Optimization of an Electric Snowmobile for CSC 2014

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ABSTRACT

McGill University's 2014 Wendigo prototype returns to the Clean Snowmobile Challenge (CSC) with a 2011 Ski-Doo MXZ chassis, new sound reduction measures, an improved towing structure, more available power and an updated accumulator to increase the snowmobile's range. Changes this year were made based on analysis, testing, and feedback from Summit Station, Greenland. The team hopes the changes made this year will help the team win the CSC and will provide researchers at Summit Station with a higher value snowmobile.

INTRODUCTION

The Clean Snowmobile competition challenges students to design and build clean snowmobiles for the real market. McGill University participates in the zero-emissions category of the event. The main goal of this category is to design a snowmobile specifically tailored for researchers in zero-emission research zones such as Summit Station in Greenland. The main sled characteristics sought are sufficient range, high towing capacity, affordability, reliability, safety and as little maintenance as possible. In addition, the competition rewards powerful and quiet sleds.

REVIEW OF 2013 RESULTS

McGill's 2013 snowmobile, built on a 2011 Ski-Doo MXZ chassis, competed reliably in all events. The team was satisfied by its performance and confident it would suit the needs of a researcher in Greenland. In 2014, the team wishes to improve its design maintain a high level of competition performance. To understand where to emphasize the design, a CSC 2013 point analysis was conducted. The following table illustrates McGill's performance in the dynamic events.

Event	McGill Score	Max Score	Improvement Potential (delta)
Range	100	100	0
Draw Bar Pull	5	100	95
Noise	150	150	0
Loaded Acceleration	50	50	0
Weight	0	100	100
Handling	43.1	150	106.9
MSRP	38.5	50	11.5

Table 1 - CSC ZE McGill Results Analysis

GOALS AND OBJECTIVES

The McGill Electric Snowmobile Team's (MEST) fundamental design goal is to produce a reliable and affordable electric snowmobile. More specifically, this entails designing an electric powertrain that easily fits inside a stock chassis with as few modifications as possible, uses reliable, maintenance-free and low cost components while maintaining high safety standards.

By reviewing competition scoring scheme and team's performance in the past competitions, the key areas of improvement and team design goals are:

1. Increased towing capacity
2. Dynamic performance improvement, particularly handling and power to weight ratio
3. Noise
4. MSRP

CHASSIS SELECTION

The chassis selection is perhaps the most important factor in the dynamic performance of the snowmobile. The selection process for our base chassis was done by comparing two general types of snowmobiles, a utility snowmobile with a long track, and a more sporting snowmobile with a short track. In doing the comparison the team drew heavily from the prior experience of the team. In the 2012 clean snowmobile challenge, the team based our snowmobile on a utility sled, in 2013, the team used a sporting chassis.

Goal (Weight)	Utility & long track	Sports & short track
Noise (2)	-	+
Drag (2)	-	+
Handling (3)	-	+
Power/weight (1)	-	+
Towing capacity (4)	+	-
Total	-4	4

Table 2 - Comparison of snowmobile types. + indicates advantage.

From our analysis, we see that the short track sports snowmobile is better for our needs. This is validated by our competition results from the last two years. In 2012, the team placed 2nd, but in 2013 with a sports chassis, the team placed 1st and sent the snowmobile to Summit Station, Greenland. There, users appreciated the high performance of a sports sled.

Based on this comparison and the team's goals and objectives, the team decided to convert the powertrain of a light weight, performance oriented and short track snowmobile. Regarding the towing capacity, the design of an improved hitch should out more

For CSC 2013, the team chose again a 2011 Ski-Doo MXZ chassis.

Figure 1 – 2011 BRP MXZ[1]

This chassis meets all of the team's requirements. Some of the main advantages of this chassis are:

- A low cost chassis
- Short track (less noise and drag)
- Large ski stance for higher stability
- Light weight for manoeuvrability and dynamic performance
- Cargo space on the tunnel

Power Train Selection

The 2014 electric powertrain was designed to offer a highly responsive, efficient and reliable package at a minimum cost.

