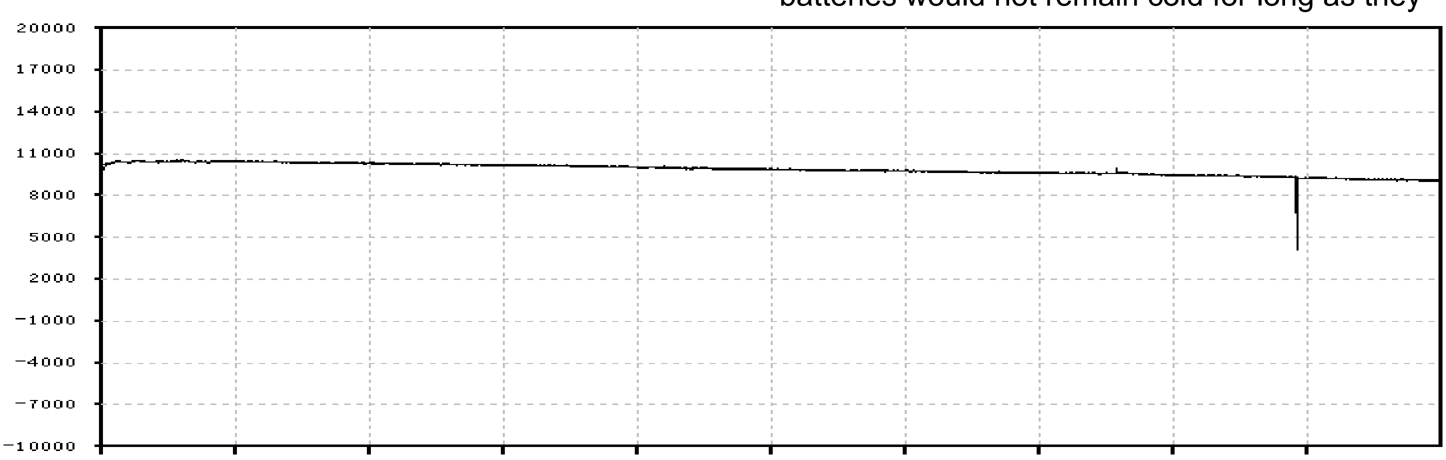

Figure 9: Headway cells cycle life chart shows how the battery loses capacity at 1500 cycles.

heat up while being used.

The pack was mounted in five columns into the former engine compartment. Each column contains 66 batteries. Each column was a sandwich made up of two thin “slices” of FR4 plastic with the Headway cells mounted in between them. Three of the columns fit neatly into the original compartment while two more where placed on the outside. The remaining batteries were mounted in a box under the seat, again sandwiched between sheets of FR4. The use of the plastic insulating sheets shelters the battery pack from any exposed surfaces. This safeguards accidental exposure to a technician working on the battery pack and/or sled as well as protecting the battery pack from shorting out. The placement of the batteries in the engine compartment added greatly to a good center of mass for the machine. The controller is also mounted under the seat close to the motor which reduces electrical transmission losses.

BATTERY CHARGER

The team selected two UL-listed battery chargers that can charge half the pack at 123 V each. The Delta-Q Universal Input QuiQ is designed for a wide input voltage range from 85 to 265 VAC, allowing universal application. The 12 A maximum current draw ensures that the charger will work reliably, even through surges and sags. The QuiQ has a high efficiency design and the near unity Power Factor combine to make the QuiQ charger extremely grid-friendly. Over 88 % of power taken from the grid is converted to real power to charge the battery.

With the new competition rules requiring a UL-listed charger, we felt we went above and beyond that requirement as our selection is both UL and CE compliant and has passed stringent EMI, safety, vibration and water ingress protection (IP) tests. This charger offers leading edge efficiency, power factor correction and GFCI compatibility for safe and reliable operation.

The QuiQ’s intelligent microprocessor controller has optimized charge algorithms designed primarily for Lead Acid batteries. We selected an algorithm that would work with our Lithium-ion batteries. Utilizing the correct algorithms helps improve battery life and minimize maintenance. QuiQ is built for onboard operation in harsh environments. Its rugged, lightweight and intelligent design provides continuous operation in any application. High efficiency power conversion allows the QuiQ to be delivered in a fully sealed enclosure, making it ideal for onboard applications in the dirtiest and wettest environments. Reliability is increased by the reduction of moving parts.

