Utah State University Electric Snowmobile SAE Clean Snowmobile Challenge 2006

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ABSTRACT

Utah State University engineering students have successfully designed, built, and tested a fully functional electric snowmobile. This snowmobile has been designed to successfully compete in all aspects of the SAE Clean Snowmobile Challenge. Efforts have been made towards cost effectiveness, safety, ease of use, practicality, and fun. Engineering analysis has been performed in all critical areas to ensure that the machine will be safe and durable. Theoretical models have been constructed to predict performance, and these models have been field tested and verified. The USU electric snowmobile is remarkably clean, exceptionally quiet, and performs well in range, utility, and acceleration.

INTRODUCTION

A team of senior Engineering students at Utah State University has designed, built, and will compete with an electric snowmobile in the SAE Clean Snowmobile Challenge 2006.

This project began several years ago as a private venture (*Sn❄wLectric*) of one of our team members. They were able to build several prototypes and demonstrate conceptual viability of an electric snowmobile. This project was then brought to the University, and a student team has been building the concept for the past year. The current prototype is capable of traveling in excess of 16 km (10 miles) at 32 kph (20 mph), with an average noise level of 60 dB. It is also capable of towing a 680 kg (1500 lb) trailer. The USU team plans to continue using this working prototype for data collection and testing, however, one main goal is to acquire a new platform with which to build a truly optimized electric snowmobile.

As a small venture, *Sn❄wLectric's* resources were limited, both in time and money. Now is the time to take the research and development of electric snowmobiles to a greater scale. Utah State University requires that seniors in engineering complete a design project before graduation. The College of Engineering has accepted this project, and a high-caliber student team has been assembled. The Department Head of Mechanical Engineering at USU (Dr. Byard Wood) has agreed to act as the faculty advisor. There is much interest among the faculty and the student body concerning this project. This high level of interest helps ensure that we will continue to have a pool of talented and committed engineering students involved with this project. As a team, the goal has been to design and build a fully electric machine worthy of notable competition in the 2006 SAE Clean Snowmobile Challenge. Main objectives in entering the competition are to:

1. Provide a competitive sled that demonstrates the viability of electric power
2. Gain recognition for alternative fuel technology, USU, and team sponsors
3. Further establish the development of alternative energy snowmobiles
4. Learn what is needed for even better snowmobile performance.
5. Establish and demonstrate performance criteria well beyond current abilities, and worthy of consideration as the basis for a market entry utility or mild recreational machine.
6. Win the SAE Clean Snowmobile Challenge 2006.

Previously, this has been a personal project with very limited human and financial resources. With a dedicated student team, university faculty advisors, and university resources, a viable electric snowmobile will become a reality.

The scope of this project currently covers a years worth of student work and competition, including the engineering and testing necessary to gain baseline data for electric snowmobile performance needs and characteristics. Future teams can then build on this foundation with the 2006 competition results and to develop clean snowmobile technology for years to come. It is anticipated that there will be much interest concerning zero-emissions snowmobiles for use in National Parks & Recreation Areas, and other public places where noise and vehicle emissions are a major concern.

ELECTRIC SNOWMOBILE CONSIDERATIONS

Electric snowmobiles will enter the market as a utility machine, but as with any new technology, the effects of time, engineering effort, market demand, and money will push electric snowmobile technology to become a reliable, practical solution for other types of users.

The history of this project has demonstrated electric snowmobiles that are easy to use, safe, incredibly clean, and remarkably quiet. We also have achieved milestones in our efforts such as speed (88kph (55 mph)), and ride-type similar to a standard snowmobile (CVT transmission and normal handling characteristics). The technology cost has also shown promise to not be prohibitively expensive. The only major limiting factor that remains regarding the electric snowmobile is range. The current range of these machines is only acceptable to a utility or short distance user. Improving the range is simply a question of energy storage, and as newer technologies become more widely developed, these machines will begin to utilize them and improve in this area. This being the case, all design decisions were made primarily around increasing the range of the electric snowmobile.

As the electric snowmobile is viewed as a utility machine, its design must be capable of a significant workload. This required workload for the Clean Snowmobile Challenge is the ability to tow a 630 kg (1500 lb) trailer. The USU electric snowmobile has been designed to meet this requirement.

In order to keep the electric snowmobile practical and cost-effective, efforts were made to use as many “off-the-shelf” parts as possible. Components were also selected to be durable, and all high voltage components, except the motor (for ventilation purposes), are hermetically sealed. Even the heat shrink used in high voltage connections uses a filler glue to help prevent moisture penetration.