The snowmobile is driven by a 3-phase HPEV AC-15 motor with a peak power output of 34 kW coupled to a Curtis Instruments 1238 motor controller. Developing a peek torque of 81Nm across a wide rpm range and having a top speed of 7500 rpm, the motor package offers improved characteristics over the stock Rotax 600 Ace engine that only offers a peak torque of 55Nm and a maximum speed of 7250 rpm[**].

The AC induction motor was selected for its lower cost and higher reliability when compared to alternative brushless and brushed permanent magnet technologies [**]. Furthermore, the higher operating temperatures allowed by AC induction motors enables the use of a simple air cooled powertrain design. The highly efficient Curtis 1238 controller can easily be tuned for maximum performance in different driving conditions.

An automated dynamometer testing system was developed to accelerate characterization and tuning of the tractive system. Figures 1 and 2 show the obtained powertrain efficiency, torque and power data. Motor control parameters were adjusted to increase peak motor torque and efficiency. Powertrain efficiency and torque test data were used to determine the gear ratio that maximized overall dynamic performance and efficiency.

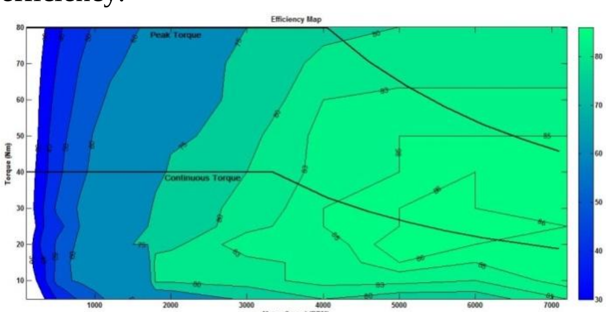

Figure 1 –Powertrain efficiency map

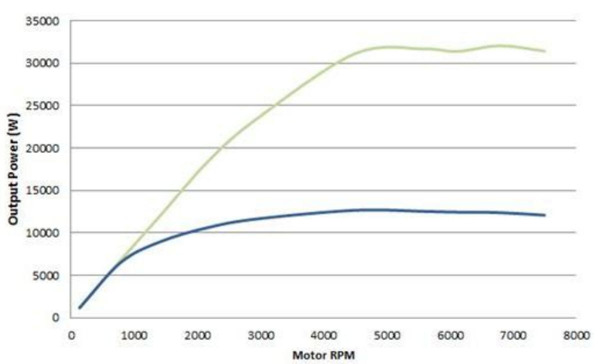

Figure 2 – Motor power curves

RANGE

The first design aspect that affects the range of any electric vehicle is the battery technology used. The main characteristic that needs to be looked at is the Gravimetric Energy Density (GED), or more simply, the energy per mass. Typically, a desired energy storage technology has to have a high GED in order to make it a worthwhile energy source. Table 3 compares the Gravimetric energy density and some other characteristics of the three main available vehicle battery technologies.

	Pb-Acid	NiMH	Li-ion
Energy Density (Gravimetic)(Wh/kg)	60	125	240
Energy Density (Volumetric)(Wh/L)	100	400	550
Electrochemical potential difference (Volts)	1.5	1.2	3.6

Table 3 – Battery chemistry comparison [2]

Clearly, Lithium-ion is an ideal choice for better range. However, even though a battery with high GED, like Lithium-ion, would improve the range, it should be compared to other battery technologies in terms of overall snowmobile characteristics including handling, agility, unchanged stock chassis and ease of conversion from a gas to electric powertrain[6].

