Energizing the Future: Rear Driven E-Rush

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ABSTRACT

The Michigan Technological University Clean Snowmobile Team is entering the 2012 Society of Automotive Engineers Clean Snowmobile Challenge with a redesigned 2010 Polaris Rush. The snowmobile has been redesigned to operate as an electric, zero emissions vehicle, using a Thunderstruck AC-20 induction motor, Curtis motor controller, Thundersky 40AH batteries, and an MTU designed rear drive system. The snowmobile has been designed for maximizing the range of fifteen or more miles while maintaining stock snowmobile performance and appearance.

INTRODUCTION

Global climate change and the effects of chemical emissions on the environment have attracted a great deal of attention in the last ten years. The effects of emissions on the environment are being closely monitored at Summit Station on the Greenland Ice Cap. The terrain at the Greenland Ice Cap however is very sensitive as it quickly absorbs atmospheric chemicals which are produced naturally or chemicals which are produced as a result of human activity. Because of the sensitive nature of the measurements being taken, a zero emissions vehicle is the only suitable replacement for travel on foot. Emissions output from conventional snowmobiles with two or four-stroke engines are enough to introduce detrimental noise to the measurements being taken at the Greenland Ice Caps.

In 2004 the Clean Snowmobile Challenge (CSC) added an additional event being a Zero Emissions (ZE) category. This refers to building a snowmobile with an electric motor and a power source of batteries to propel it. Recent advances in battery and motor technology have made a useable zero emissions snowmobile a more feasible task. This non-pollutant emitting source of transportation can make collecting data in more distant locations possible on the ice caps. This utilitarian use of the zero emissions snowmobile was reflected in the design goals for Michigan Tech (MTU) ZE entry. The goals of the Michigan Tech ZE Team can be observed in Table 1.

Table 1: MTU Goals for 2012 CSC

Category	2011 Clean Snowmobile Competition Best	MTU 2011 Achieved	MTU ZE Team Goals
Range	20.82 Miles	DNF	>15 Miles
Acceleration	11.94s	21.50s	<17s
Drawbar Pull	841 lbf	DNF	>750 lbf
Weight	479 lbs	742 lbs	<650 lbs
Noise	57 dB	59dB	<59 dB
MSRP	$11,889.40	$21,686.81	<$19,000

DESIGN STRATAGY

The Clean Snowmobile Zero Emissions Competition determined its scoring criterion in parallel with the Nation Science Foundation's design goals. 2012 begins the second year for MTU's CSC team building a zero emissions vehicle; certain aspects were concentrated on to ensure an effective re-design. These important aspects were; range, towing capacity and building an innovative snowmobile. Areas that were also taken into consideration were weight, handling, acceleration, cost, and durability.

Table 2: Zero Emissions Points

<u>Zero Emissions Events</u>	Points for Passing Event	Maximum Additional Points Awarded for Relative Performance
Engineering Design Paper	N/A	100
MSRP	N/A	50
Oral Presentation	N/A	100
Weight	N/A	100
Range	N/A	100
Draw Bar Pull	N/A	100
Acceleration + Load	N/A	50
Objective Handling And Drivability	N/A	50
Subjective Handling	N/A	50
Cold Start	50	N/A
Static Display	50	N/A
Objective Noise	N/A	75
Subjective Noise	N/A	75
No-Maintenance Bonus	N/A	100
Subtotals	100	950
Maximum Total Points	1050	

SPEED CONTROL

To control the motor, a Curtis 1238-7501 motor controller was used (shown in Figure 1). This controller is responsible for several vehicle functions. The Curtis 1238, an AC induction controller, has many programmable features for adequate control over all ranges of speed and torque. Curtis has integrated the Direct Current (DC) to Alternating Current (AC) inversion process within the system controls, which is another reason this system was chosen. To display the system parameters a Curtis Spyglass 840 was used; this display was programmed to show the accumulator voltage, current, percent of charge left, vehicle speed, motor temp, and RPM's. Through this controller, the MTU ZE team was able to define many system parameters to tune the controller for maximum efficiency and power for the snowmobile application.

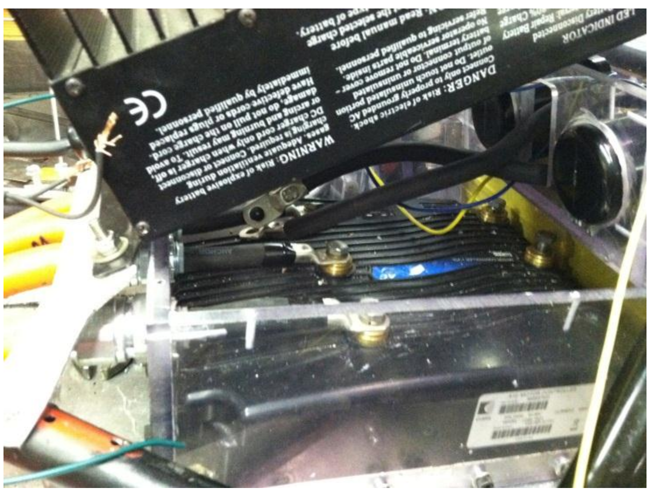

Figure 1: Picture of AC 20 Motor and Curtis 1238 Controller Mounted on Snowmobile

ELECTRICAL DESIGN

When designing the E-Rush, emphasis was placed on the location of components for serviceability, weight distribution, and minimizing the possibility of overheating. The controller was mounted on the tunnel for its desirable cooling properties and because it would be easy to access if troubleshooting becomes necessary. The charging unit was mounted just above the controller in order to make the E-Rush an all-in-one system, therefore the snowmobile could be charged at any location wherever 120V AC was supplied. By mounting the motor in the rear of the sled, more packaging room was made available in the front, also increasing the electrical system's serviceability. Having the motor in the rear also makes any potential replacement or maintenance of the motor more convenient. A separate 12 volt DC system was implemented for the use of the head light and tail light; using a separate 12 volt system was done by implementing a 96 volt DC to 12 volt DC converter.