ENERGY EFFICIENCY

To evaluate the efficiency of the Nanook EV, a comparison analysis with a standard production snowmobile was used. Assuming the best mileage a production IC snowmobile gets is 8.5 km/L (20 mi/gal), driving 32 km (20 mi) uses about 125 000 Btu of fossil fuel. This translates to 125 000 Btu / 32 km, which is 3 906 Btu of fossil fuels per km. The electric snowmobile averaged 500 W·h/km (800 W·h/mi) total energy use, which includes charging the batteries. Converting to British thermal units by multiplying 0.5 kW·h/km with 3 412 Btu/kW·h to obtain 1 706 Btu/km. Looking at how the electricity is generated will give a more accurate Btu comparison value, unless the sled can be recharged using alternative energy such as wind or solar power.

The worst-case scenario would be electricity from a coal fired power plant with an efficiency of 33 %. The fossil fuel input is 3 times the electrical power output, i.e. 3 x 1 706 Btu/km = 5 790 Btu/km. This number shows that an electric snowmobile is less efficient than a production gasoline sled. However, if a more efficient power generation is used such as a 45 % efficient power plant, then 2.22 x 1 706 Btu/km = 3 971 Btu/km which is similar to the original gasoline consumption. The fact that a typical electric vehicle still has a significantly shorter range demonstrates the large discrepancy in energy density from a gasoline-powered sled to an electric sled.

Also, it is interesting to point out that even if the energy consumption is the same in either using gasoline or electricity to power a snowmobile, there are additional energy needs in order to bring that energy to a gas tank or a wall outlet. Argonne National Laboratory’s The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model [10] can do a Fuel Cycle analysis, also known as “Well to

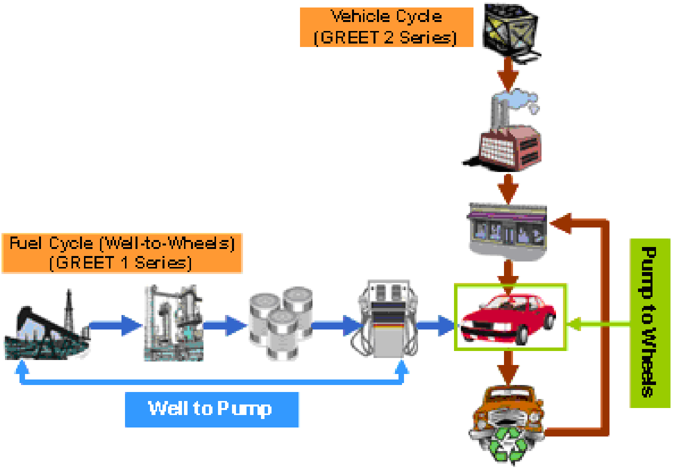

Figure 10: Demonstrational Graphics on "Well to Wheel" Analysis and Vehicle Cycle.

Wheel" (or with snowmobiles "Well to Track.")(Figure 10).

This modeling software allows researchers and analysts to evaluate various vehicle and fuel combinations on a full fuel-cycle/vehicle-cycle basis. We used this modeling software to compare snowmobile combustion vs. electric snowmobiles. We estimated that an electric snowmobile operated with an 11 % reduction in CO_2 emissions and a 10 % reduction in Greenhouse Gases (GHG) based on energy generation in Fairbanks, AK [11]. The software will also give you modeling data on other emissions as well.

AVL has a software package called CRUISE for modeling the vehicle's powertrain efficiency. AVL CRUISE supports everyday tasks in a vehicle's system and driveline analysis throughout all development phases, from concept planning through to launch and beyond. Its application envelope covers conventional vehicle powertrains through to highly-advanced hybrid systems. It performs in all fuel economies and performance tests in a single run with the same vehicle model. We did some initial computer modeling with this software. In Figure 11 we

