Development of a 2nd Generation Electric Utility Snowmobile Powered with Lithium Batteries

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ABSTRACT

The McGill University Electric Snowmobile Team, returns to the Clean Snowmobile Challenge in 2007 with a revised electric snowmobile prototype and an all new hybrid prototype. This paper covers the design and development of the electric snowmobile prototype.

The completely redesigned 2006 electric prototype shattered any preconceived idea that a utility electric snowmobile had to be heavy, big & bulky. Confident that this prototype was a huge leap in the right direction, for 2007, the team concentrated on improving the 2006 vehicle's reliability and performance without completely redesigning it from scratch as it was the case in previous years.

Key modifications for 2007 include a change of motor and battery management system. These modifications improve reliability while at the same time improving the vehicle's acceleration and top speed. The displacement of the battery pack from the rear of the tunnel to the engine bay area and the use of a wider ski stance will give the 2007 prototype improved stability and maneuverability.

Finally, a custom made vehicle management system & user interface specifically for use in the electric snowmobile was implemented. This system both increases the vehicle's reliability and its ease of use for all drivers regardless of their level of experience with electric snowmobiles.

INTRODUCTION

Utility snowmobiles are essential vehicles for a number of people. These strong, reliable, mechanical workhorses of the winter season are used in many different fields. This breed of snowmobiles can be seen at work in all of the northern part of the continent in military, search and rescue, industrial, recreational and scientific applications. While current gasoline powered snowmobiles offered by OEMs fit the basic needs of most of these applications, some utility applications are looking for something which current OEM utility snowmobiles are unable to deliver. One example of this is the need by the scientific community for a zero emission snowmobile for use in ultra-sensitive environments.

The National Science Foundation (NSF), through its civil contractor VECO Polar Resources, has expressed such a need for a zero emission snow vehicle for use at Summit Research Base in Greenland. Research at Summit includes air and ice sampling in order to determine quantities of various substances in the samples. Given its remote northern location, Summit is an ideal candidate for such sampling since it greatly diminishes the risk of the samples being contaminated by local sources of contaminants. In order to further decrease contamination risk, a “no vehicle zone” has been established up wind of the base in order to minimize contamination of samples by the base's vehicles and its electric generator. Unfortunately this also means that access to the zone must be made on cross-country skis thus limiting the amount of equipment which can be brought, extending the time required to acquire the samples and also increasing safety risks in an extremely cold and harsh environment. The use of a zero emission snow vehicle at Summit would enable researchers to keep this zone with minimal contamination while making the research safer and more efficient.

After having seen the need for zero emission snow vehicles by the international research community, the Clean Snowmobile Challenge (CSC), a student engineering design competition administered by the Society of Automotive Engineers (SAE), has decided to add a zero emission category to its competition in 2006. Now, the competition has 2 different categories with 2 different engineering goals.

1. The goal for the internal combustion engine (ICE) category is to make snowmobiles which meet the needs of tour operators while being acceptable for use in U.S. National Parks and also being in compliance with the 2012 snowmobile regulations.

2. The goal of the zero emission category is to meet the needs of the scientific community by designing a safe, reliable, user friendly, utility snowmobile which has adequate range and power while emitting the least amount of contaminants possible from its power train.

The 2007 electric snowmobile entries are evaluated on the basis of 16 criteria which can be divided into 3 categories:

1. *Team performance*
Engineering Design Paper
Oral Presentation
Static Display

2. *Vehicle Performance*
Manufacturer's Suggested Retail Price (MSRP)
Weight
Range
Towing Capacity
Acceleration
Objective Handling
Subjective Handling
Cold Start
Rider Comfort
Objective Noise
Subjective Noise

3. *Vehicle "Quality"*
Technical Inspection
Reliability

McGill's 2006 zero emission entry suffered from hard to diagnose electrical problems at the Clean Snowmobile Challenge (CSC) which forced the team to drop out of some "vehicle performance" events. The main focus for the 2007 was thus put on increasing the vehicle's reliability.

The following paper discusses how the knowledge gained from the 2006 prototype led to the design choices for the 2007 version of McGill's electric snowmobile prototype. Comparative results between the 2006 and 2007 prototypes are given to measure the impact of the changes. The main issues covered in this paper include an overview of the electric snowmobile technology and challenges of implementing such technology as well as the design choices and their effects on overall performance, vehicle ease of use and cost.

FUNDAMENTAL DIFFERENCE: ELECTRIC SNOWMOBILES VS. ICE SNOWMOBILES

Prior to reviewing the design choices for the 2007 electric snowmobile prototype, it is important to take a few lines to answer the following question: "why is the design of a practical electric snowmobile such a challenge?". The answer to this question is simple: energy density.

Using a value of 8760 Wh/l [1] as the energy available in gasoline and looking at the size of the fuel tanks offered by the 4 main snowmobile manufacturers on their utility models it can be seen in Table 1 that on average, by taking the fuel tank size of one utility snowmobile model from each manufacturer, their utility snowmobiles carry 358,722 Wh of energy on-board. As a basis for comparison, the 2006 McGill Electric Snowmobile Team's prototype carried 6480Wh of energy.

Vehicle	Fuel Volume (l)	Energy On Board (Wh)
Arctic Cat Bear Car 570	49.2 [2]	430,992
Polaris 340 LX	44.6 [3]	390,696
Ski-Doo Skandic Tundra	34 [4]	297,840
Yamaha Venture Multi-Purpose	36 [5]	315,360
Average	***40.95***	***358,722***

Table 1: On-board energy of gasoline powered utility snowmobiles

Using a mass of 0.73 kg/l (6.1 lb/gal) [6] as the volumetric mass of gasoline, the weight of the average 358,722 Wh of energy carried on-board those snowmobiles is 29.9 kg (65.8lbs).

In comparison to the gasoline numbers, Table 2 looks at the energy density of 4 of the main battery technologies mature enough for use in electric snowmobiles: lead-acid (Pb-A), Nickel Cadmium (Ni-Cd), Nickel Metal Hydride (NiMH), Lithium-Ion (Li-ion).

Battery Technology	Gravimetric Energy Density (Wh/kg)	Volumetric Energy Density (Wh/l)
Pb-A [7]	33.5	76.2
Ni-Cd [8]	54	95
NiMH [9]	60	155
Li-Ion [10]	105	284

Table 2: Energy Density of Common Battery Technologies

As Table 2 shows, the "raw" energy density of battery technologies is nowhere near the "raw" energy density of gasoline.

Why is it termed the "raw" energy density? It is termed the "raw" energy density because the numbers in Table 2 only consider the energy density of the batteries themselves. For a very accurate comparison between energy density of batteries and gasoline one should also account for the weight and volume of the containment chamber or other means of holding the gasoline and batteries on board. To that must be added the difference in weight and volume of energy transfer systems (i.e.