BATTERY CONTAINMENT

Michigan Tech's E-Rush contains adequate space within the typical engine compartment to house the batteries. The basis for the battery containment was to package the batteries in a single container while maintaining a center of gravity similar to the original engine. To achieve this, the team designed a complex container to house the 48 batteries and some associated controls. The resulting design provides a container which tightly packages the batteries and fits securely within the bulkhead. The box container was constructed of 3/8" polycarbonate material making it structurally sound and water resistant. The container was modeled within UGNX 7.5 to determine its structural rigidity. Boundary conditions, material properties, loads, and finite element mesh were applied to the design. The analysis was run with applied loads in various axes to determine if the box construction met competition standards. In Figure 2, the for/after direction Von Mises stress analysis can be seen on the final design of the container. Table 3 summarizes the loads and stresses on the battery container in all directions.

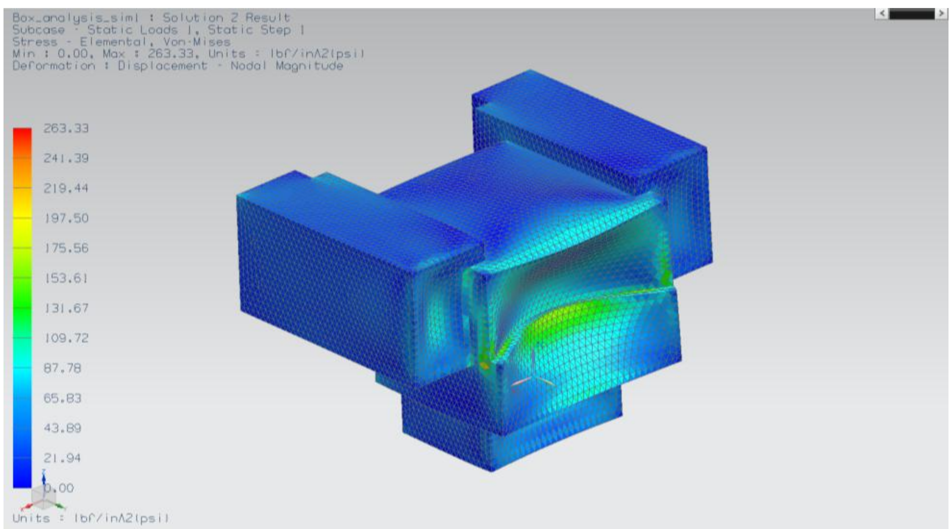

Figure 2: Final Stress Analysis Results of Battery Container

Table 3: Maximum Stress and Deflection of Battery Container Design

Axis	Load (g's)	Force (lbs)	Max. Stress (psi)	Max. Deflection (in.)
For/After	20	704.0	263.3	0.0074
Side/Side	8.0	281.6	210.1	0.0033
Up/Down	8.0	281.6	142.0	0.0093
Yield Strength of Polycarbonate (psi)			13,500	
Battery Container Weight (lbs)			35.2	

The container, which fits firmly within the bulkhead, was also fitted with supportive cages and bracketing. All brackets were constructed of 6061 aluminum angle. The brackets were designed to assist with firmly securing the container within the bulkhead by directly bolting to the chassis at existing motor mount locations. The cages not only provide structural security but will also prevent container deformation in the event of a roll over. Other aluminum brackets were also implemented to assist with rigidly housing the container.

BATTERY MANAGEMENT

To manage the LiFePO4 batteries, a battery management system was selected. This system was designed to detect if a battery cell's voltage was too low or damaged. A photo of the battery management system can be seen in Figure 4 below. The reasoning for the smaller parallel packs is so that the greatest difference in electric potential is 4.0 nominal volts rather than the 96 volts of an entire pack; if one of the potentials is different in a parallel system the system will self-level so that all of the elements are matched. This is why a battery management system is important, it monitors, for any battery in the pack; over-voltage, under-voltage, over-current, over-temperature, and under-temperature. The system that was purchased also detects an open or shorted cell so that cell failures can be detected. The current state of the BMS has some fault codes so it can easily be determined what is wrong with the system. Another reason the team is choosing the current configuration is because the monitoring scheme is half, with the two in parallel the two cells can share an input to the BMS (battery management system.

The BMS purchased for the competition vehicle is an Orion BMS. A schematic of how the battery management system is wired can be seen in Figure 3. The Orion system requires that the pack be divided into three separate groups. The modulated groups are all controlled to be match so that all of the cells have an equal voltage. The battery management system uses current and voltage probes as well as thermistors to detect any unsafe condition set by the software program of the device. Having the BMS installed allows the team to run the system and keep system levels in normal operating conditions, thus avoiding component failure.