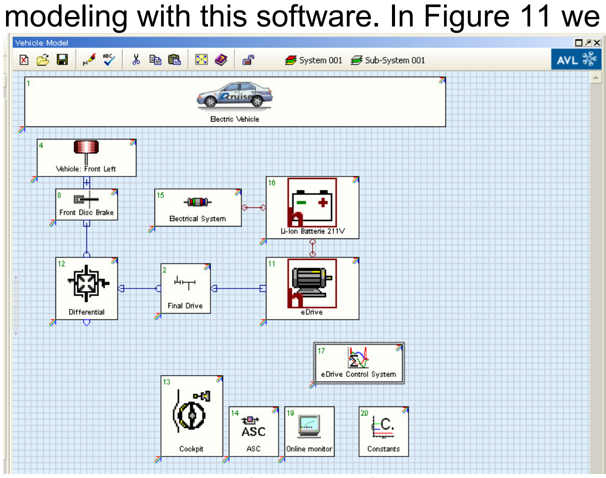

Figure 11: Example of AVL interface

Table 5: Rolling Resistance Effect on Range

Snow Condition	Rolling Resistance [rr]	Distance km	Distance mi
Slush	0.377	39.2	23.5
Ice	0.252	55.4	33.3
Powder	0.15	83.8	50.3

modified an electric car example to be an electric snowmobile. We hope to share more results during the Oral Presentations.

RANGE

For the past two years we have focused more on the range event then anything else. In order for a vehicle to be practical it must be able to transport people and cargo over a usable range. There were many design decisions made in order to reach this goal. We didn't achieve our goals last year since we expected to travel another 50 % further. What we didn't anticipate were extreme wet snow conditions. We have classifieds snow into three categories as shown in Table 5: Slush, Ice and Powder [12, 13]. Using data from the last two years of the CSC and Auth's Thesis [14] we calculated a rolling resistance coefficient. We also show our range estimation for our current sled depending on conditions.

Also, in Figure 12 we plotted Distance vs. rolling resistance which shows how the rolling resistance coefficient affects the overall distance performance of an electric snowmobile at 32 km/h (20 mi/h). Additionally, we looked at the force analysis to propel a vehicle. Typically there are four major criteria: Acceleration, Rolling Resistance, Hill Climbing and Wind Drag. Since the range event is on a level track we did not calculate Hill Climbing force. The other forces were calculated and the summation is shown in Table 6 as Required [W·h] in Column 5. We had

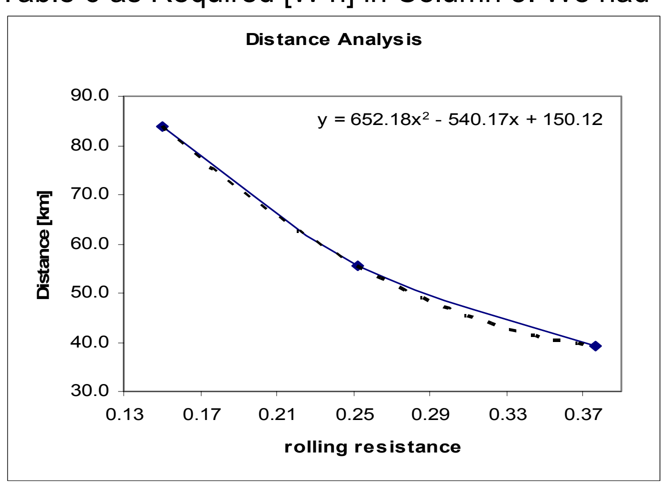

Figure 12: Effect of rolling resistance on Range Distance.

to add more acceleration events in the 2009 data because a track was not used. When we calculated [15] the rolling resistance force, we left the coefficient as a variable and calculated it last using the actual range data from four snowmobiles. We used four sleds: our Nanook, a UWM, a McGill from 2009, and a UWM from 2008. This gave us a good amount of data to compare.

There are some assumptions that we had to make: we estimated the rider's mass, and assumed 20% driveline losses for all teams. This would include both mechanical and electrical inefficiencies. We also had to look at the battery data given in previous design papers to obtain an idea of what size battery packs each school utilized. The other unknown was how much of the energy storage system each school optimized. In the end, we felt that the error between theoretical and actual range was small enough to obtain a relevant rolling resistance coefficient. We believe this data analysis is vital for future snowmobile modeling and design. Our team struggled last year without this information. We felt confident that if we had the largest battery pack we would win best range. Both UAF and UWM had similar energy consumption of 872 W·h/km and 875 W·h/km respectively, and yet the team with the larger battery pack had the best range.