Fuel pump and tube vs. battery management system and heavy gage copper wire). Lastly, the reduction in battery energy density related to cold temperature and high discharge rates should be taken into account for a true comparison between battery technology and gasoline. Taking all these factors into account can be termed the "net" energy density comparison. In general, the "net" energy density comparison will be worst for the batteries than the "raw" energy density comparison.

The rest of this section looks at how, even with the best battery technology available today and with extremely clever designs that could somehow bring "net" energy density difference to approach "raw" energy density difference, building an electric snowmobile in 2007 that can rival the performance aspects of today's gasoline snowmobiles is an incredibly difficult challenge.

In a best case scenario, as seen in Table 3, in order to have as much energy on-board an electric snowmobile as on a gasoline powered snowmobile, one would have to carry over 2800kg (6173lbs) of batteries. With new utility snowmobiles such as Ski-Doo's Tundra weighting 172kg (379lbs) (dry weight) [11], this represents a "fuel" weight 16.5 times larger than the weight of the vehicle itself. Adding to that the fact that unlike liquid fuels, the mass of the batteries will not diminish as energy is consumed, it is clear that such a vehicle to fuel weight ratio is not suitable for a snowmobile.

Energy Carrier (EC)	Gasoline	Batteries (Li-Ion)
Vehicle	Ski-Doo Tundra	
Dry Weight	172 kg	
Energy On-Board	297,840 Wh	
EC Volume	34 l	1049 l
EC Weight	24.8 kg	2837 kg
Ratio EC Weight / Vehicle Dry Weight	0.144	16.5

Table 3: Head-to-head energy carrier comparison

Table 3 only takes into account the energy on-board and not the efficiency of the 2 drive systems. The efficiency of the electric drive system is often seen as one of its main advantages over the Internal Combustion Engine (ICE). The question is, how much can the difference in efficiency compensate for the on-board energy difference.

Interestingly, Table 4 shows that even if the electric snowmobile's drive system was 100% efficient, the ICE snowmobiles would have to be powered by engines with an efficiency of less than 1% for the two technologies to be equal in terms of range and performance with the same mass of energy on-board.

Energy Carrier (EC)	Gasoline	Batteries (Li-Ion)
Vehicle	Ski-Doo Tundra	
Dry Weight	172 kg	
EC Weight	24.8 kg	
Energy On-Board	297,840 Wh	2604 Wh
Hypothetical Efficiency for Equivalent Performances	0.87%	100%
Energy Used to Propel the Vehicle	2604 Wh	

Table 4: Comparison of required technological efficiencies for equivalent vehicle performance using different energy carriers

Table 5 shows the weight difference in what can be considered an optimistic case scenario as seen from the electric vehicle's point of view. Even in this best case scenario, the electric snowmobile would need to carry over 18 times the weight of its gasoline counterparts to compete with it on a given distance at a given speeds/accelerations, in given conditions.

Energy Carrier (EC)	Gasoline	Batteries (Li-Ion)
Vehicle	Ski-Doo Tundra	
Dry Weight	172 kg	
EC Weight	24.8 kg	448kg
Energy On-Board	297,840 Wh	47 027 Wh
Hypothetical Efficiency for Equivalent Performances	15%	95%
Energy Used to Propel the Vehicle	44,676 Wh	

Table 5: Energy carrier weight difference taking into account vehicle efficiency (optimistic scenario as seen from electric vehicle)

Thus, in designing an electric snowmobile one must find applications which benefit from the technology and in which the vehicle's low energy to weight ratio (relative to gasoline snowmobiles) can either be minimized or even taken advantage of (ex: grooming X-country ski trails is often done with a snowmobile towing a heavy sled).

Regardless of the application, optimizing the vehicle's overall efficiency in transforming the energy in the battery pack into energy actually used to propel the snowmobile is of the highest importance as the electric snowmobile, despite being much more efficient than its gasoline counterparts at the vehicle level, starts with a handicap well above 100:1 when it comes to the energy density of some of today's best electric energy carriers vs. gasoline.

OVERALL PERFORMANCE

The first step in the design of the 2007 “Wendigo” electric snowmobile prototype was to compile the data gathered from the 2006 prototype and rate the snowmobile's overall performance relative to what the team considers to be the optimal electric snowmobile for use as a utility vehicle at Summit Camp and for use as an electric vehicle drivetrain research prototype for McGill’s Vehicle Engineering Research & Technology transfer (VERT) laboratory. For this assessment, overall performance was divided into 8 categories and each category was given a mark from 0 to 10 (0=issue never addressed, complete failure & 10 = optimal scenario for both Summit Camp and McGill VERT). The chosen categories were: Reliability, Acceleration, Towing & Cargo Capacity, Range, Stability & maneuverability, Noise, Ease of use and Cost.

Table 6 below shows the points given by the team to the 2006 prototype in each category

Reliability	3
Acceleration	5
Towing & Cargo Capacity	6
Range	9
Stability & Maneuverability	5
Noise	9
Ease of Use	7
Cost	6

Table 6: 2006 Performance Evaluation

Illustration 1: 2006 McGill University “Wendigo” Electric Snowmobile Prototype

RELIABILITY

From the Table 6, it can be seen that reliability was the weakest point of the 2006 snowmobile according to the team's evaluation. This aspect was thus brought up to the status of #1 priority in the design of the 2007 prototype.

Step one in addressing the reliability problem was to pin point the sources of past reliability problems and foresee other potential problems. Through this assessment, five key areas of interest were found and ranked in order of priority (1 = highest priority).

Key Reliability Areas:
1. Motor
2. Battery Management System
3. Human Judgment
4. Wiring Harness
5. Controller

1. MOTOR

The motor used in the 2006 electric snowmobile was a compact, pancake style, brushless DC motor. The motor was originally selected for its high efficiency and high power to weight ratio. Unfortunately, the power electronics on the back of the motor (converting the DC current to 3-Phase AC/Trapezoidal current) and the female keyed shaft output of the motor did not perform as well as expected in the snowmobile. The harsh environment and the severe duty cycles it endured in the electric utility snowmobile application led to mechanical and electrical problems.

Two options were investigated to address this reliability issue:
I. Repair and upgrade the existing motor
II. Acquire a new motor

The high cost and the long lead time required by the second option combined with the lingering uncertainty on whether this would be sufficient to make this motor reliable in the electric snowmobile application led the team to acquire a new motor.

Key selection criteria for the new motor were:
- Male output shaft
- Air cooled continuous power: > 7kW
- Nominal voltage: 72V
- Compatible with a series DC controller
- Capable of fitting in the opening left open by the previous motor.

