Development of a 3rd Generation Electric Utility Snowmobile Powered by Lithium Batteries

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ABSTRACT

After much success with its electric snowmobile prototype at the 2007 SAE Clean Snowmobile Challenge (CSC) and at the National Science Foundation's (NSF) Summit Station in Greenland over the summer, the McGill University Electric Snowmobile Team, returns to the SAE Clean Snowmobile Challenge in 2008 with a revised electric snowmobile prototype.

The success of the 2007 prototype convinced the team that their overall approach was a valid one. However, despite the success, some areas had shown room for improvement. Thus, for 2008, the team decided to use value engineering methodology in order to further optimize the prototype for the SAE CSC competition.

The main modifications for 2008 which came out of the value engineering analysis of the 2007 prototype are an increase in battery capacity for added range and proper sound barriers to make the vehicle extremely quiet. In order to try an offset the added weight of the extra batteries, each of the vehicle's components all the way from the suspension to the tail light were optimized in order to reduce weight while at the same time maintaining the characteristics which made the 2007 prototype a successful vehicle.

Lastly, emphasis was put on trying to use as much stock parts as possible. While this aspect is not one that is directly evaluated at the competition, the team believes that it is an aspect which is of great importance for use of this snowmobile in remote locations such a Summit Station.

INTRODUCTION

Utility snowmobiles are essential vehicles for a number of applications. According to the International Snowmobile Manufacturer Association (ISMA) website, 20% of snowmobiles are used for work or general transportation[1] (i.e. utility purposes). Unfortunately, current OEM utility snowmobiles powered by internal combustion engines cannot meet all on snow utility vehicle needs. Certain applications require direct vehicle emissions to be lower than what is currently possible with an internal combustion engine.

VECO Polar Resources (VPR), the U.S. National Science Foundation's (NSF) civil contractor for Arctic research, has expressed such a need for a zero emission snowmobile. They believe that research done at various remote arctic bases, and especially at the NSF's Summit Research Base in Greenland, can benefit from a zero emissions snowmobile. Research at Summit includes extensive atmospheric and ground (ice and snow) 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/clean air zone" has been established up wind of the main base in order to minimize contamination of samples by the base's vehicles and its diesel powered electric generator. Unfortunately this also means that, until the summer of 2007 when the McGill Electric Snowmobile was put in use at Summit, access to the zone was mainly by foot thus limiting the amount of equipment which could be brought in the "clean air zone". This extended the time required to acquire the samples and increased safety risks in an extremely cold and harsh environment. Simple tasks such as bringing hydrogen and other pressurized gas cylinders to and from the satellite camp located in the clean air zone was a long and tedious affair. The arrival of McGill's electric snowmobile in 2007 allowed researchers to carry their pressurized tanks and other scientific equipment in a much more efficient and safe manner. Furthermore, in such a remote location where safety is a very high concern, being able to have a rapid way of transiting from the main base to the satellite camp in the case of any emergency is a priceless benefit.

In order to continue to push the evolution of the electric snowmobile technology such that it can perhaps eventually replace all internal combustion engine (ICE) snowmobile at Summit and maybe find new niches, the Clean Snowmobile Challenge (CSC), a student engineering design competition administered by the Society of Automotive Engineers (SAE), added an electric snowmobile category to its competition in 2006. As defined in the competition documentation, the goal of the zero emission category is to meet the needs of the international scientific community by designing a safe, reliable, user friendly, utility specific electric snowmobile which has adequate range and power.

The 2008 zero emission snowmobile entries are evaluated on the basis of 15 criteria:

1- Engineering Design Paper
2- Manufacturer's Suggested Retail Price (MSRP)
3- Oral Presentation
4- Weight
5- Range
6- Capacity
7- Acceleration
8- Handling and Drivability
9- Subjective Handling
10- Cold Start
11- Static Display
12- Objective Noise
13- Subjective Noise
14- Technical Inspection
15- Reliability (No maintenance bonus)

McGill's 2007 electric snowmobile prototype won the overall title in the zero emission category at the 2007 SAE Clean Snowmobile Challenge (SAE CSC). Despite this win, the team felt there were still a number of areas in which the vehicle could be improved. Thus, the McGill Electric Snowmobile Team applied the Value Engineering Methodology to the 2007 vehicle in order to determine and prioritize items which needed attention as well as select which improvements would be implemented in 2008.

Overall this paper can be divided into 2 very distinct sections:

First is a general section discussing the challenges of making an electric snowmobile. This section, which is an updated version of a similar section the team presented at the November 2007 PHEV conference in Manitoba, looks in details at the main challenges encountered in designing a viable electric snowmobile. It puts these challenges in perspective by comparing the latest McGill electric snowmobile prototype to current gasoline powered snowmobiles.

Second is an overview of the choices made and implemented on the 2008 McGill electric snowmobile prototype. The reasons behind the choices are explained and when possible, comparative results between the 2007 and 2008 prototypes are given to measure the impact of the changes. Since the team used the value engineering analysis methodology for this design, this section is divided into subsections made up of the different categories which came out of the team's functional tree when the value engineering analysis was performed.

---------------------------- Section 1[2] ------------------------------

THE CHALLENGE OF DESIGNING A VIABLE ELECTRIC SNOWMOBILE

This section is an attempt at answering a question the team has been asked many times since its inception: "Why is the design of a practical electric snowmobile such a challenge?"

The team's answer to this question is simple: "It's a challenge because of the relative energy density of batteries when compared to currently permissible alternatives (mainly gasoline)".

Using a value of 8760 Wh/l [3] 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 355,875 Wh of energy on-board. As a basis for comparison, the 2008 McGill Electric Snowmobile Team's prototype carries 6480Wh of energy (battery name plate rating).