RANGE TEST

The snowmobile was driven on a 1.33 kilometer (0.83 mile) track for range testing. The sled was driven at a constant speed of 32 km/h (20 mi/h). We kept the speed constant to keep acceleration at zero as much as possible. We ran the machine until the MiniBMS alerted us that the machine needed to be recharged. We obtained 55 km (34 mi) on hard-pack snow, which we calculated to be 622 W·h/km by dividing 12.672 kW·h and the 55 km. This exceeds the old 16 kilometer (10 mile) standard which is still listed as a design criterion in the Clean Snowmobile Challenge rules, and this range can be exceeded or reduced with different snow conditions. [1] Knowing this, we tested again on a warmer day and ran the sled out on a river's surface; we were able to drive 29 km (18mi) before receiving the MiniBMS warning. This was calculated to be 1.134 kW·h/km. This amount is much higher than the power draw we saw in the first test, and shows the large amount of variability that exists due to snow conditions.

DRAWBAR PULL TEST

The drawbar pull is an interesting event in that many of the qualities that lead to drawbar pull success can be detrimental to performance in other events. Chief among these qualities is weight. A heavy snowmobile will achieve lot of traction, and thus be able to pull more. On the other hand, that weight is cumbersome in events like the range and acceleration tests.

Judging from real-world experience, it was apparent that the limiting factor in the event would not be power, but traction. In order to help improve traction, the batteries, which are the heaviest component of the snowmobile, were partially placed directly over the track. This dramatically improved traction without overly affecting handling. In order to test the snowmobile's performance in the drawbar pull, the back end of the snowmobile was attached to the back end of a truck with a tow strap and force meter. The truck was shifted into neutral, and the snowmobile began pulling it at 6.4 km/h (4 mi/h).

Once this speed was attained, the brakes on the truck were slowly applied to progressively increase the resistance the snowmobile was pulling against, until traction was lost. The highest measured force was recorded. The force

Table 6: Using Calculated and Actual Range to Determine Rolling Resistance Coefficient

Team	Rider [kg]	Sled [kg]	Total [kg]	Required [W-h]	Battery Capacity [W-h]	Drive losses (-20%)	Range Calculated [km]	Range Actual [km]	Error	[W-h/km]	rr
UAF '09	50	327	377	8747	8991	7193	26.5	26.7	0.94 %	872	0.377
UWM '09	68	322	390	8811	6750	5400	19.7	20	1.17 %	875	0.377
McGill '09	68	226	294	6422	2604	2083	10.4	9.7	7.51 %	698	0.377
UWM '08	68	313	381	5422	6092	4873	28.9	29	0.13 %	544	0.252

meter used was simply a piece of 25.4 mm (1 in) by 6.35 mm (0.25 in) aluminum with a strain gauge attached.

During testing, the maximum recorded force pulled against was 2.67 N (600 lbf) At this point, the track lost traction and began to spin out. The consistency of the snow at the test site was a loosely packed, dry powder. Loss of power was not a limiting factor during the test. Maximum pulling force can easily be improved with a different snow consistency.

NOISE

The overall sound output of the machine was found to be quite minimal. We experimented with different tracks from Camoplast and Kimpex and on light powder the sled was performing below 65 dB. To address subjective sound quality, the motor used this year has an internal fan which is much quieter. We also added a paddle damper to reduce the noise levels from the track and sprocket shaft. Also, as mentioned earlier we went with the quiet V-Belt for our traction system.

SUBJECTIVE HANDLING

With the goal of designing a sled for general recreational use, much importance was placed on the snowmobile's handling. The Tundra (Figure 13) has a narrow ski stance of 812 mm (32 in) which makes it prone to being tippy. We kept the center of mass as low as possible to keep the sled from having any tipping issues. The additional weight added to the snowmobile resides in the engine compartment. This allows for a low center of mass that the team wanted. The sled responds instantly to throttle input, a benefit associated with electric motors. Increases in speed can be made smoothly and quickly without the hesitation or 'jerking' often attributed to CVT clutches found in a traditional snowmachines. The sled is geared primarily for range by running the motor at its optimum rev/min while turning the track at a speed of 32 km/h (20 mi/h). As a result it can't pull the skis off the ground during rapid accelerations, but it does have enough torque to start and maneuver through relatively deep powder.

BRAKING-
The machine still employs the stock hydraulic disk brake system mounted on the Commutator End (CE) shaft. Since these brakes were engineered to slow the original 295 kg (650 lb) sled from speeds in excess of 80 km/h (50 mi/h), they exhibit excellent performance while slowing the new additional weight. In preliminary acceleration tests, where quick emergency style braking was required, the brakes showed little or no sign of fade. The stock rotor never showed signs of excessive heat build up.