Of the few motors that fit these requirements, one had been on the team's radar for some time: the Perm PMG 132. The PMG 132 is a pancake style permanent magnet brushed DC motor which, on top of fulfilling all the aforementioned requirements, also has higher peak power than the 2006 motor and a higher RPM per Volt constant which makes it better suited for use with a conventional, mass and spring actuated, belt and pulley CVT. With the price of the Perm PMG 132 dropping close to 70% in the past 2 years, its acquisition meant that, motor wise, the cost of the vehicle would go down substantially. Above all, it is the fact that using this motor eliminates the possibility of DC-AC conversion electronics failing that made the Perm PMG 132 the motor of choice for the 2007 prototype.

The only downside perceived by this change of motor is a small drop in efficiency of approximately 2-5% depending on the input current and voltage. The team believes that these losses are greatly overshadowed by improved performance and reliability. Furthermore, the power curve characteristics of the PMG 132 allow for a more efficient snowmobile design which can compensate for some of the losses.

2. BATTERY MANAGEMENT SYSTEM

The 2006 battery management system (BMS) was a prototype system still in development. One of its main characteristics was its ability to balance the lithium battery pack very rapidly. Unfortunately, the system, which was assembled on PCB by hand, proved to be vulnerable to temperatures changes and required highly qualified personnel for any repairs

For 2007, the BMS has been replaced with a newer more rugged system. The new BMS is assembled on a precision automated assembly line which should reduce the variability between units (important in the case a unit replacement must be performed). Overall, the new BMS is smaller and simpler than its predecessor; however, it cannot balance the pack as rapidly. This downside turns out to be a non-issue since very rapid pack balancing is not required in this application. Physically, just like its predecessor, the 2007 BMS is composed of 1 "master" and 2 "slave" boards. The "slaves" monitor the voltage of all individual cells and the temperature of sample cells. Information gathered from both "slaves" is conveyed to the "master" board which adds it to its own monitoring of pack current input/output. The "master" has some output possibilities which can be triggered based on a number of conditions. For example, the "master" can close or open a contactor which effectively turns the pack on/off by closing or opening the path from the final positive cell terminal to the rest of the snowmobile. Triggers for this contactor include: over voltage, under voltage, overheat, over current (charging or discharging) and communication problems.

A user operated switch can turn the BMS on/off when required by acting on the BMS's power source: a 75W 72V-12V DC-DC converter. The BMS must be turned on at all times for charging and discharging. However in prolonged storage periods of for shipping it can be required to turn the BMS off as it will slowly drain the battery pack otherwise

3. HUMAN JUDGMENT

One of the areas which the team felt was a true reliability issue was the fact that the 2006 vehicle lacked an on-board vehicle management system.

While the various systems and components interacting in the electric snowmobile should in general work hand in hand, it is possible for one component or system to fail for numerous reasons. In the past, other than the battery pack which has its own management system, it was up to the driver to notice if any of the components and systems were malfunctioning and take the appropriate action. This means of operation is suitable for a prototype which is always driven in the presence of its designers; however it is not suitable for a vehicle which is driven and maintained by dozens of different people which were in no way involved in the development of the vehicle. Given the use of the snowmobile at Summit Station by numerous researchers and on site staff members without the constant presence of McGill team members, the installation of a vehicle management system was believe to be of utmost importance. Such a system must be capable of detecting abnormal situation and take proper actions as programmed by the designers of the vehicle. This should ensure long term reliability of the vehicle by immediately taking care of any small problem before it can escalate into a much bigger one.

This led the team to design a customized vehicle management system (VMS) for the 2007 prototype. The main feature of this system is that it is able to communicate with the user via a Vacuum Fluorescent Display (VFD). Therefore, if the system detects an error condition, it can immediately inform the user of the problem and even turn off stop the snowmobile if required. The Matrix Orbital VFD2041-E was specifically selected for the rugged conditions of Summit station. The characters it displays are very bright and can be seen clearly up to 2.75m (9ft) away. The Matrix Orbital VFD2041-E is rated for temperatures from -40C to 80C. The combination of the VMS and the VFD can monitor temperature, voltage, current, RPM and speed and, if any of these reach a critical condition, the system can advise the user and take proper actions to avoid or limit damages.

The VMS also takes care of the "precharging" (charging of capacitors to avoid current spikes at start-up) of the Alltrax controller. In the 2006 prototype, this was done with a crude relay system that would simply wait a set amount of time before closing high power contactors. In the 2007 prototype, the VMS monitors the voltage levels and closes contactors when the voltage levels are such that they will not cause a current spike. This feature increases the useful life of the contactors. It also provides means to detect faulty conditions (a bad connection for example) and prevents the contactors from closing in this event. Another important safety aspect of the VMS is that is ensures that the snowmobile cannot be turned on while it is being charged. This prevents damage to the charger and to the charging facility.

4. WIRING HARNESS

The 2006 electric snowmobile had a very complicated wiring system with numerous connections. Both the high power and low power wire networks ran back and forth from the rear light of the snowmobile to the front bumper area. The more wire and connections are present in a vehicle the more likely it is that one connection or wire will fail at one point. Furthermore when a failure occurs, the diagnostic and the repair are made more difficult by the complexity of the wiring system thus prolonging the vehicle's downtime.

In the 2007 electric snowmobile, the component placement has been redesigned with a strong emphasis on minimizing the length of wire used and the number of connections required. The result is a design in which all the wiring is located in front of the jackshaft (except the tail light and the recharging electric inlet wires). Furthermore, a large percentage of the wires which were found in the 2006 snowmobile's electrical box have been replaced by PCB circuitry.

Unfortunately, no exact numbers are available on the length of wire and the number of connections used in the 2006 prototype; however, the team estimates that the amount of wiring has been reduced 70-75% in the 2007 snowmobile.

Illustration 2: 2006 wiring system

Note: Team veterans estimate that the percentage of wiring seen in illustration 2 represents approximately only 15-20% of the 2006 prototype's complicated wiring system.

5. CONTROLLER

The 2006 prototype was initially equipped with an Alltrax AXE 7234 controller located under the driver's seat. On March 12 2006, hours before leaving from Montreal to participate in the SAE CSC 2006, the controller fried during an early morning final test run. Unable to find a cause for the problem all the team was able to do was to replace the controller as fast a possible. In the process it was decided to move the controller from under the seat to inside the front compartment of the snowmobile just in case the failure was due to overheating from lack of air flow. The new controller has performed flawlessly in the front compartment.

Discussions with Alltrax were started in the spring of 2006. Alltrax engineers concluded that the controller must have had a faulty part and promptly replaced the faulty unit. Furthermore, they ensured the team that the controllers are overheating protected and that overheating was most likely not the cause of the failure. Overheating of the controller should result in the controller lowering its power output. While this may not have been the likely cause of the failure, the team still decided to leave the controller in the front compartment in 2007 for multiple reasons.