Vehicle	Fuel Volume (l)	Energy On Board (Wh)
Arctic Cat Bear Car 570	49.2 [4]	430,992
Polaris 340 LX	46.4 [5]	406,464
Ski-Doo Skandic Tundra	34 [6]	297,840
Yamaha Venture Multi-Purpose	32.9 [7]	288,204
Average	***40.625***	***355,875***

Table 1: On-board energy of 2008 model gasoline powered utility snowmobiles

Using a mass of 0.73 kg/l (6.1 lb/gal) [8] as the volumetric mass of gasoline, the weight of the average 355,875 Wh of energy carried on-board those snowmobiles is 29.66 kg (65.38lbs).

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 [9]	33.5	76.2
Ni-Cd [10]	54	95
NiMH [11]	60	155
Li-Ion [12]	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 does the team term it the “raw” energy density? The term “raw” energy density is used 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 2008 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) [13], 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 carrier (EC) 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)

Despite being much more efficient than its gasoline counterparts at the vehicle level, the electric technology 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. 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 cross-country ski trails is often done with a snowmobile towing a heavy sled).

Having looked at what the main challenge is in designing a viable electric snowmobile, the following section looks at how, despite this challenge, the McGill team, once again in 2008, designed what it believes to be a viable utility electric snowmobile for use in ultra sensitive environments.

---------------------------- Section 2 --------------------------------

THE VALUE ENGINEERING DESIGN METHODOLOGY

In order to maximize its chances of winning the 2008 SAE CSC, the McGill Electric Snowmobile Team decided to use a proven design methodology to design its 2008 prototype. The value engineering design methodology which the team used is a 7 step methodology which enables designers to both target the most important areas of improvement and select the solutions which will bring the most value to the overall design for a given goal.

The 7 steps of the value engineering process are:

1- Organization
2- Information
3- Function Analysis
4- Creativity
5- Evaluation
6- Development
7- Implementation and Follow-up

This part of the report is mainly organized based on the results of the function analysis and for each function, the other associated steps are discussed.

However, before getting into the different functions of the vehicle it is important to know some key points from the initial Organization and Information phases.

One of the first decisions taken was that the 2008 prototype would be a no compromise snowmobile. Previous McGill electric snowmobile prototypes were a compromise between research use of the vehicle, the true needs of the scientific community at Summit Station and good performance at the SAE CSC. It was decided that the 2008 snowmobile would be designed solely to win the SAE CSC 2008. In theory, given the mandate of the SAE CSC Zero-Emissions category, the snowmobile with the best performance at the CSC should be the best design for use by the scientific community. Thus, the team assumed that the competition rules and scoring scheme were the best guidelines to follow in terms of making the 2008 prototype.

DESIGN CONSTRAINTS

Before going into the details of the design choices which went into optimizing each function of the vehicle, it is important to point out some design constraints which are not part of the Value Analysis.

1- Frame Selection
2- Battery Cells Selection

Given the team's available resources it was decided early in the process that the 2008 prototype would have to be based around the available Ski-Doo RF frame which the team already owns. Given the good performance of this chassis in the past this was not a constraint which was perceived to be detrimental to the design of the 2008 vehicle.

The same was decided for the lithium ion cells which would compose the 2008 prototype's battery pack. Given the high cost of new batteries and the fact that these cells have performed flawlessly in Greenland over the summer, it was decided that the Lithium Technology Corp. 45Ah HP cells the team already owns would be the building blocks of the 2008 electric snowmobile battery pack.

Thus, in doing the value engineering analysis, on top of complying with SAE CSC rules, any design suggestion would have to obey these 2 constraints.

Function Analysis

With the target objective determined, the team established the vehicle's function tree. The key functions of the tree are given in the list below.

1. Be "Greenlandable"
2. Be light
3. Tow heavy load
4. Accelerate fast
5. Attain high speeds
6. Travel far
7. Handle well
8. Minimize noise
9. Start cold
10. Be low cost

The following pages look at how the design of the 2008 McGill Electric Snowmobile Prototype was optimized in order to achieve the best possible value score based on the above functions derived from the value engineering analysis.

BE "GREENLANDABLE"

Throughout the value engineering exercise, the team used the term "Greenlandability" to represent the sum of the characteristics which would make the vehicle optimal for use at Summit Station.

This function, based on the current SAE CSC point scheme, is not directly evaluated but rather subjectively included into the grading scheme of the design report and presentation. Furthermore, the no-maintenance bonus of 100 pts, in the team's opinion, fits under the umbrella of "Greenlandability".

Right from the start, the team knew, based on the success of the snowmobile which was sent to Summit

Station that without doing any changes they had a very "Greenlandable" vehicle to start with.

As seen in this excerpt from VECO Polar Resources' newsletter dated June 2007[14] the snowmobile lived up to the needs of Summit Station.

> "Finally at Summit, Tracy Dahl reports that the zero-emissions electric snowmachine from McGill University (winner of the Clean Snowmobile Challenge, sponsored in part by the NSF) passed performance tests at Summit Station last week. "On the first day after we set it up, I went 20 kilometers (with a brief re-charge in the middle)," Tracy writes, "and hauled many tons of cargo to/from [the satellite] camp. The biggest load was the mobile weatherport. It was absolutely the maximum it could handle, but it got the job done." Tracy mentions that he pushed the machine to define its limits, but "I failed to break it, trying as hard as I could." Hats off to McGill!"

One thing the team has learned over the past two years is that the key to "Greenlandability" is first and foremost reliability in the most extreme winter conditions. Performance comes in a far second along with ease of use. Since performance and ease of use were already known to be adequate for use at Summit Station, the team concentrated its efforts on even further improving reliability.

In order to do this, the team looked at the results from the snowmobile's stay in Greenland over the summer. While during its 2 month stay the snowmobile did not encounter major issues, a thorough investigation of all its components upon its return to McGill found that some parts were showing signs of premature wear. Thus the first item addressed was to eliminate this problem.