A set of 20 LTC lithium ion cells were used to manufacture the battery pack for Wendigo 2014 Snowmobile. This choice was made partially for reliability purposes which will be discussed in the future sections and partially for their performance with regards to the snowmobile's range. PSAT (Powertrain Simulation Analysis Toolkit) Simulations have shown that the snowmobile can easily guarantee the 10 miles range that is required. Furthermore, this pack was utilized in the CSC 2012 and 2013 offering a smooth transition to the present snowmobile. The endurance run of the 2012 has shown that the snowmobile can reach the endurance estimates, as the much heavier 2011 BRP Tundra LT (In reference to our current 2011 BRP MXZ) used in this competition was able to attain 9.84 miles. In 2013, the same pack was used but unfortunately the team did not have a chance to properly optimize the system. Even so, the snowmobile managed to travel 8.1 miles. As it can be seen, these cells are ideal for this project and they have proved themselves countless times in the past. This year the overall system is lighter and is optimized for maximum efficiency which will, pending snow conditions, allow us to reach the 10+ miles requirement.

The new feature that has been added to this year's design is a Mode Switch. There are three different system configurations which can be achieved by this switch. The mode designated for range, is designed to achieve maximum efficiency.

Looking at Figure 1, it is obvious that the controller and the motor system are most efficient at higher speeds. However, extensive PSAT simulations have shown that the condition of the snow and the friction that it applies to the snowmobile is much higher at higher speeds. This reduces the final range drastically, despite the improvement in motor system efficiency. These simulations were done for a 3.2 kWh battery pack. Figure 3, shows that the snow condition will reduce the efficiency at high RPMs. Therefore, 3000 RPMs was chosen as the value which optimized the relationship between motor system efficiency and the friction forces. The mode switch will ensure the system will operate in this region.

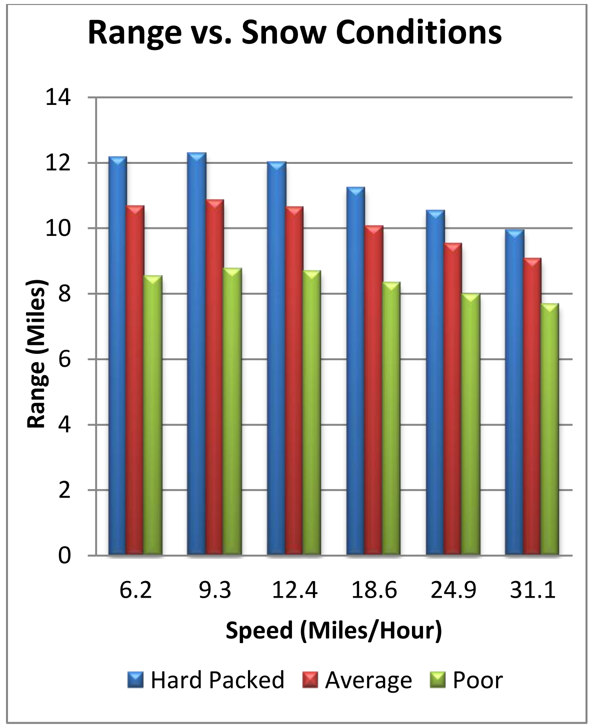

Figure 3: Effect of speed on range in different snow conditions

Another parameter that was looked at was the gear ratio. A high gear ratio is desired, as that would allow the motor to operate at high RPMs and the track to operate at low RPMs. The Wendigo design couples the motor shaft directly into the chaincase. Due to the spatial limitation of the chaincase the highest ratio that can be achieved is 3:1. To achieve higher ratios, a secondary gear reduction is required. However, a secondary ratio would reduce the overall drive train efficiency (belt drive is around 95% efficient) as well as limit space in the engine bay for batteries. Therefore, the 3:1 ratio was selected which will guarantee the optimal rpm of 3000 described previously.

Furthermore, the effect of different current maps on efficiency was investigated. As it can be seen from Figure 4 this parameter does not have substantial effects on efficiency and therefore, it was optimized for handling and acceleration which will be discussed later in this report.