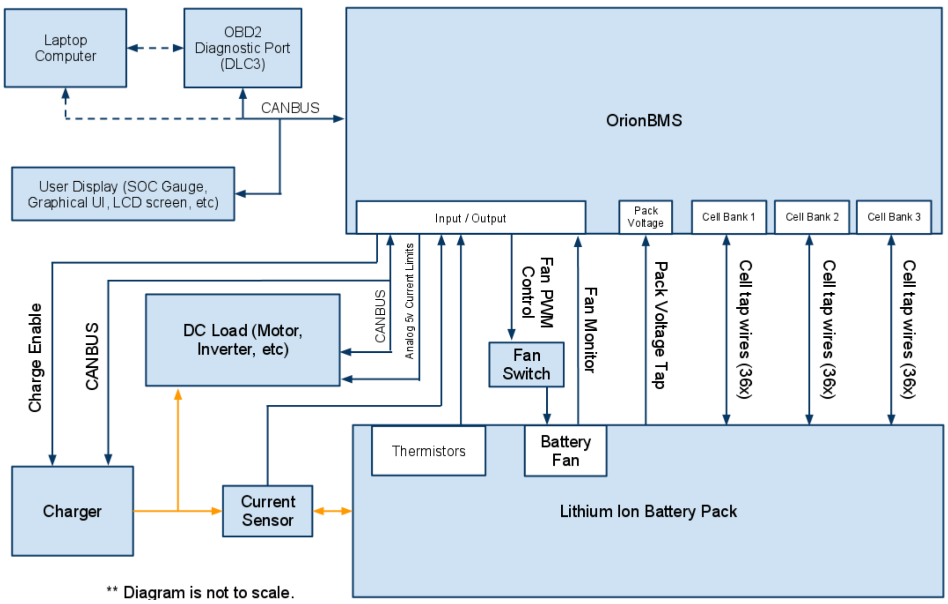

Figure 3: BMS Schematic

SYSTEM CHARGING

To charge both of the systems of the Michigan Tech Zero Emissions sled, two different chargers are needed to accommodate for the different battery types. To charge the LiFePO4 batteries a 1500W high frequency/power factor control (HF/PFC) ElCon battery charger was chosen. This specific charger was chosen because it had the ability to change the charging cycle depending on the type of battery. The charger also has a sensor for temperature and voltage as a safety control. Charging the E-Rush is a simple process. The charger is mounted under the hood of the snowmobile and recharging the batteries is as simple as running an everyday extension cord from the wall to the snowmobile.

The control relay for the charging system is controlled by the battery management system. It detects whether the batteries are in a stable enough state to accept charge. This mode is entered by changing a switch on the dashboard to 'Charge Mode.' When the BMS is in charge mode it determines if the batteries can be charged by checking for faults and battery conditions. If this check is completed the battery management turns on the relay to the input of the ElCon. During this charge state, the HV is isolated by the most positive and negative contactors to ensure safety.

High Voltage Fusing

Fusing the battery system must be done based on how the battery systems are configured. The 2012 competition rules state that single-series string configurations must have a single fuse rated to handle the series current and voltage. In a parallel configuration, each cell must be individually fused; since the batteries are wired in a combination of series and parallel the team will have to have a fuse for each parallel cell. The final design can be seen in the schematic of Figure 4. The schematic of Figure 4 follows the rules set by the competition judges. Since the total pack current is limited to 500 Amps the parallel cells are to be rated for half of the series amperage rating.

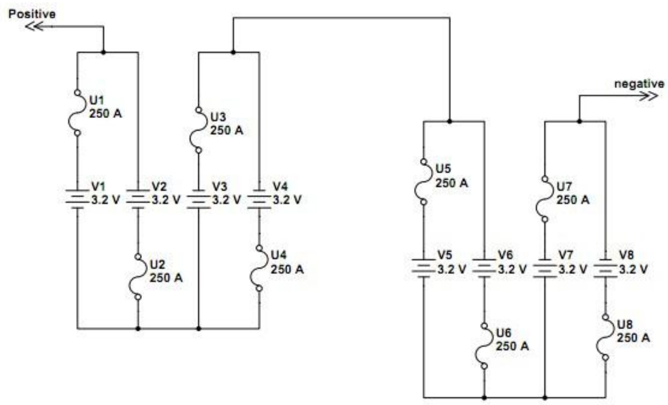

Figure 4: Fuse Schematic

For the 2011-2012 year, the team has implemented a DC to DC converter to remove the need of a separate 12V charger. With this implementation only one charging device is needed, the 96V high voltage charger. DC-DC switched-mode converters are electronic devices used whenever DC electrical voltage needs to be changed efficiently. In many ways the DC-DC converter is a DC equivalent of an AC transformer, where the DC output is simply stepped up or down according to the topology and needs of the design.

An important distinction between DC to DC converters is that some offer full dielectric isolation between their input and output circuits and others do not. Essentially, non-isolation converters are used when voltage needs to be stepped up or down by a relatively small ratio like 4:1 or lower. There are five main types of high efficiency (+80%) non-isolation converters the buck, boost, buck-boost, and charge pump converters.

Since the required DC to DC conversion is 8:1 for the ZE sled and safety should always be implemented, it would be ideal to use an isolated converter. The rules also state the HV circuitry must remain ungrounded from the chassis, essentially requiring full isolation. All isolated topologies include a transformer, which essentially isolates the high and low voltage circuits from each other, because there is no direct electrical connection in a transformer. The transformer allows for an output voltage higher or lower than input, as long as power in is equal to power out for ideal analysis, by simply adjusting the turns ratio. They also allow both sides to have different common points (typically referred to as grounds).The Mean Well SD-150D-12 purchased by the 2011-2012 MTU Clean Snow Team offers isolation up to 1500V (shown in Figure 5). This is an order of magnitude greater than the High Voltage battery packed used in the design.

The SD-150D offers a wide input range between 72 and 144Vdc. This is important as testing of the MTU ZE snowmobile showed that at no load full throttle to idle had battery pack spikes of ~20V to 120Vdc. Also at full load, full throttle the pack voltage can drop 20V to 80Vdc. It is important to have a constant 12V source and not damage the internals of the device along with other auxiliary 12V devices located on the snowmobile.

Figure 5: SD-150D-12 DC to DC Converter [4]

For the competition, it is important to be as conservative as possible when it comes to energy use. The less energy dumped as heat, the longer the sled can drive for the endurance challenge. The DC to DC converter offers efficiency between 80% and 85% at the power output of our current configuration consisting of head and tail lamps, relays, contactors and switches. At a total of 36 watts output on the 12V rail, 6.35 watts would be wasted as heat due to the DC to DC converter. This is minimal compared to the 7.8kWhr battery pack and 50HP motor.