The overall design of the snowmobile was kept as simple as possible for several reasons. First; a simple design minimizes the number of components, energy losses, and cost. Second; simple design minimizes the number of things that can go wrong. Third; maintenance and replacement should consequently be less-expensive. Finally, a simple design will cost less. The performance and strength of the USU electric snowmobile’s design is in how these components are implemented and adjusted.

In this snowmobile, the high voltage components are overbuilt, and smaller components would cost less money. For example, the motor used this year is a 48.5 kg (107 lb) Advanced DC 203-06-4001, and the typical retail cost of this motor is $1299. A 37 kg (82 lb) Advanced DC X91-4001 could have been used instead, at an average retail cost of $990 [1].

The major high voltage components are purposely overbuilt based on past experience with the energy demands of a higher performance profile than the one that is used for the Clean Snowmobile Challenge. Basically, the main electrical components in the USU snowmobile are capable of taking any kind of expected load requirement, even drag racing. These overbuilt components also bring an additional safety factor to help avoid damage in extreme loading.

Higher voltage component are also desired to minimize battery discharge rate and resistive losses. Two fundamental equations were used to decide electric vehicle power configuration. The first is the electric Power Equation:

$$P := I \cdot V$$

where P = power (Watts)
I = current (Amps)
V = voltage (Volts)

For an equivalent power requirement, one can increase I and decrease V, or increase V and decrease I.

The second is the Resistive Losses Equation:

$$\text{Losses} := I^2 \cdot R$$

where I = current (Amps)
R = resistance (Ohms)

Thus, it is desirable to minimize the current in order to minimize losses. This is accomplished by increasing the voltage to obtain the required power, while keeping the discharge current as low as possible.

Another major factor in choosing to use higher voltages is the impact of discharge rate on battery life. The lead acid battery characteristic discharge curve is a logarithmic function, with greater discharge rates leading to lower available capacity and discharge life. Thus, a linear reduction in the amount of current required yields a logarithmic increase in battery life:

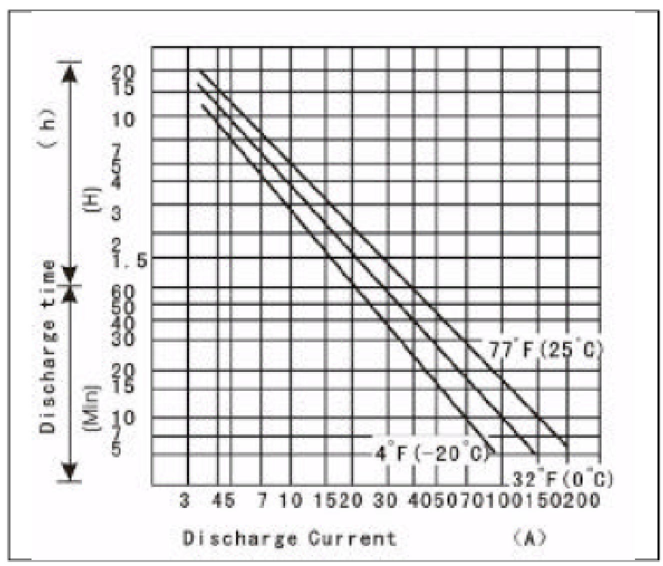

FIGURE 1: MANUFACTURERS PLOT OF DISCHARGE RATE VERSUS DISCHARGE TIME FOR LEAD ACID BATTERY. [2]

Notice from Figure 1 that battery life is also adversely affected by a decrease in temperature, thus to maximize range, temperature drop at the batteries must also be minimized.

For economic reasons, our team utilizes a Valve Regulated Lead Acid Absorbed Glass Mat (VRLA AGM) battery pack. These are inexpensive, readily available, simple to charge, and fairly rugged. They are, however, very heavy. Each battery weighs 17.2 kg (38 lb), therefore a 120 volt battery pack weighs 172 kg (380 lb) [2]. This component is the greatest weight penalty in electric snowmobile design.

If funding were available, a Nickel Metal Hydride (NiMH) battery pack would be used. This would effectively cut the weight of the battery pack by 58.5 kg (129 lb) while still giving the same energy capacity. With even more funding, a Lithium-Polymer (Li-Poly) battery pack would be used. This would cut the weight of the battery pack by 135 kg (299 lb) while still giving the same energy capacity, when compared to lead acid. This would bring the weight of an electric snowmobile within the typical weight range of current gasoline sleds, and would also lead to great improvements in range.

SAFETY

In electric vehicle design, a major concern is the presence of high voltage components and circuitry. The USU Electric Snowmobile team has held rider safety in mind in the design of all aspects of the snowmobile.

The entirety of the high voltage battery pack is contained within a single sealed and insulated battery box. A vent is used to prevent any dangerous gas build up during charging operations. This box is designed to hold the batteries securely in the event of any impact or accident, including rollover.