All the parts showing premature wear were located in the snowmobile's mechanical drivetrain, between the motor and the track drive sprockets.

Numerous new designs were though of to try and eliminate the problem and some of them even integrated new concepts which would possibly improve the vehicle's performance. However, all had one major flaw: how could these new designs absolutely guarantee they would increase the vehicle's reliability? They could not guarantee it unless they could be tested in the field for hundreds of hours.

Answering this question ended up being what led the team to its solution to the problem. The team realized that there was one drive system with thousands of hours of use which had already shown it was reliable in a Ski-Doo RF chassis in utility snowmobile applications: the stock OEM drivetrain.

Thus the team redesigned the packaging of all the components under the hood in an attempt to make the electric drive system compatible with the snowmobile's stock OEM mechanical drivetrain.

In the end the team was able to replace all drivetrain components from the driver pulley all the way down the line to the track driveshaft with the stock OEM drivetrain components.

The biggest modification was replacing the custom made belt drive secondary ratio with the stock chain drive secondary ratio and its chain case.

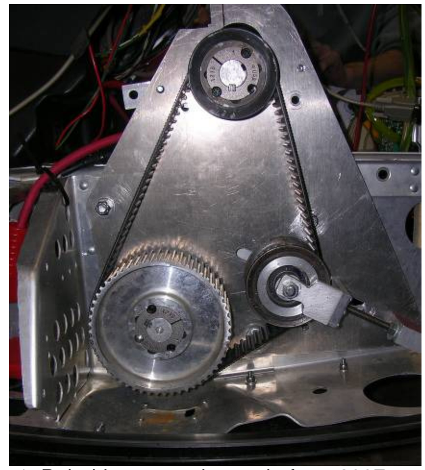

Figure 1: Belt drive secondary ratio from 2007 prototype

Figure 2: Stock OEM chaincase installed in the place of the belt drive on the 2008 prototype

This modification was only the beginning since a cascading effect ensued. Installing the stock chaincase changed the position of both the track driveshaft and the countershaft (jackshaft). These new shaft positions created interference between the custom brake system of the 2007 prototype, located on the driver's left hand end of the trackshaft and the CVT's driven pulley.


Figure 3: Custom brake and CVT driven pulley on the 2007 prototype

Thus, further packaging modifications had to be made to accommodate the reinsertion of the stock brake system on the driver's right hand end of the countershaft.

Figure 4: New brake position on 2008 prototype (above chaincase)

Not only did this change in jackshaft position impact the brake system, it also changed the center-to-center distance of the CVT. Thus, a completely new motor mounting system had to be implemented to accommodate this change.


Figure 5: 2008 prototype without the aluminum motor mounting plate

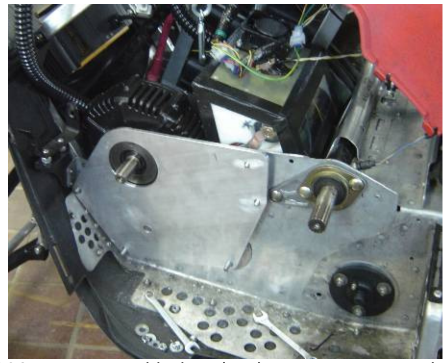
Figure 6: 2008 prototype with the aluminum motor mounting plate

In the end, while it might sound simple at first, reverting to the stock OEM drivetrain ended up being a sizeable endeavor. However, the team is now confident that it has addressed the biggest need of the McGill electric snowmobile prototype when it comes to "Greenlandability".

What's even more interesting is that in doing so, the team was able to improve on two other functional areas of the vehicle: weight and performance.

Another area which was targeted by the team to make the vehicle as reliable as possible was to minimize the number of accessories, thus reducing the chances of some small component failure creating a domino effect which makes the entire vehicle unusable. So for 2008, the only accessories found on the vehicle are analog meter which give the driver the 2 most important pieces of information on the vehicle: battery voltage and motor temperature. Other than this, no extra features were added to the vehicle since it was evaluated that the extra risk involved in doing so did not outweigh the benefits.

BE LIGHT

Points attributed to weight represent 8% of the maximum allowable amount of points at the SAE CSC. The 2007 prototype was the lightest snowmobile of the competition and amassed the maximum amount of points in the weight event. However, this event is scored on a relative scale thus not only must one try to be the lightest, but one must try to be the lightest by the biggest margin.

With that in mind, the team set out to try and further reduce the weight of the lightest ever SAE CSC snowmobile (all categories included) since weight was introduced as an event.

The first weight savings were found in a somewhat unlikely place. When the team took the decision to try and install the stock OEM drivetrain, initially, it looked like it would also translate in a weight increased. The custom aluminum track driveshaft of the 2007 prototype was 66% lighter than the stock OEM one. The custom brake system was 50% lighter than the stock OEM system and the belt from the secondary drive 80% lighter than the stock OEM chain. However, when it came to weight, the 2007 drivetrain system was not perfect, it had one major flaw: packaging.

In assembling the 2006 and the 2007 mechanical drivetrain the team had to mount two thick aluminum plates, one on either side of the engine bay, in order to mount the entire drivetrain. This was necessary at the time since, by SAE CSC rules, the team has to use a stock OEM chassis. Not surprisingly, this chassis was not configured with all the mounting points and reinforcement sections the team needed for its custom drivetrain. By installing the stock OEM mechanical drivetrain for 2008, the team is taking full advantage of the stock chassis (and all the OEM R&D behind it!) and is thus saving a considerable amount of weight. Furthermore, the mounting plates from the 2007 chassis actually dated back to the 2006 prototype and optimization of these plates for weight was never carried out over the years. This time, as the entire drive system was being repackaged, the few remaining custom mounting brackets have been optimally designed to save weight. The end result was that the drivetrain change, despite some weight increase on some components ended up saving close to 3kg overall.