The DC to DC also has load and line regulation within 0.5%, a leakage current of less than .75mA, 150mV ripple, over load and over voltage protection, and hiccup recovery from faults. The hiccup recovery ensures that once the fault is gone, like over voltage or overload, the DC to DC will automatically start working again without having to press any buttons on the device. Since the DC to DC will be enclosed in the battery box, this quality is important to increase ease of use.

Since the BMS must have an "always on" 12V power source which records and stores important information about the battery pack, a 12V sealed lead acid battery will be used with the DC to DC converter. This battery will act as a source of power if the DC to DC fails and as a power source when the snowmobile is off. The DC to DC converter will be implemented as to charge the 12V aux battery much like an automobiles alternator by wiring the 96V input to the isolated sides of the most positive and negative contactors.

SAFETY PRECAUTIONS

Because the MTU E-Rush has an accumulator voltage of 96 volts, it is considered a high voltage system and extra safety precautions were taken to ensure the electrical system was as safe as possible. Because the accumulator has the highest energy content in the system; the accumulator received extra attention in its safety protocol. Lithium Iron Phosphate (LiFePO4) batteries were not only chosen because of their higher energy density but also because LiFePO4 are more stable than Lithium Ion, making the pack safer and more predictable. The snowmobile had several areas which contained different electrical potentials within the system to operate properly; special measures were taken for each of these areas based on the potential voltage. All systems over 30 volts that were exposed had Electri-Flex Liquidtight Flexible Nonmetallic Conduit placed over the wire to protect them from any human contact. All potential differences of less than 30 volts had orange split loom to protect the wiring from corrosion, which could short the system and create a system failure. Proper safety instructions were distributed to allow the MTU ZE team to be aware of the possible dangers.

Safety was also taken into consideration by isolating the high voltage in all cases. Isolation relays with a 96Vdc contact rating and 12Vdc coil rating were used when it was necessary to switch the menu push button and key switch signal from the motor controller. Although these wires are only signal wires (carry fewer than 2 Amps) precaution was still taken to ensure safety. High voltage signal wires leaving the energy storage container going to the BMS were also placed in conduit to isolate the high voltage from the 12V system and chassis ground. A Bender GFCI IR125Y-4 to monitor the chassis potential and compare it to the insulation resistance of unearthed DC control systems, the high voltage. If the high voltage was too short to the chassis, the bender would trip the relay controlling the most negative contactor. This would keep all high voltage energy within the energy storage container which was built with 3/8" polycarbonate and reinforced with an aluminum cage.

CHASSIS SELECTION

For the 2012 SAE Clean Snowmobile Competition Michigan Tech chose to utilize Polaris' 2010 600 Rush chassis. There were many design criterions considered when choosing a chassis for the competition. Some of the criterion which played a role in the selection were vehicle weight, vehicle handling, rear drive motor mount options, and storage for the electrical devices. This chassis was chosen for its lightweight tube-frame construction and mono-shock design, large accessible engine bay, progressive rate rear suspension, and most importantly because the rear suspension design adapted well to the rear drive construction planned for the E-Rush.

The rear suspension of the Rush chassis is easily adjusted based on the weight distribution of the sled as well as for the rider. The snowmobile came equipped with Walker Evans clicker shocks; the mono- shock in the rear has 19 clicker positions and provides a suspension travel of 14 inches. The adjustability of the suspension on the Rush chassis allows for simple suspension changes to be made to compensate for the extra weight of the electrical components added to the snowmobile. The Polaris Pro-Ride chassis has an easily accessible large engine compartment. This was beneficial as it helped with the storage of the electrical components used to power the snowmobile, as well as increase the ease for maintenance of the E-Rush. The stock Polaris Rush chassis used as the base platform for the E-Rush can be seen below in Figure 6.

Figure 6: Stock Polaris Rush Unmodified

WEIGHT

The bare Rush chassis weighs 271 lbs. The light weight chassis was chosen because a significant amount of weight will be added to the snowmobile after the electrical components are mounted. In order to reduce the final weight of the snowmobile as much as possible the bare chassis should begin as light as possible. The LFP batteries chosen weigh about 3.3lb individually, utilizing a 48 battery design this equates to a total of 158 pounds. Along with a 12 volt battery there is a sum of 170lb of energy storage added to the E-Rush. The motor was an added weight of 53 lbs and the controller weighed 12 lbs. The design of the battery box accumulated 35lb of polycarbonate added to the sled. Consolidating the weight of the energy storage, motor, controller and energy storage compartments the weight concludes to add 270lb to the weight of the 2012 E-Rush. The final design weight of the E-Rush is expected to be less than 650 lbs.

For an increase in the storage capacity of the sled the original gas tank was used to create a carbon fiber shell. This carbon fiber shell creates more storage area for electrical components as well decreases the final weight of the snowmobile. Because the engine compartment was used to house batteries and electrical components, the E-Rush maintains a clean stock appearance. The batteries were positioned in the engine bay to allow for a more equal distribution of weight. With the electric motor in the rear of the snowmobile and the batteries in the front, the two heaviest components of the electrical system work to maintain a balanced distribution of weight.

MTU ZE POWER TRANSMISSION

The E-Rush features a very unique rear drive system which is a first for Clean Snowmobile Challenge. The driveshaft of the E-Rush was relocated from the front of the track and skid to the rear where the idler shaft generally resides. This change was made to increase driveline efficiency of the snowmobile by pulling the track directly down the rails of the rear suspension rather than pulling the track from a more remote location and using idlers to direct the track around the skid. Effectively the rear drive system has the portion of the track which is “slack”, or not under tension, making changes in direction around idler pulleys in the suspension rather than having a track under high tension making these same changes in direction. Because the driveshaft and drive motor have been moved to the rear of the snowmobile, the chaincase internals can be eliminated to reduce the weight of the E-Rush and this facilitates the need to relocate the braking system of the snowmobile.