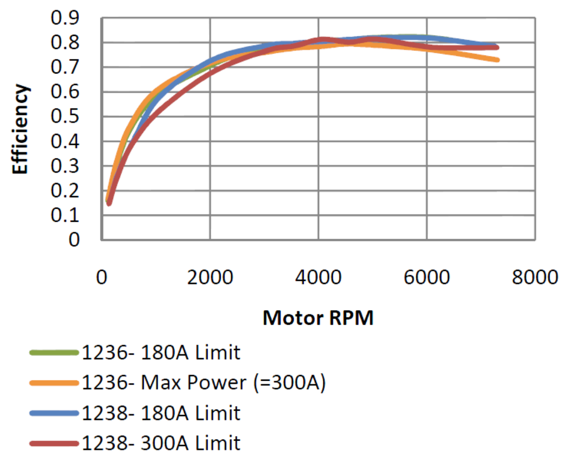

Figure 4: Effect of RPM on Efficiency

DRAW BAR PULL

The performance of the sled in the draw bar pull event depends on the amount of force it can transmit to the ground within the traction limit. This implies that the higher the motor output torque, the better the sled can perform as long as traction is available. The slip-gain optimized 1238 controller at 300A limit delivers maximum torque which makes it the best choice for draw bar pull and loaded acceleration events.

The Curtis Instruments motor controllers are highly customizable. For the different current limits tested, the controllers were fine-tuned by adjusting system parameters such as slip-gain to maximize low torque. Maximizing low-end torque is a logical choice for an electric snowmobile because of the gains possible in the CSC scoring scheme and for towing heavy equipment on the Greenland Ice Cap. Figure 5 shows how much the torque curve varies with the slip-gain parameter for the 1238 controller. For both current limit maps peak low-end torque gain of approximately 15% was achieved over a range of range 2000 rpm.

For this year's competition, particular attention was also put on improving the towing

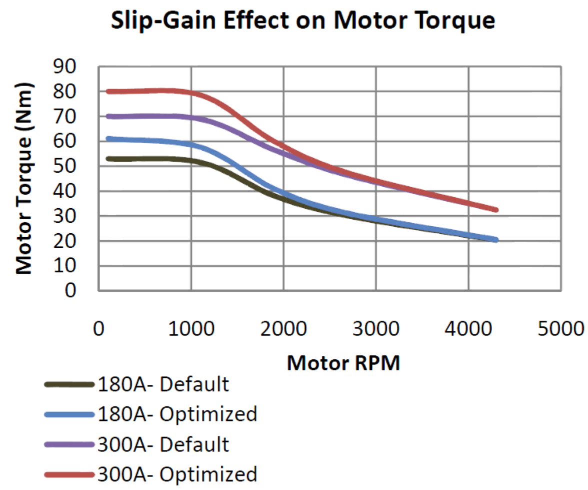

Figure 5: – Motor torque versus RPM

capabilities of our sled, considering the fact that the snowmobile towing capacity is often limited by traction rather than motor torque. By comparing the track specifications of our 2011 sled (BRP Tundra 2006) to this year's snowmobile (BRP MXZ 2011), one can tell that the LT has superior traction capabilities due to its larger, longer and more profiled track (154x16x1.5" versus 136x15x0.75"). More specifically, an analysis of previous year's results for the draw bar pull event allowed the team to correlate the ratio of the pulling force to the applied weight, shown in Table 4.

	Year	McGill University				
		Total Mass	Rear Mass	Pull Force	Total Mass + 75kg Force ratio	Rear + 60 kg Force ratio
		Kg	Kg	N	N/Kg	N/Kg
1	2007	227	91	1660	5	11
2	2008	263	158	1867	6	9
3	2009	226	100	1759	6	11
4	2010	233	110	2870	9	17
5	2011	233	109	2113	7	12
	AVG	**236**	**114**	**2054**	**7**	**12**

Table 4 – Pull force to weight analysis based on previous year's results.

These results are based on the assumption that the driver's weight front-rear distribution is 20-80%. Moreover, one should note that in 2010, the draw bar pull was done on grass, explaining the higher forces. Interestingly, the team found out that for each kilogram of weight added on the rear suspension, the pulling force was increased by 12 N. Therefore, in order to significantly increase the sled's towing capabilities, the team had to engineer a system that would maximise weight at the rear of the snowmobile.