In order to maximize weight savings for the rest of the vehicle, the team compiled a thorough component's weight list.

For each of the components the following questions were then asked and the actions resulting from the answers were taken:

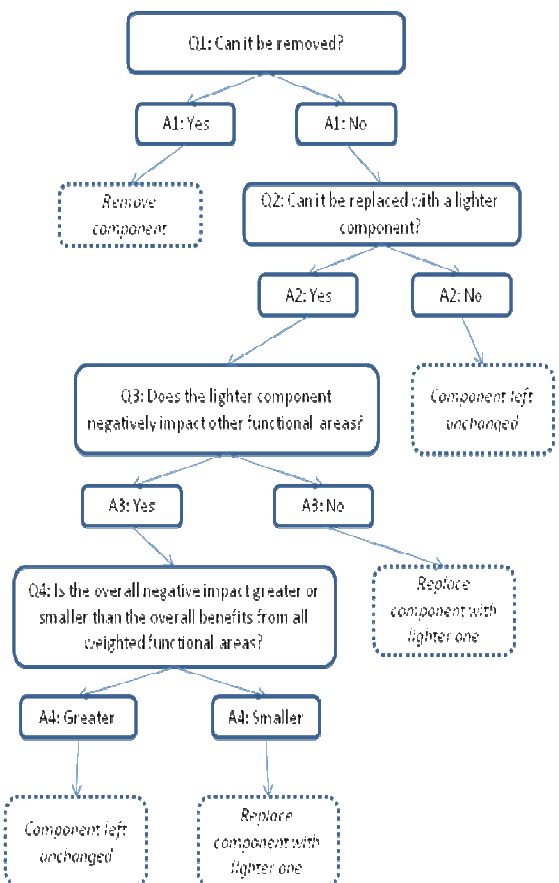

Figure 7: Vehicle weight analysis program flow chart

Through this exercise, close to 20kg of weight were removed from the vehicle. The most noticeable change is the replacement of the original 3.45m (136 inch) track with a 3.07m (121 inch) track. In order to do this, the team removed the SC-136 suspension from the 2007 prototype and replaced it with the 3.07m (121 inch) AD Boivin ZX2 plastic composite suspension.


Figure 8: McGill prototype with SC-136 rear suspension


Figure 9: McGill prototype with ZX2 rear suspension

The original SC-136 suspension was already very light but this change in suspension still enabled the team to save a few pounds. The key however is that this opened the door for more weight savings on the track. Changing from the 3.45m x 0.38m x 0.031m (136" x 15" x 1.25") Rip Saw track to the 307m x 0.35m x 0.025m (121" x 14" x 1") Hacksaw track enabled the team to save over 4.5kg.

The rear suspension and track change account for roughly half of the weight savings achieved through the team's weight analysis program. The rest of the weight savings come from an array of smaller savings such as a change in motor controller (~1kg saved) and even a change in windshield (a few grams saved!...).

Each gram removed from the snowmobile not only improves its performance in the SAE CSC weight event but a low weight can potentially help in certain performance events. Unfortunately low weight over the track can also hurt in the SAE CSC capacity event. In then end the weight analysis program helped the team keep the vehicle weight just below 350kg despite the fact that heavy items were added to improve the vehicle's range and minimize the noise it produces.

PERFORMANCE

Vehicle performance is a broad term. To better value engineer the different areas that make up the snowmobile's performance in the zero emission category, the team divided performance in to 5 functions:

1- Tow heavy load
2- Accelerate fast
3- Attain high speeds
4- Travel far
5- Handle well

1- TOW HEAVY LOAD

In order to try and maximize towing capacity, the team looked at some of the different criteria that affect it. The key ones were found to be:

I. Traction
II. Torque

I. Traction

Traction is the most important of the two criteria. Without traction, the strongest motor in the world can't even move the snowmobile itself, let alone a load in tow.

Unfortunately, many things make up the vehicle's overall traction and thus it is not easy to predict what the final result will be. For example a setup which gives great traction on a hard or icy surface may provide almost no traction in loose powder snow.

There are 3 main areas where loss of traction can possibly occur:

i. CVT belt
ii. Track drive sprockets
iii. Track/snow interface

i. So far, CVT belt slip has not been a problem with past McGill electric snowmobile prototypes. The use of good quality belts has, to date, been sufficient to ensure that this area would not be the weakest link in the traction chain.

Other than the use of good quality belts, very little can be done to this area without significantly impacting other performance criteria. Thus until CVT belt slip becomes the limiting factor, the team chooses to concentrate on other areas.

ii. Given that the team used a very loose track setup for better driving efficiency, slippage between the track drive sprockets and the track, (ratcheting), has been a problem in the past.

This problem was solved in 2007 with the use of anti-ratchet drive sprockets which engage every open window of the track. The team is satisfied with this component and decided to continue using it on the 2008 prototype.

iii. Track/snow interface slippage has proven to be the biggest limiting factor in terms of load towing capacity in the past. Tests seem to demonstrate that the low weight of McGill's vehicles is not a stranger to this phenomenon. The traction at the track/snow interface seems to be a function of the track and the normal force on it. On a given hard packed snow test area, an increase in normal force on the track seems to improve traction at the track/snow interface. Track size and lug profile also seem to have an effect on traction at this interface. However, all of these interactions seem to vary greatly depending on the type of snow surface. Since the event's snow surface is unknown until the day of the event it is very difficult to optimize track/snow traction.

What the team decided to do was to have an all around good aggressive track lug pattern (Camoplast Hacksaw) which is predominantly geared towards groomed packed snow. Playing the odds, the team believes the conditions at the competition are most likely going to be similar to groomed packed snow.