In order to move the driveshaft of the snowmobile from its original location to the rear of the machine a custom driveshaft was required. A piece of one inch hexagonal steel stock was used to provide a press fit with the hex drivers used. The ends of the driveshaft were then machined round to an outside diameter of one inch and mounted in mounted pillow block bearings which were bolted to the rails of the rear suspension. The mounted pillow block bearings used were sized and selected based on a bearing rating equation, Equation 1, which calculates hours of life based on rated load, actual load, operating rpm, bearing quality, and a life adjustment factor. Equation 1 is based on L_{10} life which means that ninety percent of a group of bearings will survive for the calculated number of hours if mounted, maintained, and operated according to the parameters used to calculate the given life value in hours.

$$L_{10}=\left[\frac{Radial\ Rating\ (lb)}{Radial\ Load\ (lb)}\right]^3 * \frac{B}{Operating\ rpm} * Life\ Adjustment\ Factor \quad (1)$$

Bearing life, in hours, was calculated using the radial load rating of an available flange mounted bearing, 3,147 pounds, a worst case anticipated radial load value of one fourth the final weight of the snowmobile, 150 pounds, a constant B value dictated by the ISO bearing certification method, and an average operating speed of 1027rpm (27.5mph). Because the bearings will be subject to cold temperatures, moisture, salt, dirt, and other contaminants, the life adjustment factor was set to one half. Using these parameters a bearing life of 75,000 hours was calculated which at an average speed of 27.5mph is well over 10,000 miles, the average life expectancy of a snowmobile. The bearings chosen for the rear drive system have been left oversized for two reasons. The more robust bearings will provide more reliability and the one inch inside diameter of the bearings works well when machining one inch hex shaft for drive shafts because this is a standard driver configuration. Should rear drive units become standard, use of already available parts would create an advantageous manufacturing situation.

In order to accommodate the bearings used for the driveshaft to spin, the back portion of the rails needed to be enlarged to allow clearance for the one inch driveshaft to pass through them. The rear portion of the .1875" rail was removed from the stock Polaris suspension rails and replaced with a thicker and larger square area portion of .25" aluminum to provide more area for the flange of the mounted bearings as well as to cope with the added stress of the drive components. A 1.125" slot is located in this rail addition in order to allow for a .0625" clearance on each side of the 1.00" O.D. driveshaft. In addition, square bushings were machined to ride inside of this slot to serve two purposes. First, the bushings fill the space between the flange of the bearing and the bolt head giving a clamping surface to tighten the bolts and secure the bearing to the rail. Second, the bushings allow the mounted bearings and therefore the driveshaft to slide forward and backwards in the 1.125" slot allowing for track tension adjustment using a track tensioning bolt. Figure 7 below shows the basic components of the MTU ZE rear drive system.

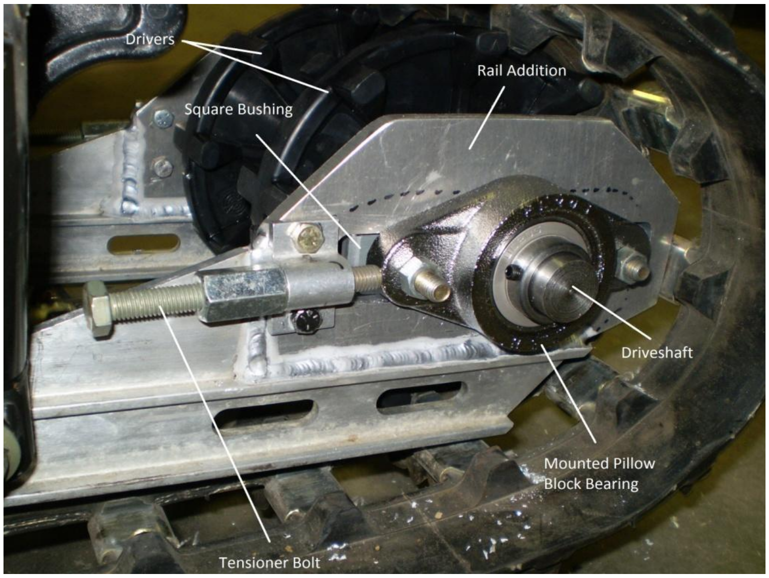

Figure 7: MTU ZE Rear Drive

BRAKE RELOCATION

The Michigan Tech Clean Snowmobile team has decided to relocate the braking system on the Zero Emissions Electric snowmobile. This decision comes with many benefits to the overall performance and design of the snowmobile. These benefits include braking efficiency and power benefits as well as weight reduction and battery packaging benefits. While the process is full of benefits, this is not to say that there are not difficulties associated with this project.

It is a relatively safe assumption to make that the brake location of a stock snowmobile is fairly common knowledge among snowmobile enthusiasts. The brake is usually located on the drive shaft, which in a stock snowmobile, is buried under the hood behind the engine and exhaust components. This location would normally make sense because there is plenty of room to package the engine components with room to spare under the hood under normal snowmobile configurations. In the case of the Zero Emission (ZE) snowmobile, everything is completely different. The front end plastics are not serving the purpose of containing an engine, but instead they contain all sixty of the batteries needed to power the snowmobile. Packaging sixty rectangular batteries that need to be wired to each other as well as wired to battery management units and the electric motor and containing them within the stock plastics becomes a much more painful challenge. This challenge becomes more difficult when some of the packaging space is taken up by a driveshaft that is not even used as well as a bulky braking system. Battery packaging was a lot of the motivation behind the decision to relocate the brake. The new location became the rear end of the snowmobile. This idea made more sense because, as mentioned the brake is normally on the active driveshaft and the active driveshaft for the ZE snowmobile is the rear axle. This allowed for the driveshaft on the front of the skid to be removed and replaced with a custom made axle. Since the front axle was no longer responsible for stopping the rotation of track, the axle no longer needed to be a driveshaft with drive cogs. The driveshaft was instead replaced with a simply designed axle to support the track. The new axle consists of a shaft that bolts into the same location as the original driveshaft. This shaft utilizes two bogey wheels to guide and support the track in a similar fashion as the driveshaft. As mentioned before, battery packaging played a large role in the decision to relocate the brake. The new front axle reduces the challenge of fitting the batteries because it does not protrude from the underside of the tunnel as the brake and driveshaft system did.