There are two important components in determining the friction force and thus the traction capability of our snowmobile: the friction coefficient μ, and the normal force. When considering the friction coefficient, one can either attempt to change the ground conditions, or snow, or the track can be changed. Since we have no control over snow or ground conditions at the competition, the latter is the obvious choice. This corresponds with our results from Table 4.

A simple first choice would be to increase the weight of our snowmobile. However, weight is also an important category in this competition as well as having adverse effects on acceleration and handling. In addition to this, the weight would need to be located atop the track, so as to maximize the normal force on the track and not other portions of the snowmobile. Unfortunately, our spatial layout of the snowmobile tends to put the majority of our components in the engine bay, thus limiting the benefit of additional weight.

With both weight and improving the friction coefficient off the table, it seemed as though little could be done to improve the draw bar pull without adversely affecting other portions of the snowmobile. However, another important force exists in the Free Body Diagram of the snowmobile in draw bar pull as shown in Figure 6.

The force transmitted from the buggy that is used to measure the effectiveness of our draw bar pull has a slight downward component that increases the normal force on the track of the snowmobile. If the angle at which this force is transmitted, the normal force could be increased. To do so, an elevated hitch mounting point was proposed. By raising the point to which the force was transmitted, the normal force would hypothetically increase. However, before tackling this issue, data from previous competitions was analyzed as shown in Table 5.

	Year	Pull Force
		N
1	2007	1660
2	2008	1867
3	2009	1759
4	2010	2870
5	2011	2113
	AVG	2054

Table 5: McGill University Drawbar Pull Results

Based on the assumption that the pulling force is measured along the axis of the rope, it was found that the average pulling force was 2054 N, and knowing the rope angle of both last year and this year designs, one could conduct a force analysis, shown in Figure 4. Note that the X-component remains the same in both designs; however, the Y-component, the pulling force, P and the angles change.

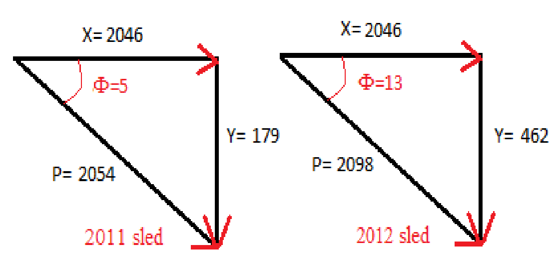

Figure 6: Free Body Diagram

Analysis of Figure 6 shows the pulling force increase, P= 44 N, and Y=283 N. Moreover, based on our previous analysis, it was shown that the ratio of pulling force to weight is 12N/kg. Therefore, one must factor the increase in Y-component to accurately measure the new pulling force, P. From our calculations, Y= 283 N = 29 kg, and thus the increase in pulling force from the additional vertical weight equals to:

12 N/kg * 29 kg = **348 N**

With this in mind, it is clear that in increase in the height of the mounting point increases the attainable pulling force. However, extensive effort was put in to determining the *optimal* height above the snowmobile the new mounting point would be located

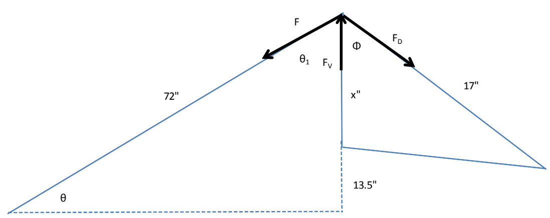

Figure 7: Hitch Free Body Diagram

In the above diagram, the left most point represents the connection with the buggy. The topmost point represents are hitch mounting point and the right most point represents a connection of the hitch to our chassis. The 72" between the mounting point and the buggy is an estimation of the length of the rope connecting the two vehicles, while the 13.5" represents the height of the standard mounting point of our snowmobile when under a force.