Furthermore, the team plans on having different riders dressed in SAE CSC approved rider gear for the event. This will allow the team to send either a lightweight driver or a heavy weight driver and perhaps even a passenger on the snowmobile for the competition based on the snow conditions at the event venue.

II. Torque

In the event where no slippage occurs, torque becomes the main limiting factor. Ever since the team has implemented the use of a CVT system in its vehicles, the only times when torque has been the limiting factor is when the team, for specific purposes, has electronically limited the power of the motor to a very low level.

The 2008 SAE CSC competition snowmobile will have full motor power and thus it is unlikely that it runs into a motor stall condition before slippage occurs.

In numbers, what does this mean?

Given the maximum torque of the motor and the gearing ratios of the 2008 electric snowmobile prototype, the track driveshaft can possibly receive up to 335Nm of torque at any speed from 0 to 10 km/h. Given the size of its drive sprockets this means that, in a no slip condition, the snowmobile is capable of exerting a forward force of over 3500N.

All vehicles in the 2007 competition lost traction at the track/snow interface in the draw bar pull. Based on the results of the competition, if it is assumed that avoiding slippage is mainly a function of weight and friction at the track/snow interface, the team has estimated that the track/snow friction coefficient for the 2007 event was around 0.2 at best. Given the 2008 vehicle's weight, friction would need to go up by more than a factor of 4 (nearing a friction coefficient of 1) in order for the motor to reach a stalled condition.

Basically, when it comes to towing a load, the team feels it has done most of what it could legally do to the snowmobile in order to try to maximize this performance area without negating these positive effects with major drops in performance elsewhere. The current format of the competition does not encourage the team to sacrifice other performance areas to have more pulling capacity than what the 2008 snowmobile now has.

2- ACCELERATE FAST

Good acceleration is definitely a component of the competition's drag event, but it also plays a role both in the objective and subjective handling events.

Minimizing vehicle weight and ensuring good traction are two key elements of good acceleration. Since both of these elements have been previously touched upon in other sections, this section will concentrate on the third element of good acceleration: maximizing power to the track.

The key to maximizing power is not to have the biggest motor possible; it is to have the most well balanced system possible. Since most SAE CSC events where acceleration comes into play are short duration events, maximum power does not need to be sustained for prolonged periods of time. This is good since overheating of electrical components is the main barrier to high power; and for a given set of environmental conditions, heat is a function of power, efficiency and time.

In order to maximize performance the team created a large data base of motor, controller and battery data from both dynamometer testing and on snow testing of components. This database was very valuable in selecting components and optimizing their parameters for the required performance. It was also very costly to assemble since the limits of some component were found the "hard way", with some components going up in smoke.

Using the information from this database, the team assembled a motor/controller/battery package based around the Perm PMG 132 motor, the Alltrax AXE controller and the Lithium Technology Corp. 45Ah HP cells. Optimization of parameters through advanced powertrain modeling and simulation as well as in field testing produced a powertrain configuration which, for a short period of time, can provide more than twice the amount of power than what the latest McGill electric snowmobile sent to Summit Station in Greenland had available to it.

The next step in having a well balanced system was to ensure that this maximum power could be transmitted to the track throughout the vehicle's speed range. To ensure that this aspect would not nullify all the efforts put into the motor/controller/battery package, an extensive on snow CVT testing program was implemented. The team acquired multiple Powerblock 50 and Invance pulleys from CVTech R&D and each pulley was set to a different calibration. The snowmobile was fully instrumented with an Isaac Instruments V7 Pro data acquisition system. Two drive cycles were performed in sequence with each pulley combination. The first run was a "full throttle" acceleration and the second one was a constant speed run. CVT pulley combinations were changed after each pair of test runs while the battery pack was recharged back to its original state before the next pair of runs.

As an optimal setup started to emerge, other pulleys were re-tuned to a slight variation of this setup and the testing continued until the team felt confident it had an optimal CVT configuration to take full advantage of its motor/controller/battery package.

In numbers, the end results are the the following: the snowmobile will normally pull 0.25 G of longitudinal acceleration off the start. Table 6 below shows some typical times taken by the snowmobile to attain a certain speed from a standstill on moderately packed snow.

Speed (km/h)	Time (s)
10	0.8
20	2
30	4
40	8.6

Table 6: McGill electric snowmobile acceleration times

As one can expect, acceleration was not the only performance criteria being evaluated in this test program. The vehicle's top speed and its efficiency at cruising speed were also being closely evaluated.

3- ATTAIN HIGH SPEEDS

Maximizing the vehicle's top speed, just like maximizing its acceleration, has a lot to do with maximizing power to the track. However, unlike acceleration, which is linked to power to the track throughout the vehicle's shifting range, top speed is a function of power to the track when the CVT is fully shifted.

This parameter was taken into account when the CVT testing program outlined in the previous section was implemented. However, a high top speed only plays a small role at the SAE CSC. The main place where it is taken into account is in the acceleration event where the electric snowmobile usually accelerates for the first part of the run and operates at maximum speed towards the end of it. Given the small role of top speed at the competition, while it was taken into consideration, its relative weight was small compared to acceleration and more importantly cruising speed efficiency when determining the best drive ratio and CVT configuration.

The chosen final configuration results in a top end speed which varies between 45 and 55km/h depending on the conditions.

4- TRAVEL FAR

In 2007, McGill's snowmobile travelled 11 miles in the SAE CSC endurance event starting with approximately 3200Wh of potential energy in its battery pack. This was enough to give the team the maximum amount of points in the event. Ten (10) points were given per miles travelled up to a maximum of 100pts.

In 2008 the grading scheme for this event has changed and there is no more limit to the number of miles traveled for points. Points are distributed on a scale relative to the highest and lowest distance travelled by snowmobiles in the event. Thus similarly to the weight event, the team's goal is to not only be the snowmobile that goes the farthest, but to try to do this with the biggest possible margin compared to the other snowmobiles.