1. The replacement controller performed flawlessly in that environment
2. A ramp down of power is not as drastic as a complete failure but is still, in the team's perception, a reliability issue and thus should be avoided by ensuring proper air flow for cooling.
3. Placing the controller in the front compartment in the new layout of components minimizes wire lengths and the number of connections.

Changes made mainly for reliability reasons do affect other performance areas assessed in Table 6. The change of motor is most likely the one which influences other areas the most starting with acceleration performance, one of the areas which marked the lowest in 2006.

ACCELERATION

Unfortunately, unlike other performance areas which were well documented on the 2006 prototype, acceleration was not. No explicit data was gathered on either the “G's” or the time from 0 to X speed. The only information available is the team members “feel” for how it performed.

As it was seen in Table 6, the team member's “feel” resulted in a low mark in terms of how it was believed the electric prototype should behave acceleration wise. Most felt it was too sluggish.

Key areas of focus for acceleration performance were determined as:
1. Motor
2. CVT
3. Track drive system
4. Weight & rotating inertia
5. Controller calibration

1. MOTOR

While the decision of replacing the 2006 motor with the Perm PMG 132 was mainly one of reliability, it was also well known that the Perm PMG 132 had more peak power capability than its predecessor. Right away, this meant that acceleration performance would likely be on the rise in 2007.

2. CVT

In order to take advantage of the higher peak power of the new motor, the CVT system had to be well calibrated to the Perm PMG 132's output torque and RPM characteristics.

In 2006, the team went all the way to the point of combining the softest spring available and the heaviest weights available in its CVTech Powerblock CVT drive pulley in order to try to match the CVT's shifting characteristics to the motor. The results felt much better than the stock calibration but the team still felt that the CVT's RPM shifting range was too high for the motor's output characteristics. Having reached the limits of the options readily available from CVTech at the time, the team settled for that configuration for 2006 knowing that a motor with a higher RPM/Volt constant would be required in order to fully match the characteristics of the Powerblock CVT to the drive motor's characteristics.

Interestingly, the new Perm PMG 132 does have a higher RPM/Volt constant than the 2006 motor. Upon obtaining the first acceleration/CVT test results using the Perm PMG 132 and the 2006 CVT calibration, the team was pleasantly surprised to see that the shifting of the CVT fit perfectly with the Perm PMG 132's performance curves. Thus no change was implemented in the CVT calibration.

Results:

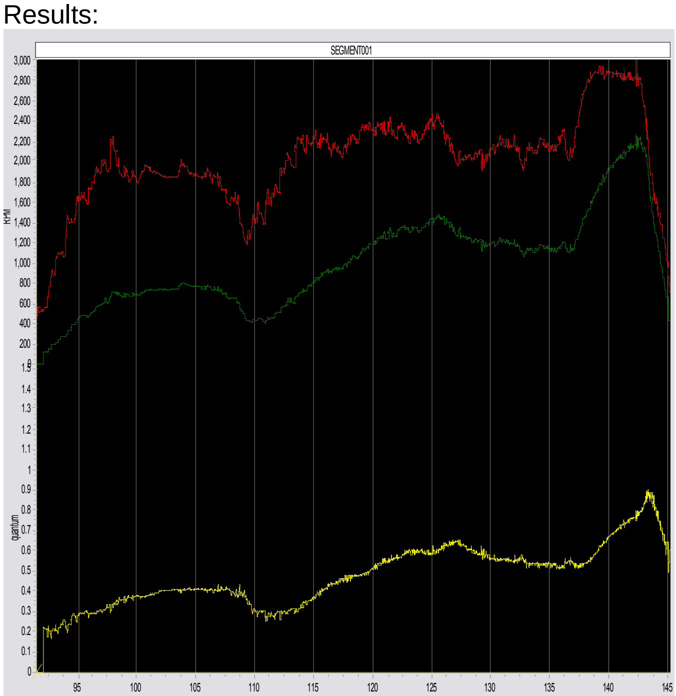

Illustration 3: CVT Test results

The red line is the motor's RPM and the green line is the jackshaft RPM. At the bottom the yellow line shows the CVT shifting Ratio. With a CVT setup which keeps motor RPM's between 2800 and 3000, the electric snowmobile accelerates rapidly to 25km/h (15.6MPH). Past this point CVT shifting is what primarily regulates speed. Since the motor's maximum RPM varies with voltage and in turn voltage varies with current draw and battery charge level, CVT calibration on an electric vehicle is fairly different form CVT calibration on an ICE vehicle. A CVT calibration which performs well at high battery charge levels will likely be very unpleasant to drive at lower charge levels. The opposite is also true. Given the format of the SAE CSC competition in which most events are short in duration, the team opted for a CVT setting which favors performance with a full battery pack.

3. TRACK AND DRIVE SYSTEM

The 2006 electric snowmobile prototype used Ski-Doo Tundra's original track and track drive sprockets to transmit the vehicle's power to the ground. Track tension was kept to a minimum for improved cruising speed efficiency. Track ratcheting under hard acceleration would occasionally happen depending on snow and temperature.

With the new motor and the matching CVT calibration it became clear right away during the first on snow tests that under low track tension the new drive system would always ratchet during heavy acceleration and sometimes even during mild acceleration.

The team saw to possible solutions to the problem:
I. Tightening the track
II. Use “Anti-Ratchet” track drive sprockets

The second solution was selected as it would allow to run with minimal track tension and thus keep the constant speed efficiency advantages of running a looser track without compromising acceleration performance.

In order to implement the “Anti-Ratchet” sprockets which have drive teeth that mesh into the track's windows for extra grip, the team had to replace the 2006 track, which had 1 open window for every 2 closed windows, with a track with all windows opened. The replacement track is a 15” X 136” fully clipped Camoplast Ripsaw Track with pre-drilled stud holes. Also, the tips of the rear suspension rails were removed to allow clearance between the rails and the drive sprockets. Lastly, a center idler wheel was installed to ensure that the track rails do not lodge themselves in track windows, an undesired effect known as “spearing”.

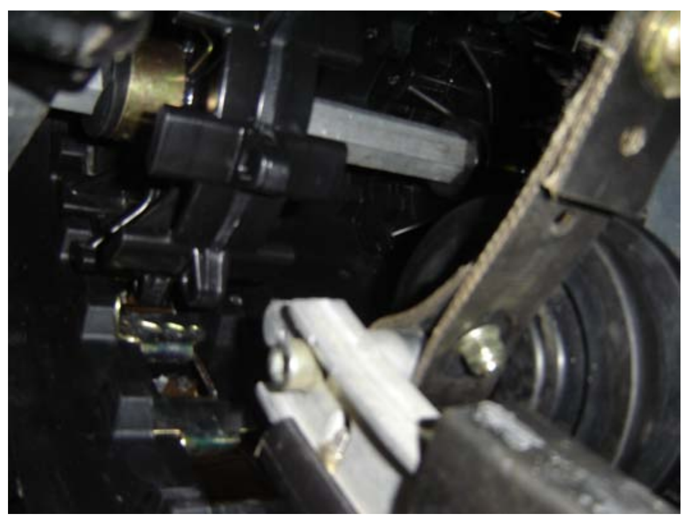

Illustration 4: Anti ratchet sprocket with anti stab wheels and Ripsaw track

As a result of the change the team was able to eliminate ratcheting even under the hardest of accelerations while at the same time keeping a loose track setup.