Since the ZE sled has previously been used in a Clean Snowmobile Challenge Competition using the zero emission, rear drive setup, there was already an established driveshaft suitable for attaching the rotor to. This fact sort of made some of the decisions for itself. The options for where to mount the rotor came down to either the same side of the skid as the drive pulley, or the opposite side. Having a lengthy driveshaft in place on the left side of the skid made the mounting location very clear. Making the driveshaft longer on either side of the skid was decided to be unnecessary due to having sufficient length to mount the caliper while keeping the existing drive pulley setup. It was decided to locate the rotor between the drive pulley and the skid on the driveshaft. The rotor will be one inch from both the skid and the location of the drive pulley on the shaft. This will allow sufficient space to ensure that the caliper will fit while allowing the drive pulley to be used as it was last year. Figure 8 shows the new location of the brake rotor.

Figure 8: Brake Rotor Position

According to the Clean Snowmobile Challenge rule book, the use of commercially available brake components mounted on the track shaft is allowed. A brake rotor mounted on the track shaft may be no smaller than 7 inches in diameter and the total surface area may not be reduced by more than 15% surface area. The brake components chosen for the ZE sled are a mix of Pro-ride chassis and FST chassis components. The FST brake rotor was machined down to 7 inches in diameter as specified for a track shaft mounted brake. Due to the “light-weight wave” design of the Pro-ride rotor, the total surface area of the pad braking area was increased. All the calculations for total rotor area and pad braking area are given below.

Stock braking area:

$$Circle\ Area = \frac{\pi}{4}(8in^2 - 4.1875in^2) = 36.49\ in^2$$

$$Hole\ Area = (72\ Holes)\frac{\pi}{4}(0.325in^2) = 5.97\ in^2$$

$$Triangle\ Area = (12\ Triangles)(1.95in)(0.45in)\left(\frac{1}{2}\right) = 5.265\ in^2$$

$$Total\ Area = Circle\ Area - Hole\ Area - Triangle\ Area = 25.26in^2$$

Stock average pad braking area:

$$\frac{Solid\ Area - (Hole\ Area + Triangle\ Area)}{Solid\ Area} = 0.6921$$

$$Pad\ Area = (1.55in)(0.8786in) + (0.575in)(0.8786in) = 0.5052\ in^2$$

$$Average\ Pad\ Braking\ Area = (0.5052in^2)(0.6921) = 0.3496\ in^2$$

New braking area:

$$Total\ Area = \left(\frac{\pi}{4}\right)(7in^2 - 4in^2) = 25.92in^2$$

New average pad braking area:

$$Pad\ Area = (1.55in)(0.8786in) + (0.575in)(0.8786in) = 0.5052\ in^2$$

Percent increase in average pad braking area: $\frac{0.5052in^2}{0.3496in^2}(100\%) = 144.51\%$

As the calculations show, the total rotor surface was actually increase by 0.66 square inches and the braking pad surface area was increased 144.51%. There should be no shortage of braking power with the new, lighter, more efficient braking design. Figure 9: Brake Caliper Position better shows the location for the brake caliper and rotor.

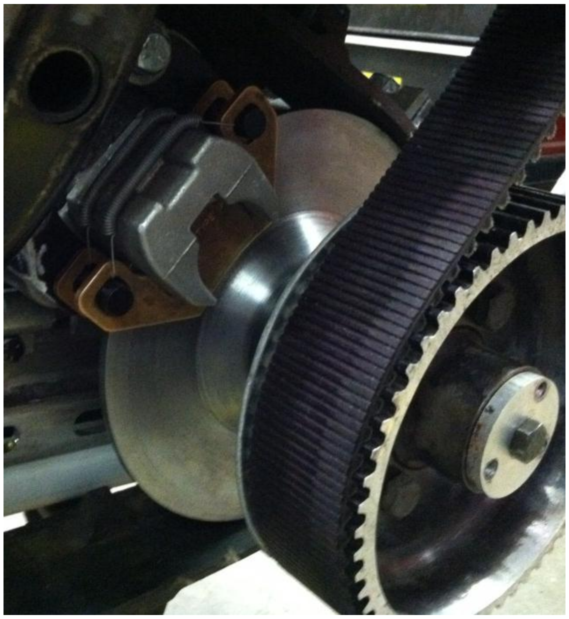

Figure 9: Brake Caliper Position

As can be seen in figure two, the caliper will be mounted to the existing motor support bracket. This was decided to be the best possible location due to multiple factors. First, the caliper can be mounted to existing structural support members; meaning that the likelihood of failure is reduced as well as the need for additional support is reduced. The motor support where the caliper is mounted does not rotate with other geometry within the rear suspension. This is critical as the caliper needs to be solid mounted. This location also provides for the easiest and simplest routing of the brake line.

MOTOR MOUNT

Because the E-Rush uses a unique rear drive system a motor mount designed specifically to function with the E-Rush rear suspension had to be fabricated. The motor mount is designed to move with the rear suspension of the snowmobile so that belt tension is constant regardless of the position of the rear suspension. The first step of creating the motor mount design for the E-Rush was determining the major sources of stress that would be placed on it. Michigan Tech's E-Rush AC-20 motor is capable of creating a torque of 105 ft-lbs and it weighs 53 lbs. These two motor performance values formed a basis for the stress analysis on the motor mount. Several design concepts for the motor mount were modeled in Unigraphics. Below, in Figure 10, are two of the ideas that were modeled and then imported into a Finite Element Analysis (FEA) program called Abaqus.