BALANCE –
The snowmobile is well-balanced front to back and side to side. Since the gas engine and clutches were spatially replaced with a motor and battery pack that weighs more, the weight over the front skis is greater than the stock values. This allows for better steering of the snowmobile. Last year we learned that having to much weight over the track was not helpful in the subjective handling test.

Figure 13: 2006 Ski-Doo Tundra 300F in unmodified form.

OVERALL HANDLING –
The snowmobile exhibits a high overall level of comfort and performance. The seat is slightly elevated to simulate the popular high-rise aftermarket seats, decreasing the angle of the rider's knee and thus reducing joint and leg fatigue. The gauges are located in the stock locations which still permits easy visual access. The original cable style throttle block was removed in favor of a resistor trigger which is more comfortable, reducing wrist and thumb fatigue which is common on traditional snowmobiles. While the power was reduced and the weight was increased, the sled is still enjoyable to ride. It is by no means bulky or sluggish as many would envision an electric snowmobile to be. Aesthetically, it still retains its performance oriented styling and stance. Although some snowmobiles are used in commercial or research applications, the majority

of the market is driven by recreational consumers. With this in mind we feel it is important that our final result still retained its original ability to provide a fun and comfortable ride, which the Nanook EV Two surely does.

WEIGHT

The published dry weight for the original sled is 167 kg (370 lb). Filling all the fluids adds conservatively 36 kg (80 lb) bringing the total to 203 kg (448 lb). The Nanook EV tips the scales at 295 kg (650 lb). The net weight increase is limited to 92 kg (202 lb). While this weight increase may at first glance appear to be very large, it is important to point out that the original snowmobile was very light compared to other models. This allows the new weight to still be competitive with many four-stroke gasoline powered snowmobiles available. The team did some weight calculations to determine how weight affects range. It appears about 27 kg (50 lb) can reduce range by 3 km. We weren't happy with the battery pack mass, but it was an adequate compromise. In the future the team will use more exotic materials to lighten the sled, and attempt to find a lighter battery pack with similar energy density.

ACCELERATION

The acceleration rate is very challenging for an electric snowmobile. Although the acceleration event was deleted from this year's competition, acceleration performance is what the public would like to know. This is unfortunate because running the snowmobile at a faster speed hurts the possible range. The high power demands of the event require high electrical currents being fed to the motor (upwards of 600 amps), and the large forces involved push the mechanical components to their limit. As with the drawbar pull event, traction is a major concern, though not as critical.

The most important aspect of optimization for this performance is adequate motor sizing and gear selection. If the motor is too small, then the snowmobile will not be able to meet the minimum performance criteria for enthusiasts. If the motor is too large, the snowmobile may do well in the acceleration event, but the excessive loads that it places on the electrical system will hurt its performance in the distance event and harm its long-term durability. We believe the motor we selected, at 15.47 kW (21.75 hp), is the perfect size to provide both versatility and performance.

OBJECTIVE HANDLING

This year's modified event requires towing a 454 kg (1 000 lb) sled through a course for time. We tested the sled with this weight, and found no issues so far. We let our riders do several practice runs since this event will rely greatly on driver skill and experience.

COST

One advantage in working on a limited budget during this project is that our Manufacturer's Suggested Retail Price (MSRP) is extremely low. We went with a brushed DC motor to save $3,000 off the final price. We used Lithium Iron Phosphate batteries to save another $2,000. We used stock V-Belt Pulleys to save another $700. This $5,700 in savings should make us competitive against other teams, and make more researchers interested in acquiring a machine.

The Challenge rules have been adjusted this year to reflect representation of costs. However, recent commercial snowmobile pricing has been on the rise for the last several years. This makes most chassis used in 2010 prohibitively expensive to convert to electric. We are thankful that the rules allow for a credit on the original motor; however this is not a realistic if you were planning a conversion business. Unfortunately none of the four major snowmobile manufacturers have taken an interest in a commercial electric sled. We realize there are major shortcomings in electric snowmobiles for certain user groups. However, a recent start-up company named Premier Recreational Products has developed a gasoline powered family-sled for under $4K [16]. Using a chassis like this in a conversion would have an instant weight savings, and would be less expensive overall to convert.

2009 CHALLENGE RESULTS

During the 2009 Clean Snowmobile Challenge, the Nanook EV performed admirably. All components performed as designed, and in some instances performed better than expected.