4. VEHICLE WEIGHT & INERTIA OF ROTATING MASS

When examining this area of possible improvement, the team came to the conclusion that most of what could be done to lower vehicle weight and inertia of rotating mass had been implemented in 2006. This includes:
-Aluminum jackshaft
-Aluminum trackshaft
-Lightweight belt drive secondary ratio
-Lightweight brake disk placed in the track shaft for lower RPMs
-The lightest snowmobile of the 2006 SAE CSC (all categories included) by over 45kg (100 lbs) [Officially 521lbs vs. 623lbs]

The team did not pursue other improvement in this area. However efforts were made to keep all these features in the vehicle and try to keep the total weight as low as possible while performing improvements in other areas.

5. CONTROLLER CALIBRATION
The Alltrax AXE 7245 controller has a variable acceleration response rate which can be set by the user. The 2006 prototype had its acceleration ramp up rate set at 8 on a scale of 15 (15 being the fastest response rate). The rate was set in the middle of the available range to lower the shock loads on start up. Despite this measure, the motor's female drive shaft and its mating CVT male driveshaft were deformed over time by the repeated shock loading at startup.

The new Perm PMG 132 motor is now coupled to the CVT via a spider coupler which can dampen the shock from startup on a hard acceleration. This allows the controller to be set at higher “throttle” response rates and thus improve acceleration.

In order to give a better idea of how this controller setting influences the vehicle's acceleration the following test was performed:

The vehicle was raised on his warm-up stand and the time it took for the jackshaft to go from 0 to 3700 RPM with the accelerator set at full power was measured.

Table 7 below shows the results of this test.

Controller Setting	Time (s) from 0 to 3700 RPM
1	2.6
8	1.9
15	1.5

Table 7: Influence of controller ramp up setting on acceleration (no load)

Once all these improvements were implemented, the team measured the maximum amount of longitudinal G's encountered under hard acceleration as well at the time it took to accelerate the vehicle from 0 to 20km/h and from 0 to 40 km/h (0 to 12mph and 0 to 24 mph).

The maximum amount of longitudinal G's measured on flat terrain was 0.35. This result was obtained on multiple occasions.

In terms of acceleration time, the snowmobile can accelerate from 0 to 20km/h (0 to 12mph) in 1.6 seconds and from 0 to 40km/h (0 to 24mph) in 7.8 seconds.

TOWING AND CARGO CAPACITY

Utility snowmobiles are often used to transport cargo. There are two main ways of doing so: transport the cargo on-board or tow a trailer sled with cargo on it. While the SAE CSC currently only tests the second method, the McGill Electric Snowmobile Team tried to improve both ways of transporting cargo with the electric snowmobile.

In 2006, the electric snowmobile prototype received the maximum amount of points available in the SAE CSC draw bar pull event. While the event was not officially a “pass/fail” event, it's structure (1 point per foot traveled with a 1500 lbs load up to 100ft.) effectively made it very close to one since the most difficult part of the draw bar pull is the start. For the 2007 SAE CSC, the draw bar pull event structure has changed. The new structure gives the maximum amount of points to the electric snowmobile capable of pulling the highest load regardless of distance and speed.

The key elements for this event are the vehicle's bottom end torque and its traction.

Maximum bottom end torque has improved by over 15% from 2006 to 2007 as a result in the change of motor. Furthermore, this higher bottom end torque can be sustained longer than the 2006 peak bottom end torque could be sustained.

In terms of traction, there are 4 key areas which could potentially slip under high torque. They are the following:

1. CVT – Belt
2. Synchronous Sprockets – Belt
3. Track Drive Sprockets – Track
4. Track – Snow/Ground

1. The use of a relatively new belt for the event is the most the team believes to be reasonable to do in terms of reducing the chance of slippage without compromising anything else in the CVT system.

2. The team believes that the secondary ratio is less likely to slip than the CVT's V-belt due to the meshing between the synchronous sprockets and belt. The key to ensure proper meshing is to ensure that both the sprockets and the belt are of high quality and in good condition. Furthermore, proper belt tension is critical.

The system used on the 2007 electric snowmobile is a Gates Polychain GT2 8mm pitch and 36mm width synchronous belt and pulley system. All design specs are well within Gates design guidelines.

3. As discussed in the "Acceleration" section, track ratcheting was an issue in 2006. The use of anti-ratchet plastic drive sprockets not only serves the purpose of better acceleration but also increases positive engagement between track and sprockets to reduce the chance of track ratcheting when pulling heavy loads.

4. The possibility of slippage between track and ground varies heavily depending on the surface used to run the draw bar pull at the 2007 SAE CSC. Since this is not pre-determined, the team optimized the track not for the SAE CSC but for the real life requirements of the snowmobile.

Since this snowmobile will be used as a utility vehicle at Summit Station in Greenland, the choice of track was made based on the snow conditions found at the NSF's research base. Wind blown snow is the predominant type of snow this snowmobile will face while in service in Greenland, thus a Camoplast Rip Saw track with an aggressive mid-size height lug pattern was selected to ensure good traction at the top of the Greenlandic glacier.

Illustration 5: Typical wind blown snow conditions at Summit station

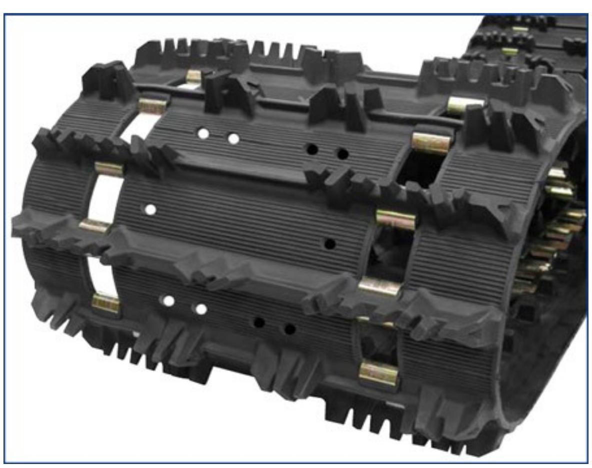

Illustration 6: Camoplast Ripsaw Track [12]

Another factor in the track's traction is the weight which is supported by the track. Unfortunately, in making this electric snowmobile as light and nimble as possible, very little weight is left on the track to give it extra traction on harder surfaces. However, the improved design of this 2007 prototype leaves room for 95 l (25 gallons) of cargo on board the snowmobile, and all this space is located right above the track. For real-life use, the result is that a trailer sled is not even required for carrying up to 95 l (25 gallons) of cargo that can fit on board. If the cargo exceeds this volume or if the shape of some items does not fit in the available space, only then is a trailer sled required and this trailer sleds only need to tow the exceeding cargo which could not be carried on board. Thus the trailer sled will be lighter and the weight on the track heavier than if all the cargo was being towed on the sled. This should overall significantly increase the amount of cargo carried by the snowmobile before track slippage occurs.