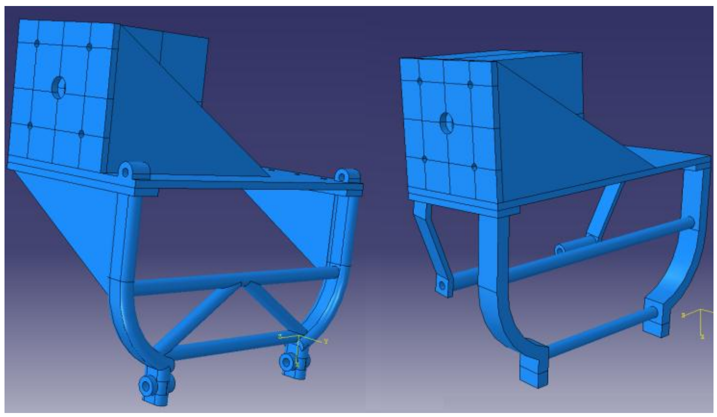

Figure 10: Two design concepts for the E-Rush motor mount

Boundary conditions, loads, material properties and a finite element mesh were applied to all motor mount concept designs. The analysis was run and the program output was used to determine what areas of the design showed high stresses and could potentially fail. In Figure 11, the final output from Abaqus of Von Mises Stresses on the final design that was implemented into the E-Rush can be seen. Through design iterations based on outputs from Abaqus the motor mount was made lighter while retaining the required strength to hold the AC-20 electric motor in dynamic riding situations. Without the effective implementation of FEA while designing the motor mount the material switch that was made from steel to aluminum would have not been made and a significant weight loss for the E-Rush would have been missed. Table 4 below summarizes the three best concept designs that were modeled and analyzed for the motor mount.

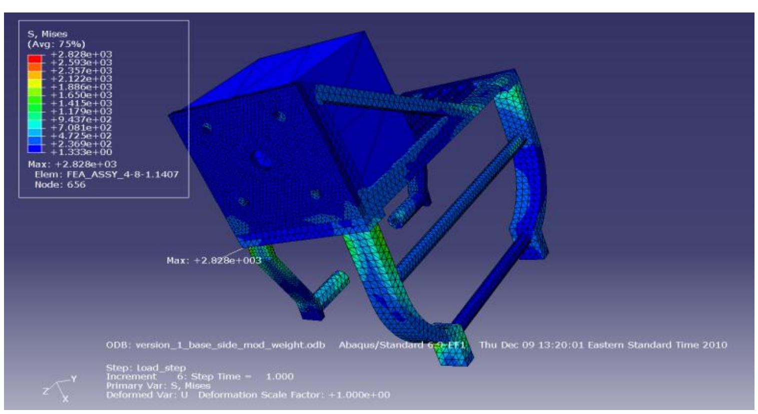

Figure 11: Von Mises Stress Plot from Abaqus of Final Design

Table 4: Maximum Stresses seen per design along with Factor of Safety and Weight.

	Max Stress (psi)	Max Displacement (in)	Yield Stress (psi)	Factor of Safety	Weight
Design 1	3,106	.01136	36,000	11.5	48.06
Design 2	2,726	.001636	36,000	13.2	36.26
Mod Design 2	2,828	.001871	36,000	12.7	25.75

RANGE

Range is one of the most critical performance aspects of the ZE competition at Clean Snowmobile Competition. Because so much importance is placed on the distance the E-Rush can travel in one charge several design aspects, some of which were mentioned above, were modified in order to increase range as much as possible. One of the largest factors which impacts the range of the E-Rush is the electrical hardware which has been chosen. The LFP batteries, Curtis motor controller, and AC-20 motor were chosen together because they have been purposefully packaged with one another. The synergy between the three major electrical components works to produce the greatest possible range. In addition, several mechanical aspects of the snowmobile were altered in order to decrease any mechanical losses that may be present in the system. The primary means by which mechanical losses were minimized was through the implementation of the rear drive system. This reduced the number of moving parts in the system as well as the number of times power is transmitted from one system to another. This reduction of moving parts and reduction of power transfer directly results in less friction and less wasted energy. A reduction in wasted energy equates to greater range. The final design parameter used to increase range was continually working to reduce weight. A reduction in weight means the electrical system has less mass to power and can then move the snowmobile a farther distance. Weight was kept as minimal as possible by selecting a light weight chassis and optimizing designs such as the motor mount to make them as light as possible while maintaining strength.

DRAW BAR PULL

One of the main design concerns that the MTU ZE team faced was the drawbar pull. After choosing the AC-20 high torque electric motor additional factors that affected the pulling ability of the snowmobile were taken into consideration. Mounting the motor on the rear of the snowmobile helped to distribute weight towards the rear of the machine and place weight onto the track increasing traction. Additional traction for the draw bar pull is provided by using the Ice Ripper XT pre-studded track. The studs in the Ice Ripper track are placed in the tips of the lugs for the best possible penetration in ice and snow and will aid in the snowmobiles pulling ability. Equations 2 and 3 below are used to calculate the draw bar pull force of the E-Rush.

$$\mathrm{DP} = \frac{TxR}{r - RR} \tag{2}$$

$$\mathrm{RR} = \frac{GVW * R}{1000} \tag{3}$$

DP- Drawbar Pull (lbs)
T- Torque of motor (in-lbs)
R- Gear Reduction
r- Radius of drive wheel (in)
RR- Rolling Resistance (lbs)
GVW- Gross Vehicle Weight (lbs)
R- Rolling resistance of the surface (lbs)

Equation 2 has been used to calculate the drawbar pull of multiple types of vehicles such as trucks and trains and the MTU team has applied these same equations to the E-Rush for a rough estimation of pulling power. The rolling resistance was calculated using Equation 3, with the rolling resistance of the surface, 37 pounds, being obtained from a table of rolling resistances for various materials. When inputting a torque of 105 lbs, rolling resistance of 24.05 lbs, gear reduction of 2 and the radius of the drive wheel of 3.5 inches, the estimated drawbar pull was calculated to be 695 lbs.