Pulling Force (lb)	775
μ	0.7
$W_{snowmobile}$ (lb)	500
W_{PERSON} (lb)	180
Φ deg	29
x"	**21.25**

Table 6: Hitch Parameters

By selecting a target pulling force, including a typical friction coefficient of rubber on snow, considering the weight of the snowmobile and snowmobile operator as well as Φ (shown in Table 6), which is a design limitation of our chassis, we were able to calculate an optimal height of 21.25". The target pulling force was chosen as a substantial increase to last year's pulling force of 569 lbs, while considering our maximum pulling force (Torque Limited) to be 800 lbs. To simplify manufacturing of our hitch, the final height selected is 20".

Figure 8: Hitch Design

The eventual design of the hitch is shown in Figure 8. Special consideration was given to supporting the mounting point in case of a lateral force. Although large lateral forces are not expected due to the buggy being straight behind the snowmobile, failure of the hitch was considered unacceptable. As such, multiple diagonal supports feed into the mounting point.

NOISE ATTENUATION

Noise produced by snowmobiles is a major issue in rural areas where snowmobiles are driven. The noise emitted is disruptive to both wildlife and people who inhabit the area surrounding snowmobile trails. Since exhaust noise is the primary noise source of a conventional snowmobile, electric snowmobiles generate far less noise then their internal combustion counterparts. For a snowmobile, any decrease in noise is beneficial for the environment, people who live close to trails and the snowmobile user. It can also advance safety; one issue for alpine search and rescue teams is the danger of causing a secondary avalanche. A low noise snowmobile would reduce the likelihood of inducing an avalanche, and would therefore be ideal for this application.

Based on our experience in Greenland, the noise from a gas snowmobile makes it difficult to communicate by radio. For working in remote areas, and doing research, this makes travel difficult, sometimes even dangerous. For this reason a quiet snowmobile is very important to the researches and managers at the base.

Past attempts have been made to reduce the noise of the snowmobile, including adding padding to parts of the chassis to reduce vibrations. It is difficult to pinpoint exactly where noise from an electric snowmobile is developing from, but the leading hypothesis is that it is coming from the interactions between the track and track wheels, and between the track and the snow. To reduce this noise, an enclosing skirt has been built to surround the track of the snowmobile and to reduce and isolate noise emissions.

A padded skirt is mounted beneath the foot rails, and is mounted using Velcro to ensure adjustability and easy removal. There are clevis and cotter pins to further secure it. The padded skirt is composed of three layers – two fabric layers and inner stuffing. The inner fabric layer (facing the track) absorbs noise from the track, the stuffing further absorbs and reduces that noise, and any remaining noise is reflected by the outer fabric layer back through the stuffing and inner fabric layer towards the track. In this way, the skirt dissipates sound energy from the track first and contains most of what cannot be eliminated by reflecting it back towards the track.

The inner stuffing is wood flour, which testing proved to be more effective than fiberglass insulation, cotton, chalk, various foams, and a variety of other materials at eliminating noise, particularly in irritating higher frequencies. This was found using a standard testing procedure which involved placing a wall stuffed with the various materials between a sound meter and speakers playing snowmobile noise at a standard volume. Details of the test will not be explained in detail here. The reasons for the effectiveness of the wood flour is that it is very sound absorptive, and because it has a small particle size, these can be easily set in motion by noise, which allows them to effectively convert sound energy into kinetic and thermal energy through movement and friction.