On board cargo can either be stored under the seat or on the snowmobile's rear cargo area. The rear cargo area can be outfitted with an optional "easy on/easy off" cargo box.

Illustration 7: Cargo area equipped with optional cargo

RANGE

The requirement for the electric snowmobile range event at the SAE CSC is for the vehicle to travel the maximum distance it is capable of, up to a maximum of 16km (10mi), at a speed of 32 km/h (20mph). In 2006 the McGill Electric Snowmobile Team's prototype failed to complete the event due to a blown component in the low power electronics PCB which ensured proper commutation in the vehicle's BLDC motor. The vehicle thus stopped short of the 16km (10mi) despite still having energy available in its battery pack. Tests were conducted after the 2006 competition to find the vehicle's actual range. While results vary depending on snow condition, terrain and weather, in general the snowmobile was capable of a range around 9 to 9.5 miles. This good performance relative to the CSC requirements explains why "Range" ranked high in Table 6. Nevertheless, substantial efforts were engaged in trying to attain the 16km (10mi) goal.

Two key factors must be taken into account in order to perform well in the range event:

1. Amount of energy on board
2. Efficiency of the vehicle at transferring energy into forward motion

1. AMOUNT OF ENERGY ON BOARD

The 2006 electric snowmobile had a 20 cell series pack (20S1P) composed of Lithium Technology Corporation (LTC) 3.6V, 45AH (@ C/2) High Power cells, for a nominal voltage of 72V. This means that the snowmobile had a maximum of 3240 Wh of energy available on board.

Increasing the amount of energy available on board can directly increase the range of the vehicle. It is thus an avenue worth investigating. Early in the investigation, the team put forth one rule for the possible energy increasing solutions: the main battery pack must be made of the same type of LTC cells which were in the 2006 prototype. Once this rule established, the team looked a 3 ways of increasing the on board available energy.

I. Add cells to the existing series string
II. Add cells in parallel to the existing series string
III. Replace the DC-DC converter with a second battery pack

I. Adding cells to the series string increases the amount of available energy by increasing the pack voltage. The team investigated the possibility of adding 2 cells to the existing 20 cells thus giving the snowmobile 10% more on board energy.

This possibility was rejected partially due to the fact that in order to make it work, the following changes would need to be implemented:
-Replacement of on board charger: the replacement charger which the team would have to install is heavier bulkier and costs 3-4 times as much as the existing charger and it is not a sealed design.
-Adding 2 cells requires the use of another slave BMS PCB board. Thus, this would increase the complexity and cost of the BMS.

The other reason of rejection was that, the initial voltage of a 22 cell pack is 92.4V. According to the motor manufacturer, this voltage would be pushing the motor to its limits, thus such a voltage could be a reliability issue.

II. Adding cells in parallel, unlike adding cells in series, does not increase pack voltage, it increases pack capacity (# of Ah). In order to safely increase the pack capacity, a complete string of 20 new cells must be added to the existing one. The new pack would then have a nominal voltage of 72V and a capacity of 90Ah. Increasing on board energy in this manner avoids the voltage related problems of adding cells in series. Unfortunately, unlike adding cells in series, it is not possible to add only a small percentage of energy. The least amount of energy which can be added is to double the pack's energy. This also means that the pack's volume, weight and cost are doubled at the same time.

Given the requirements of the SAE CSC 2007, the team was unwilling to double the volume, weight and cost of the pack.

However, it is worth noting that if a particular application requires extra range and this application can justify the reduction in cargo space, stability, maneuverability and the increase in cost for adding cells in parallel, the 2007 prototype can accommodate up to 4 strings of 20 cells in parallel (20S4P). The resulting range achievable on flat terrain with hard packed snow would roughly be four times the 2006 snowmobile's range (i.e. approximately 60km (37.5miles)).

III. Most of the energy in the snowmobile's battery pack is used to propel the snowmobile; however, a small percentage of the pack's energy is used to power all the on board electronic systems. These systems all run on voltages lower than 72V. To power them, the 2006 design used a 72V-12V DC-DC converter. One way of increasing the on board energy without changing the existing 72V pack is to add a second battery (12V), which replaces the DC-DC converter.

Disadvantages to such a system are that it brings in a new level of charging complexity. It requires two distinct charging voltages. Two chargers are thus needed. While the extra complexity and costs are much lower than those entailed by the previous solutions, the actual benefits from this solution are also much lower than the ones brought by the previous solutions. Tests have shown that the amount of energy dedicated to the on board electronics during a day time continuous trip represent less than 1% the energy used by the snowmobile. Despite being the lowest cost scenario, the complexity and monetary costs of this solution were judged to be prohibitive to implementation given the limited benefits involved.

After having reviewed all 3 potential ways of increasing on board energy without changing the type of cells used, the team decided against increasing the amount of on board energy. Any increase in range thus needs to come from a more efficient usage of this fixed amount of energy.

2. EFFICIENCY OF THE VEHICLE AT TRANSFERRING ON BOARD ENERGY INTO FORWARD MOTION

The team's first step in the process of improving energy efficiency in order to attain the required range at the required cruising speed was to quantify the vehicle's energy per mile requirement with the new Perm PMG 132 as the drive motor. Tests were conducted on a hard and flat snow base with 7cm of week old snow above it and 3 cm of fresh snow on top of it all. The power required for the snowmobile to maintain a constant speed of 20mph in these conditions translated into an overall attainable range of 7.5 miles.

Based on the results of this preliminary test, the team knew that, in order to receive the maximum amount of points in the range event, overall vehicle efficiency had to increase by 33%.

Given that changing major electrical drive components such as motor and controller was not an option, very little could be done in terms of electrical efficiency. Still the team tried to minimize electrical losses as much as possible. To accomplish this, the team shortened the high power wires and increased the wire size to reduce losses in the wiring. Event though its energy saving potential was small this improvement was readily implemented since it was also seen as a reliability issue.