On flat ground, the distance the snowmobile can travel on a single charge at a given speed and in given conditions is mainly a function of two parameters:

I. The amount of energy on-board
II. The snowmobile's efficiency at converting the on-board energy into motion

I. <u>The amount of energy on-board</u>

Given the relatively high efficiency of McGill's vehicle, the amount of energy on-board is the most important factor when it comes to the how far the snowmobile can go on one charge.

The new grading scheme prompted the team to make a substantial change to its battery pack. Instead of the single string of 20 cells in series used in 2007, the team decided to implement 2 parallel strings of 20 cells in series. This decision was not without impact on other functional areas of the vehicle (e.g. weight, MSRP) however the team carefully evaluated these impacts and decided that doubling the size of the battery pack was worth the cost in those other functional areas.

The initial 20 Lithium Technology Corp. cells which were used in Greenland were left in their respective locations on the snowmobile (i.e. in the engine bay: 10 partially wrapped around the motor and 10 in a rectangular box between the rear of the motor and the brake and chain case assembly).

Figure 10: Original cells in the engine bay

A new rectangular box was constructed in order to house the 20 added cells. This box was mounted on top of the snowmobile's tunnel.

Figure 11: New box housing the new parallel string of 20 cells

One very interesting characteristic of this new 20S2P battery pack configuration is that not only does it double the amount of energy on-board, it also increases the pack's efficiency at converting its stored up potential chemical energy into electrical mechanical energy.

II. <u>The snowmobile's efficiency at converting the on-board energy into motion</u>

Just like maximizing the snowmobile's power is not as easy as acquiring a powerful motor, improving the snowmobile's efficiency is not as easy as simply acquiring a more efficient motor! The entire combination of drive system components must be looked at as a whole.

Before going through this drive system optimization process, the team had to determine what operating point it would be optimizing for. The SAE CSC event in which efficiency is the most important is the endurance event. The rules of the competition state that this event will be conducted at a speed no greater than 32 km/h (20MPH). The 2007 endurance event was done with a target speed of 24 km/h (15MPH). The team thus decided to optimize the efficiency of the drive system for a vehicle speed of approximately 24-32 km/h (15-20MPH) on flat hard packed snow.

The first efficiency improvement the team implemented came from the use of the added 20 cells in parallel with the ones from the 2007 prototype. How did those new cells increase efficiency?

The rated amount of energy stored in a battery is only valid at a given discharge rate. For the vast majority of batteries, as the discharge rate increases, the actual amount of electrical energy available from the battery in one discharge cycle diminishes.

One extreme example of this is McGill's first electric snowmobile prototype which, based on the name plate rating of the batteries, had 2808 Wh of energy in its batteries. However, these batteries' name plate rating was at a discharge rate approximately 40 times lower than the discharge rate required at cruising speed. The amount of electrical energy actually available from the batteries when the vehicle was a cruising speed was approximately 1400Wh; thus, as a result of this roughly half the rated amount of energy was actually available to drive the vehicle.

It is not possible to know in advance what the exact discharge rate for a given drive cycle will be since it is highly dependent on the snow conditions. Nevertheless, in the case of the 2008 prototype, based on data gathered from on snow testing on flat moderately packed snow, the average discharge rate expected during the endurance event at the SAE CSC is expected to be around 100 to 120 amps. This discharge rate is over 13 times higher than the discharge rate at which the batteries' name place capacity was measured. Even though the lithium cells used by McGill University are specially formulated to reduce efficiency drop at high discharge rates, this high discharge rate does still have a cost efficiency wise. By adding a second string of 20 cells in parallel to the first string, each string of 20 cells only has to supply half of the total current. Thus it is estimated that each cell will have an average discharge current of 50 to 60 amps during the endurance event. Estimates from battery manufacturer data show that at this discharge rate the difference between name plate capacity and actual available electrical energy should be less than 6%.

Having improved the efficiency of the battery pack, the team then turned to the motor/controller combination to look for efficiency improvements.

Two motor/controller combinations had successfully been implemented in the 2007 McGill electric snowmobiles in 2007. One 72V combination was used to win the SAE CSC 2007 and a different (48V) combination was used in the prototype that spent the summer at Summit station. Given the manufacturer data sheets both of these motors we almost equivalent performance wise: similar power, similar RPM/torque ratio and similar efficiency throughout the operating range. The 48V motor sent to Greenland was a little bit lighter and had a slightly more compact design. These two advantages initially made it the front runner to be the motor of choice for the 2008 prototype. However this changed when the team established its motor and controller database. As part of the establishment of this database, the motor/controller combinations were tested on a dynamometer and their efficiencies measured. The team found that for any given power output the 48V combination was approximately 7 to 8% less efficient that the 72V combination.

Further investigation showed that this was due to the fact that controller efficiency was primarily linked to its pulse width modulation (PWM) duty cycle; the higher the duty cycle the better. In order to properly operate within component limits, the 48V motor/controller combination was running at a 33% lower duty cycle than the 72V motor/controller combination. Thus, despite the smaller size and the lower weight of the 48V system, the difference in efficiency of the two motor/controller combinations made the team choose the 72V combination for use in the 2008 prototype.

Lastly, after having optimized the efficiency of the electrical side of the drivetrain, the team turned its focus towards ensuring that the mechanical side of the drivetrain was optimized for a cruising speed of 24 to 32 km/h.

Two key areas were targeted to achieve this: the calibration of the CVT and the track tension. Both aspects were part of an extensive on-snow test program to find the best possible setup in terms of efficiency. The on snow test program also looked at how the CVT calibration affected the vehicle's acceleration and how the track tension affected the vehicle's noise. Unfortunately the team quickly realized that it was not possible to get the best of both worlds simultaneously.