The first test in the competition was the range event. As range was a major focus for the design of the original Nanook EV, this test was critical to validate many of the design choices. During the test, the snowmobile was able to cover 27.6 km (16.6 mi). This distance was shorter than the anticipated range; however, it was still within the range simulations. Given the fact that the conditions during the test were not ideal and that all the other teams saw reduced performance compared to previous years, it is reasonable to assume that the reduced range was a result of the conditions, not problems with the vehicles systems. The Nanook EV's performance in the range test was the best in the competition. The next farthest range was achieved by the UWM team with 20 kilometers (12.4 miles).

During the draw-bar pull test, the Nanook EV was capable of pulling against a force of 2.437 kN (548 lbf). This was much larger than the predicted result. We believe that our load cell used for measuring during initial testing may have been faulty. Our performance earned second place, behind UWM's result of 2.557 kN (575 lbf). This result is excellent considering the fact that the Nanook EV was not equipped with studs, which would have greatly increased traction in the competition conditions.

In the objective handling event, the Nanook EV was able to place second despite lesser acceleration performance than some of the other sleds. This was largely due a combination of the well tuned suspension, easy handling characteristics, and high performance skis.

In addition to these competition highlights, the Nanook EV was also the least expensive snowmobile present. This was great validation of the design, considering that cost effectiveness and maximum range were the two primary design goals, and also the two events we won. The Nanook EV finished second overall in the competition, a great performance for a rookie team. A graphical summary of the competition performance compared to the other teams is shown in Figure 14.

SUMMARY

Having completed testing and competition with the Nanook EV 1 and 2, it is clear that the design goals were met. Because of a successful 2009 season and our current testing, we feel confident of success in March 2010. A zero emissions snowmobile that is capable of excelling in the areas of range, pulling power, noise, handling, and weight has been produced once again, and this machine can have a broad range of uses outside the scientific research market. The Nanook EV2 is a low cost, durable, easily reproducible snowmobile that is a pleasure to ride. We believe we have developed a breakthrough product that will alleviate some of the criticisms of electric snowmobiles.

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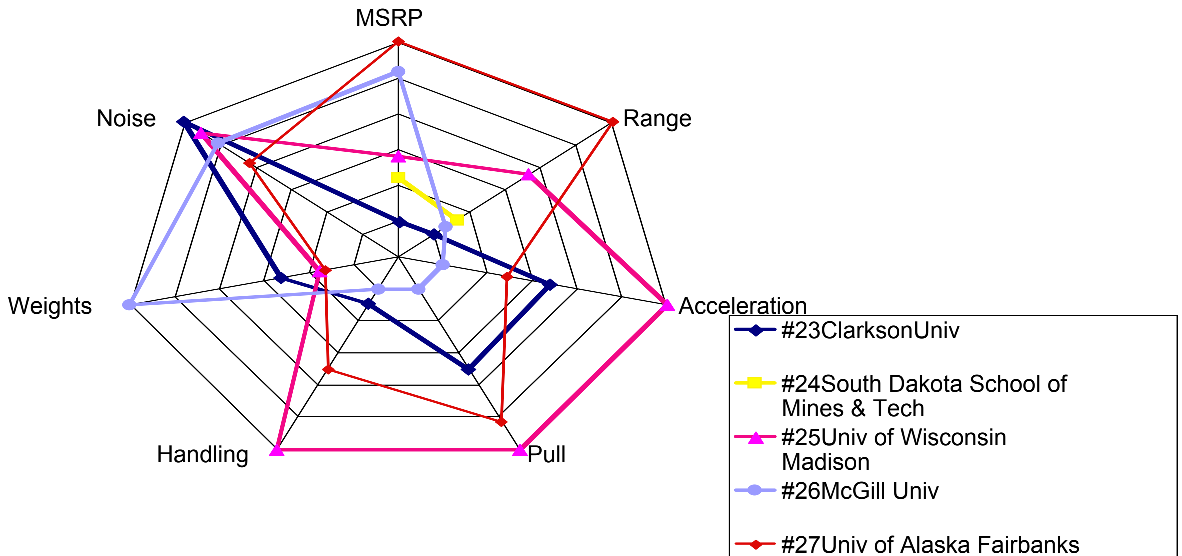

Figure 14: 2009 Challenge Objective results radar plot.

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Figure 16: University Alaska Fairbanks Snowmobile Ice Sculpture with team members.