With very little energy efficiency improvement to be made in the electric drive system, the team put all its efforts into making the mechanical drive parts as efficient as possible. The team thus experimented with a number of different ways of trying to minimize energy losses in the mechanical drive system. The most notable areas of experimentation are the following:

1. Track tension
2. Track bending radius
3. Track/slide friction

1. TRACK TENSION

During the summer of 2005, the team's original electric snowmobile prototype built on a 2001 Ski-Doo Summit received a set of 7 teeth drive sprockets (replacing a set of 9teeth drive sprockets) in an attempt to increase the vehicle's low end torque. Immediately the team noticed that it had to tighten the track in order to keep it from ratcheting on the 7 teeth sprockets. Once this tightening was performed, the snowmobile, equipped with wheels instead of skis, which could previously be rolled along by a single person, became almost impossible to roll unless two team members pushed and pulled with all their strength.

This anecdote is what sparked the team to look more into the losses due to track tension. In order to quantify the relative effect of track tension on the power required to turn the track, the snowmobile, equipped with 9 teeth anti-ratchet sprockets, was set up on the warm up stand and power requirement and track speed were measured at “wide open throttle” for different track tension settings.

The results: The loose track used 10% less power and ran 3.2 km (2 mph) faster than the tight track.

From these results the team knew that being able to run a loose track was an important part of having an efficient drive system.

Following this, the team experimented with different track tensions during on snow testing. Tests with a loose track were consistently faster than tests with a tight track for the same power draw. Differences of 4.8-6.4 km/h (3-4 mph) in vehicle top speed were common occurrence.

2. TRACK BENDING RADIUS

The possible effects of track bending radius, just like track tension, came to the team's attention in the summer of 2005 with the implementation of the 7 teeth drive sprockets. After noticing that track tension made it very difficult to move the snowmobile around, the team got in the habit of loosening the tension before moving it around by hand. While this action helped ease the task of moving the snowmobile around indoors, the team still felt that it was more difficult to move than when it was equipped with the 9 teeth drive sprockets. Thus for the 2007 prototype, the team planned to quantify the relative difference in the power required to drive a track with sharp and soft bends.

Given that the track's bending radius up front at the drive sprockets could not be increased due to clearance issues between the track and the tunnel as well as between the drive sprockets and the suspensions rails only the effect of the rear bending radius at the idler wheels could be investigated. The team thus ordered a set of idler wheels with a diameter of 22.86cm (9in) to compare their effect relative to the vehicle's original idlers which measured 16.19cm (6-3/8in) in diameter.

The team planned to perform a test similar to the one used for track tension. Unfortunately, due to delays in the delivery of the components and unforeseen obstacles in the installation of the bigger idler wheels the team was unable to perform the test in time to include the results in this report.

Nevertheless, the test will be performed as soon as possible and, based on its results, a decision will be taken on whether or not the bigger idler wheels will be implemented on the 2007 prototype.

3. TRACK/SLIDE FRICTION

There are many different types of sliders available on the market and each manufacturer seems to claim that its product is capable of improving stock vehicle efficiency and performance through the use of a more slippery material. Wondering if these claims were true, the team decided to put them to the test.

Using the stock suspension equipped with anti ratchet sprockets and running the Camoplast Ripsaw track as loose as possible, the team measured the vehicle's power requirements for the stock sliders and a set of sliders with PTFE inserts.

No significant improvements on power requirement were observed during these tests.

It is worth noting however that the manufacturer suggests a break-in period of 50-60 miles. Unfortunately, given the limited range of the electric snowmobile, this amount of mileage on the PTFE inserts could not be attained prior to comparative testing.

The team will continue to monitor the performance of the PTFE inserts as they accumulate mileage and a decision will be taken prior to the competition as to whether the original slides or the PTFE slides will be used for SAE CSC 2007.

While the track tension testing justified the use of anti-ratchet sprockets, the slider testing fell short of the team's expectation as a measure to improve the vehicle's range. Running a loose track alone cannot compensate for the motor's loss of efficiency compared to the 2006 motor. Thus, unless the use of bigger wheels or the breaking in of the new track and the PTFE slides provide significant increases in efficiency, the team believes that the snowmobile will likely finish just short of its 16km (10mi) goal at the competition if the event is performed in conditions similar to those found in and around Montreal in February (wind blown snow). However, if the event is performed on a surface which eases the snowmobile's progress or if the team can come up with a last minute means of improving the prototype's efficiency there is a possibility that the snowmobile may attain its range goal.

STABILITY AND MANEUVERABILITY

While the 2006 snowmobile was very maneuverable at low speeds, its desirable low speed characteristics were overshadowed by its lack of stability as soon as the vehicle reached higher speeds. The driver had to actively lean into turns to compensate for the vehicle's high center of gravity and narrow ski stance. This characteristic is what led the team to rate this area of performance so low in Table 6.

This undesirable characteristic was established as being the result of poor weight distribution and a narrow ski stance with a soft independent front suspension setup.

The suspension issue was improved by replacing the 81.3cm (32in) wide independent suspension with a newly marketed 99 cm (39in) wide suspension with a torsion bar linking the A arms of both sides. Illustration 8 below shows the 2006 suspension (gray) superimposed onto the new, wider, 2007 suspension.

Illustration 8: 2006 suspension superimposed onto the 2007 suspension

Once the suspension improvement was implemented, the team tackled the weight distribution issue. The main source of problem in the weight distribution issue was the placement of the batteries on the rear cargo rack which substantially raised the height of the vehicle's center of gravity while also moving it rearwards.

The team knew from the start in 2006 that this was far from being an optimal position for the battery pack; however, delays in component delivery left the team with no other choice than to take the last minute decision of placing the battery pack on the cargo rack. Thus it had been known since March 2006 that one of the challenges for 2007 would be to find a way of moving the battery pack as much as possible into the engine bay.

It was initially thought to be impossible to fit the *entire* pack in the engine bay; however, a clever re-arrangement of the components changed this. Through this major re-arrangement and the use of new components (new Perm PMG 132 motor and a more compact DC-DC converter for example) the team was able to free up a volume in the engine bay in which all 20 lithium cells and the BMS could fit.

As a result of the mounting of the entire battery pack in the engine bay, the weight distribution between the track and the skis has significantly shifted towards the skis in the 2007 snowmobile as it can be seen in Table 8 below.

	Track	Skis
2006 Vehicle Weight Distribution	63%	37%
2007 Vehicle Weight Distribution	44%	56%

Table 8: Comparison of weight distribution between 2006 and 2007 electric snowmobile prototypes

In terms of height, the center of mass of the battery pack is 14cm (5.5in) lower on the 2007 prototype than on the 2006 prototype.

The result from these improvements is a much more stable ride at all speeds with increased maneuverability at higher speeds. Low speed maneuverability has effectively remained the same other than the fact that the vehicle's overall width has increased by 4 inches (Note: ski width was smaller than vehicle width in the original configuration).