The best CVT setup for efficiency at cruising speed was far from giving the best acceleration and the most efficient track tension emitted a louder and more annoying sound that some other less efficient track tensions. The gains in efficiency from the top scenarios did not justify the drop in acceleration and the increase in noise.

Thus, on both fronts the team had to make some efficiency compromises. The CVT was setup to the most efficient setting which the team deemed gave adequate acceleration. The track tension was mostly optimized for noise with efficiency being a second level priority.

In the end, the team is very confident it will once again this year break the 16 km (10 mile) mark. While last year this accomplishment came as a surprised since the snow conditions were ideal and the speed was 25% lower than what the team had anticipated, this year the team thinks it will likely drive over 16 km (10 miles) regardless of the speed selected by competition organizers and the snow conditions at the event.

So far the snowmobile has been tested in various snow conditions and the results demonstrate that even in over 20 cm of fresh snow, the snowmobile's power draw never exceeds 11 kW to maintain a steady speed of 32km/h or below. As the path gets tracked out, the vehicle's power draw to maintain this speed goes down up to 30% after 4 passes in its tracks. These results are why the team is confident that the 2008 vehicle should be able to drive more than 16km at the SAE CSC.

The team wants to emphasize that it is very hard to determine the exact mileage the snowmobile can attain at the SAE CSC since both the speed and the snow conditions at the event are not know in advance. However, the results obtained so far are promising. The thick fresh snow previously discussed is a not an ideal scenario. In an ideal scenario, tests have shown that the power draw at the battery can go down 50 and even 60%. Results obtained on hard, previously rained on, snow indicate that depending on the speed at which the event is conducted and the snow conditions at the event venue, it is not impossible that the 2008 prototype could more than double its performance from 2007 and travel an unprecedented 36km.

5- HANDLE WELL

The 2007 the McGill electric snowmobile prototype was a huge leap forward in terms of handling characteristics compared to the 2006 prototype. The fact that the 2007 prototype won both the zero-emission subjective and objective handling events at the SAE CSC is one indication of this. The team believed that the prototype's good handling characteristics were mainly a combination of low weight, low center of gravity, good weight distribution and good suspension settings.

In 2007 the new front suspension setup was implemented at the same time as a repackaging of the snowmobile which lowered the center of gravity and improved weight distribution. Thus, the team wasn't exactly sure how much the new suspension actually contributed to the good handling characteristics compared to the combined improvements of CG height and weight distribution. The reasoning was that if almost all the improvement was due to CG height and weight distribution then perhaps the heavier and more expensive front suspension from the 2007 snowmobile could be removed and the original front suspension system could be used to lower the vehicle's MSRP and weight.

The team thus did some testing with both suspension setups. In the end, all riders were unanimous: the wider suspension with stabilizer bar from the 2007 prototype played a substantial role in the good handling characteristics of the vehicle. All agreed that the increase in cost and weight were well worth the difference in handling characteristics. Thus, the 2008 prototype is equipped with the wide stance suspension which can be found on the higher end Ski-Doo snowmobiles using the RF chassis (e.g. Freestyle Park, Freestyle Backcountry).

Looking to further improve the snowmobile's handling characteristics, the team focused on the rear suspension to make the 2008 prototype's handling even better than its predecessor.

The 2007 prototype was equipped with a 136 inch rear suspension system with no possible suspension adjustment settings. While longer tracks can be useful for floatation in deep snow, on groomed and hard pack conditions, which tend to be the norm both at Summit Station and at the SAE CSC, they are usually not at an advantage compared to shorter tracks.

The team witnessed a good example of this during the filming of an episode of Discovery Channel's Mean Machines in the fall of 2007. During the shoot, the McGill electric snowmobile stunned everyone in attendance (including its designers…): on a tight handling course up and down a hill, the McGill electric snowmobile equipped with the new 307m (121 inch) ZX2 rear suspension from AD Boivin and driven by a novice driver beat out a stock 97kW (130HP) Yamaha Venture snowmobile driven by a professional driver. All in attendance, including the Yamaha representatives were unanimous: the key to the electric snowmobile's victory was its 307m (121 inch) track length with the ZX2 suspension; the Yamaha was equipped with a 366m (144inch) track.

The combination of the 307m (121 inch) length and the adjustability of the ZX2 suspension (over 20 possible settings including 3 geometry setting changes) have proven to make a noticeable improvement to the already good handling characteristics of the McGill electric snowmobile. Its revolutionary all plastic composite design also make it lighter and less costly than the original stock OEM suspension.

MINIMIZE NOISE

In the past, too concentrated on ensuring that the snowmobile's performance and reliability was on par with its expectations, the team had neglected the fact that noise is a large component of the SAE CSC. In the zero emission category, 24% of the competition's points are directly related to the snowmobile's noise. Furthermore, the fact that 75% of those points are given on a scale relative to the best and worst performers, this omission almost cost the McGill team the overall title in 2007; and this, despite the fact that its prototype was extremely quiet, recording only 64db based on the SAE J192 standard.

For 2008 the prototype's noise received extra attention despite the team's limited resources to attack the problem. Equipped with nothing more than a sound meter and the team member's ears, McGill's first "semi-scientific" attempt at making the already quiet electric snowmobile even quieter was conducted.

The SAE J1161 standard will be used in the noise test for zero emission snowmobiles at SAE CSC 2008. Thus, the team tried as much as possible to follow J1161 sound testing procedures while conducting its tests.

While location and wind conditions were not optimal for testing, other parameters such as db scale, response speed, vehicle speed and location of the db meter relative to the vehicle's path were all as required by SAE J1161. The snow base was hard snow which had received some rain in the previous week and it was covered with 1cm of fresh snow.