COST

The cost of building any electric vehicle is often very large when compared to other sources of propulsion. Because battery, motor, and motor controller technology is new and in high demand it often carries a large cost. Care was taken in the design of the E-Rush to use readily available and in production parts whenever possible. In addition, any custom fabricated parts that were made for the E-Rush can be easily machined using computer numeric controlled machines. The final price computed for the E-Rush was estimated at $16,994.09. This price is relatively higher compared to currently available internal combustion snowmobiles but the technology used in the E-Rush is currently in high demand and under intense development. Time and further development of the electrical components available on the market will act to decrease the cost of the E-Rush.

SAFETY, PERFORMANCE, AND RELIABILITY

Throughout the design process several key aspects of the E-Rush were kept in mind. The E-Rush was designed for safety, manufacturability, reliability, and serviceability. The safety of the E-Rush was maintained from stock and improved by relocation of the braking system to a fail-safe location which cannot be effected by drivetrain failures such as breaking a chain. With the reduction of noise from exhaust and engine noise it becomes easier for the rider to hear things that are going wrong with the snowmobile thus increasing rider awareness and safety.

The manufacturability of the E-Rush was held in high regard during the design process. The rear drive system is constructed of readily available parts which need minimal modifications to operate properly on a subsystem level. This means that extra machining process have been minimized to as great an extent as possible. The mounted pillow block bearings used in the rear drive system need only a small flat machined in their end to interface with the track tensioning system. In addition, only simple machining processes need to be performed to a standard one inch piece of hexagonal stock to create the rear driveshaft used to interface with already available hex shaft snowmobile drivers. The focus on design for manufacturability allows for existing snowmobile manufacturers to integrate zero emissions options on already existing snowmobile platforms with the need for only a few new parts or machining processes.

Because the Clean Snowmobile Competition Zero Emissions Category is based on utility for scientific advancements in a harsh environment, reliability and serviceability were a key aspect of the E-Rush design. Reliability was attained by using oversized and greaseable bearings. Proper lubrication was vital to long life and smooth operation of rotating assemblies especially those operating in extremely cold and wet conditions. In addition, the overall design of the E-Rush has been kept as simple as possible with few moving parts for easy maintenance and service. The rear drive configuration allows for only one power transmission from the motor's output shaft to the driveshaft eliminating problems that can be encountered with the many moving parts associated with clutches and chain cases. Additionally, the snowmobile's rear drive system can be completely disassembled and reassembled with basic hand tools. The theme of serviceability continues with the two piece design of the motor mount which allows for the arms which bolt to the rails of the rear suspension to be removed from the cradle and bolt circle which hold the motor. This makes motor installation easier while working around the track, allows for replacement of smaller components rather than one large one reducing the cost of replacement parts, and also makes manufacturing the motor mount simpler (design for manufacturability).

SUMMARY

The E-Rush has been designed to provide an effective mode of transportation for summit station scientists on the Greenland Ice Cap where emissions from an internal combustion engine cannot be used due to their adverse effects on measurements being taken. The overall goals of the E-Rush were to maximize the range of the snowmobile on a single charge as well as to maintain the stock platform performance. The MTU designed rear drive system serves to increase driveline efficiency, reduce weight, and reduce design complexity. Electrical design for the snowmobile has also had the same focus. The Hi-Performance AC-20 motor was chosen for its high rated power as well as its efficiency, the Lithium Iron Phosphate batteries were chosen for their high power density and relatively small size and weight, and the fully programmable Curtis Motor Controller was chosen to maximize the effectiveness of the motor and batteries together. The design decisions for the E-Rush have kept both the design goals as well as competition constraints in mind to create a practical solution for zero emissions transportation on snow.

REFERENCES

1. "40Ah ThunderSky." Lithium Batteries, Empowering EVs. Web. 22 Feb. 2012. http://lithiumstorage.com/index.php?main_page=product_info&cPath=&products_id=30

2. ThunderStruck Motors - Electric Vehicles, Electric Vehicle Accessories and Components. Web. 1 Sept. 2010. http://www.thunderstruck-ev.com/

3. "2012 SAE Clean Snowmobile Challenge Rules." SAE International. Web. 22 Feb. 2012. http://www.sae.org/servlets/pressRoom?OBJECT_TYPE=PressReleases&PAGE=showCDSNews&EVENT=SNOW&RELEASE_ID=1344

4. "Curtis Instruments - Motor Speed Controllers, Programming & Systems Control (Data Sheets)." Curtis Instruments | Instrumentation, Motor Speed Controllers, Battery Chargers. Web. 22 Feb. 2012. http://www.curtisinstruments.com/index.cfm?fuseaction=cDatasheets.dspListDS&CatID=1&siteID=1

5. "HowStuffWorks "Calculating Drawbar Pull"" Howstuffworks "Auto " Web. 22 Feb. 2012. http://auto.howstuffworks.com/auto-parts/towing/equipment/tow-bars/drawbar-pull1.htm

6. "Energizing the Future: Rear Driven E-Rush." MTU Keweenaw Research Center. Web. 22 Feb. 2012. http://www.mtukrc.org/mtu2011.htm.

7. "The BMS Schematic." Web. 22 Feb 2012. http://www.orionbms.com/wp-content/uploads/2011/08/OrionBMSWiringManual1.006.pdf

8. "DC to DC Converter." Web. 22 Feb 2012. http://pdf1.alldatasheet.com/datasheet-pdf/view/259418/MEANWELL/SD-150D-12.html

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