NOISE

No accurate noise information was available from the 2006 snowmobile. What the team knew however was that it was possible for a driver and a passenger both wearing open face snowmobile helmets to communicate verbally while driving at 40km/h (24mph). Furthermore, it was also known that a rear facing “spotter” was capable of communicating verbally with a snowboarder being pulled by the snowmobile with approximately 12m (40ft) of distance between them. This information is what led the team to rank the snowmobile's noise performance relatively high in Table 6.

Despite the high ranking of noise performance in Table 6, the lack of numerical data for noise levels was something which the team wanted to change and thus effort was put into gathering noise data.

The team first acquired a simple sound level meter (Radio-Shack Cat. No. 33-2055).

The snowmobile's sound levels were recorded with the vehicle driven by the Perm PMG 132 Motor with anti ratchet sprockets, the Camoplast Ripsaw track as loose as possible, the batteries mounted on the rear cargo rack and no additional sound insulation foam. The snowmobile's noise levels were measured at 20 and 40 km/h (12 and 24 mph). Four different positions were used to measure the noise: on the snowmobile near the driver's head, 4.5m (15ft) away from the vehicle at a height of 1.5m (5ft), 6m (20ft) away at a height of 1.5m (5ft), 9m (30ft) away at a height of 1.5m (5ft).

This test was conducted on lightly tracked out and wind packed week old snow under a cloudy sky and with a temperature of -9C by using the dB A scale.

The maximum dB readings from the test are presented in Table 9 below.

Location	Speed	
	20km/h (12mph)	40 km/h (24mph)
Driver's head	76 dBA	86 dBA
15ft	71 dBA	78 dBA
20ft	68 dBA	76 dBA
30ft	66 dBA	74 dBA
Ambient Noise	<50dBA	
Noise at “idle”	<50dBA	

Table 9: 2007 Snowmobile noise data

EASE OF USE

Above and beyond all the improvements previously discussed, there are some interesting features on the 2007 electric snowmobile which make it the most easy to use electric snowmobile the McGill Electric Snowmobile team has built to date. First of all, most of the user friendly features of the 2006 prototype are present in the 2007 prototype. This includes the high efficiency on-board charger with electrical inlet and breaker.

Illustration 9: Strategically placed electrical inlet

On top of all the perks which were present in the 2006 prototype, the 2007 vehicle is equipped with a new custom made driver information center. This system, displays all the information a driver can require: voltage, current, RPM, speed, outdoor temperature and state of charge of batteries. Moreover, since an electric prototype is operated slightly differently than an ICE snowmobile, the system also helps the user learn how to operate it. For example, the noise from an ICE can tell you when a snowmobile is ready to be driven. This is not the case for the electric snowmobiles. Therefore, a very useful function of the display is to tell the users when the snowmobile is ready to go. Since this information is shown on a vacuum sealed high brightness display it can easily be read even in direct sunlight at temperatures down to -40C.

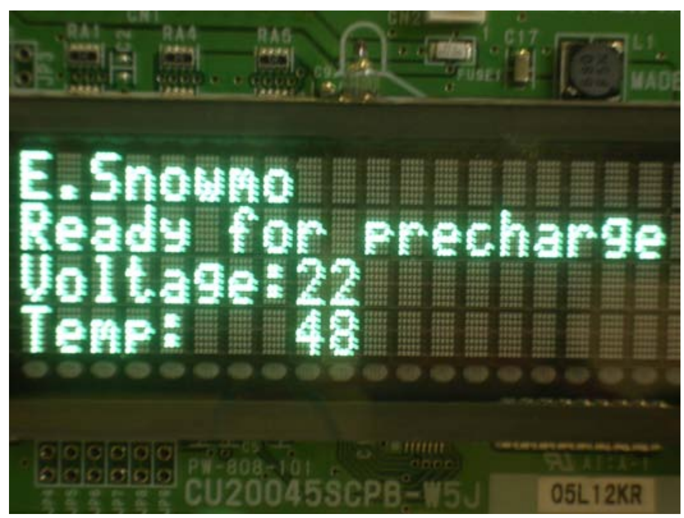

Illustration 10: Electric Snowmobile high brightness VFD

The driver information center is also coupled to a custom made data acquisition system which records battery voltage, battery current, two RPM sensors and two temperature sensors. After a run, data from this system can easily be downloaded onto a computer for analysis. This allows for some easy troubleshooting if the snowmobile is not performing as well as expected. Furthermore, it can also be used as a simple development tool when the data to be analyzed does not require to be acquired via a professional system such as the Isaac V7 Pro Black Box which the team often uses for product development.

COST

The 2007 edition of the SAE CSC requires all teams to submit a Manufacturer Suggested Retail Price (MSRP) as if 5000 units of their vehicles were produced. This is determined by first selecting the current production model which most resembles the team's prototype. The MSRP of this snowmobile is considered to be the baseline MSRP of the prototype. To this baseline MSRP, the team must add the cost of extra components which are not present on the baseline snowmobile. This last requirement of the competition is somewhat misleading in terms of the MSRP for the electric snowmobiles since it means that the electric prototypes carry the cost of the baseline vehicle's engine, exhaust system as well as its fuel system and air intake system. The 2007 McGill electric snowmobile prototype is built on the same Ski-Doo RF chassis as the 2006 prototype. For the 2007 SAE CSC the baseline MSRP used is the MSRP of the 2007 Ski-Doo Tundra which is of 4,799.00 US$.

There are 3 major components on the electric snowmobile not present on the baseline snowmobile which, among them, define over 95% of the vehicle's cost above the baseline MSRP. Furthermore, of all things not present on the baseline chassis, the team firmly believes that choice, placement and calibration of these same 3 components also directly dictates 95% of the vehicle's performance. These components are: the batteries, the motor and the controller.

The cost breakdown of these key components in the 2007 electric snowmobile is outlined in Table 10 below.

	Cost (US$)
Batteries (with BMS)	4,900.00
Motor	750.00
Controller	535.00
Component Total	**6,185.00**
Vehicle base MSRP	4,799.00
Total Vehicle Cost	**10,984.00**

Table 10: 2007 electric snowmobile cost

CONCLUSION

Right from the start of the design process for the 2007 electric snowmobile prototype, the team felt it had a strong basis to start with in its 2006 prototype. Thus, unlike in previous years, no revolutionary changes were made to the vehicle but instead, the vehicle received considerable improvements and fine tuning in a number of areas. The end result is a snowmobile which outperforms its predecessor almost all across the board and it does so at a lower cost.

It is clear that electric snowmobiles will by no means replace their gasoline counterparts in the short term. The large OEMs are not currently equipped to manufacture, service, and sell such vehicles. Unless the demand changes through new legislation, the production of such vehicles for a marginal market would very unlikely be commercially viable in the short term for the big OEMs.

Nevertheless, by improving on its predecessor, the 2007 McGill electric snowmobile prototype demonstrates what one can expect from such a utility vehicle and, in doing so, expands the size of niche market which could be served by electric snowmobiles in the short term.

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