A number of different snowmobile configurations were tested both objectively (db meter) and subjectively (team member ears) to determine which had the best sound characteristics. Objective sound results were measured in db and subjective results were measured on a relative scale of 1 to 10 with 1 being the most annoying sound according to the team members' judgment. In order to try and eliminate relative bias towards one configuration or another which could be caused by the gusty wind on that day or the uneven traffic on a near by highway, each configuration was tested until results could be repeated to the satisfaction of all team members in attendance.

First the team set out to define the extremes of the test: the best and worst noise performance configurations. The best noise performance was obtained by inserting sound insulation everywhere possible under the hood, closing all hood openings and then wrapping the outside of the snowmobile with egg crate shaped 3 inch thick polyurethane foam all the way down to the ground.

Figure 12: The 2008 prototype wrapped in sound absorbing foam

In this configuration the snowmobile recorded 58db and was given the highest possible mark of 10 on the subjective scale.

The worst configuration which received the mark of 1 on the subjective scale and measured 64db on the sound meter was the configuration of the electric snowmobile for the 2007 SAE CSC: no sound insulation inside or outside of the vehicle and a very loose track tension.

Having established the references for the relative scale, the team tried to pin point what was the contribution breakdown to the overall results.

Four track tensions were tested:

1- Too tight
2- To manufacturer specifications
3- Slightly looser than manufacturer specifications
4- As loose a possible

Tension	Objective result (db)	Subjective result (1 – 10)	Comment
1	62.2	6	Main noise seemed to come from rear suspension vibration.
2	60.8	7	There wasn't one sound in particular which was overtaking the others. Just a relatively constant "humming" sound.
3	62.0	3	Some metallic rattle sound; not very pleasant.
4	63.7	1	Very distinctive metallic rattling sound which was observed to come from the tack guide clips hitting the rails from flapping of the loose track at the front between the drive sprockets and the rails

Table 7: Track tension sound test results

The results from this test indicate that the ultra loose track tension the team used in the past (Tension 4 in Table 7) to help with the vehicle's drive efficiency apparently played a major role in the noise generated by the snowmobile.

After having tested the effect of track tension on noise, the team tested the effect of sound absorbing foam on noise.

The tests showed that having a sound absorbing barrier along the rear suspension would in general reduce the sound by approximately 2 db. Also, this sound absorbing skirt could increase the subjective sound score by as much as 5 points for loose track configurations. Tighter track configurations saw a significant but less drastic improvement of 2 or 3 subjective points.

The sound absorption foam wrapped on the outside of the snowmobile's hood had little to no impact on sound when the inside of the hood was packed with sound insulation foam.

The sound insulation foam inside the hood on its own improved the db score by approximately 1 to 1.5 db. On the subjective scale sound improvements ranged from 0.5 points to 1.5 points depending on the configuration of the rest of the vehicle.

As a result of all these tests and given the fact that sound is a major component of the overall SAE CSC scoring scheme, the team decided to tighten its track tension to the manufacturer's specification (tension 2 in Table 7), install sound absorbing foam throughout the interior compartment of the snowmobile and install a sound barrier skirt along the snowmobile's track.

These changes directly affect the vehicle's weight, efficiency and MSRP; however, given the very high value of the noise event, these changes are believed to far outweigh their negative side effects.

START COLD

Being able to get the electric snowmobile started after cold soaking overnight mostly has to do with the vehicle's battery pack. Since the lithium cells are the same as the cells used in Greenland and team knew from data gathered at Summit Station that the snowmobile consistently started in the morning even if the cell's internal temperature was well below freezing very little was done to improve this function. Simply the team ensured that any new component installed on the snowmobile would be able to handle the cold temperatures of an outdoor stay overnight.

BE LOW COST

Again in 2008 the McGill Electric snowmobile team expects to have one of the most costly snowmobiles of the competition with an MSRP above 25 000$.

Why is this?

The most important thing to notice is the cost breakdown of the vehicle. The chassis itself represents approximately 10% of the total value, the motor less than

4% and the controller approximately 2%. The battery pack alone makes up almost 80% of the vehicle's value. Almost all of the value of the vehicle comes from the battery pack.

Again, one may ask: why is this?

This is the result of the SAE CSC's new scoring scheme for 2008 which highly rewards designs which can go very far (unlimited mileage in the endurance event) combined with the fact that there is no limiting factor, other than a high MSRP (which is not worth as many points), to what can make up a team's battery pack. Based on the team's analysis of the situation, the best solution to meet the needs of the competition was to have the best possible battery pack no matter what the cost was.

One may then ask: did you just ignore the cost of your vehicle in favor of other factors?

No. The team is well aware that all other competitors may come to the conclusion that the best possible battery pack, no matter what the cost, is the best solution. That is why all the other components on the vehicle have been chosen with cost in mind. The result: McGill's 2008 electric snowmobile is based on the lowest cost snowmobile chassis on the market and its motor/controller combination is once again this year expected to be one, if not “the”, least expensive of the competition.

In simple terms McGill's electric snowmobile is a very low cost base vehicle which can then be customized to a customer's performance needs and its budget.

In this case, the SAE CSC was taken as the customer. When analyzed as a potential customer, the SAE CSC comes out as a customer who puts very high value on a large number of performance criteria and very little value on what it will cost money wise to have all this performance in a vehicle. As a result of this analysis, it should be no surprise that the McGill team's very low cost electric snowmobile design saw its price shoot up when time came to add the battery pack: this is what the client's requirement list asked for.

CONCLUSION

The McGill Electric Snowmobile Team, using its experience from previous years and some newly acquired knowledge believes it has managed to make a viable electric snowmobile despite the challenges this entails.

So far results have shown that the use of value engineering methodology was a good choice since the snowmobile has shown improvements in a number of performance areas with the biggest improvements being related to the SAE CSC events which can earn the team the most points.

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