Figure 9: Sound testing rig in use, with Brüel and Kjær 2270 Sound Level Meter

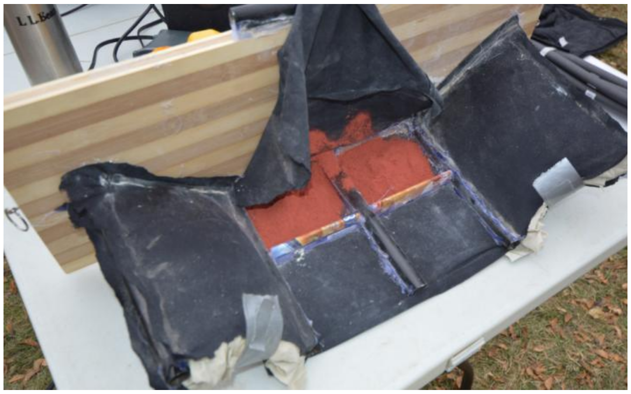

Figure 10: Sound testing rig on its side, pockets open. Lower pockets partially filled with red chalk dust.)

The inner sound absorptive layer is made from Gore-Tex, which is commonly used for water repellent outerwear. It has the uncommon property of being both sound absorptive and impermeable, and is used by noise-control companies such as Echo Barrier for these properties. These properties are needed to transmit track noise to the sawdust without letting any water in. Gore-Tex is also very light, extremely durable and tear-resistant, and suitable for low temperatures.

The outer fabric layer is all-weather vinyl fabric, which is intended for snowmobile use. It is also waterproof and durable, but is more sound-reflective than absorptive, allowing it to contain any noise not dissipated by the Gore-Tex and sawdust.

The layers are sewed together, and the seams are sealed with tent sealant to keep out moisture.

The skirt geometry is designed to provide maximum coverage with minimum interference. It is important that the skirt make contact with the snow, as noise elimination is reduced exponentially as gaps grow. However, it is held out from the track so that it does not get caught. It attached to a mounting mechanism composed of a series of L-brackets attached to the snowmobile foot rests.

It should be noted that this skirt is a prototype, and it is expected that observations from its use in competition will lead to challenges to assumptions made during its design, and future refinements.

Driver Comfort / Control

Externally, Wendigo 2014 is unmodified from the stock MXZ chassis. In terms of comfort, the large windshield and heavily padded seat are retained. Fitting the battery pack in the engine bay of the chassis, as opposed to under the seat means that there is space for a comfortable seat. As well, having the weight over the skis makes the sled more manoeuvrable and easier to drive. The stock configuration carries through to the driver interface. The BRP dashboard has been re-engineered to monitor signals from the motor controller and battery management system. The dashboard displays speed, battery state of charge, and has warning lights for over-temperature situations or low cell voltage. By keeping the same display, it is easy for any snowmobile user to drive Wendigo 2014. Finally, the driver controls are kept as similar as possible to the original sled. The reverse switch, throttle and cranking sequence are the same. One additional switch has been added to control the power modes of the snowmobile. The mode switch allows three modes: a high power acceleration/towing mode, medium power manoeuvrability/normal driving mode, and lower power high efficiency mode for increased range. These three modes give more driver control, and also let a new driver run the snowmobile at a very safe low power setting. Overall, the design goal for the driver interface was for there to be no discernable difference between a stock gas snowmobile and the electric snowmobile, until it is turned on.

Safety

Safety is a priority in Wendigo 2014. The main safety area on the snowmobile concerns battery management and separating the powertrain from the driver. The battery pack is controlled by a BMS (battery management system). The BMS monitors individual cell temperature and voltage to make sure every cell operates in a safe condition. As well, the BMS communicates with the motor controller and safety shutdown circuit in the snowmobile to make sure that the battery pack cannot be turned on unless the system is operating as it should. Physically the battery pack is protected by electrical grade fibreglass panels, and an aluminum firewall. The firewall sits between the driver and the battery pack. To protect the driver from drivetrain failure there is a second shield over the connection between the motor and chaincase.

CONCLUSION

The fundamental design goal of the McGill Electric Snowmobile Team was to produce a reliable and affordable electric snowmobile. Emphasis was placed on a design which is easily converted from a gasoline machine. More specifically, the objectives were to enhance the towing capacity of the sled, to reduce noise at the source, to increase the power output and to increase range. Based on this year's design and analysis, the team expects to increase its towing capacity, reduce noise, and have an improved range.

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