This battery pack must be connected manually and electrically before any energy is delivered to the drive train. The manual connection is an Anderson-style connector, and this is mounted to the clutch cover. Consequently, this connection must be broken before the drive train can be accessed. This connection is also broken as the first step whenever the hood is opened. The electrical connection is a hermetically sealed solenoid-style contactor, and this switch is energized by an auxiliary 12 volt system. This contactor must be activated by means of a keyed switch. This circuit may be broken by either a handle mounted kill switch or by breaking a wrist-connected safety tether connection switch. No energy is delivered from the batteries to the drive train electrical components unless both systems are fully connected.

ENGINEERING DECISIONS

The engineering process that our team followed in making important decisions was to build a weighted decision matrix. For example, the first major decision faced by the team was concerning what type of battery to use. Economic reasons led to Lead-Acid technology being the only feasible option, it was then a choice of which specific technology. The following is an example of the decision process that was used:

Weighted Decision Matrix: Battery Type			
type 22 case, 55 Ah, lead acid battery			
scale: 1 (low) to 5 (high)			
type	**AGM**	**Gel**	**Flooded**
weight	-	-	-
capacity	-	-	-
charge rate	5	4	5
discharge rate	3	4	5
safety	4	4	2
maintenance	5	5	2
durability	5	5	2
cost	4	2	5
cold performance	5	5	2
TOTALS	**31**	**29**	**23**
Decision: AGM batteries.			

FIGURE 2: EXAMPLE OF DECISION MATRIX USED TO GUIDE PROJECT ENGINEERING CHOICES.

The matrix takes the decided important factors into account, and then assigns a score to each possible choice, based on each factor. The highest scoring option is the best choice, based on the chosen criteria. This decision process was used to help decide all major variables for the Utah State University Electric Snowmobile.

TEAM AND DESIGN PAPER STRUCTURE

The tasks of the electric snowmobile were divided into three major areas: Drive Train, Chassis, and Electrical responsibilities.

DRIVE TRAIN

The Drive Train team was responsible for everything involving power transmission from the motor to the track shaft. The main duties of this team were in the design and testing of the transmission and motor. They also were responsible for the motor mount, brake, chain case and reverse, drive train noise reduction, and everything else having to do with the region between the motor shaft and driven shaft.

ELECTRICAL

The Electrical team was responsible for all high voltage systems, low voltage systems, data acquisition and signal processing, and battery testing. They also participated in motor testing and analysis.

CHASSIS

The Chassis team was responsible for all exterior areas of the snowmobile (nothing under the hood). Their main duties were in the suspension and battery box / seat. They also were responsible for skis, alignment, track tension, handling, rider comfort, track noise reduction, and ensuring that the frame of the snowmobile will be strong enough for vertical suspension and towing duties.

DESIGN PAPER ORGANIZATION

The content of this design paper is subdivided and presented in terms of which team did the majority of work on that particular aspect of the project, in order as presented above. Each team section contains a discussion of major competition objectives (range, draw bar pull, cost, noise, and then other relative factors). This discussion is followed by representative modeling and testing for each team, Final design decisions are discussed throughout.

Mathematical Modeling

Mathematical models were developed to help the team understand the energy requirements of the snowmobile, perform predictive analysis, and compare design options (i.e. finding a gear ratio as an optimized function of required torque, current draw, acceleration, and towing performance). These models also helped the team to find which areas of the snowmobile would yield the greatest improvement in desired factors when modified.

Initially there were two separate models, one by the Drive Train team and the other for the Chassis team. The Drive Train model was used to inspect energy losses as a function of the components between the motor and the drive shaft. The Chassis model was used to analyze losses in suspension components and geometry, and also to tune track tension and ride performance. These models were eventually combined to form an overall model. The initial models were based on experimental data, and continued to be used for analysis specific to their components. However, the overall model was generated to compare with full field test data. All full scale predictive analysis given in this report is based on the overall model.

Energy models were built using Mathsoft Mathcad, Microsoft Excel, and Intel FORTRAN 90/95 software. The use of this software made perturbation of possible solutions simple, and helped uncover the full scale effect of changing variables.

MISCELLANEOUS TASKS

Most team members were assigned a secondary responsibility in addition to their engineering responsibilities, such as administrative logistics, financial duties, or webmaster.

Team assignments were not entirely exclusive, as team members helped out wherever they could outside their assigned expertise.

Figure 3 gives the organizational structure of the USU electric snowmobile team. This figure also shows which team member contributed to each section of the project.

USU ELECTRIC SNOWMOBILE TEAM ORGANIZATION

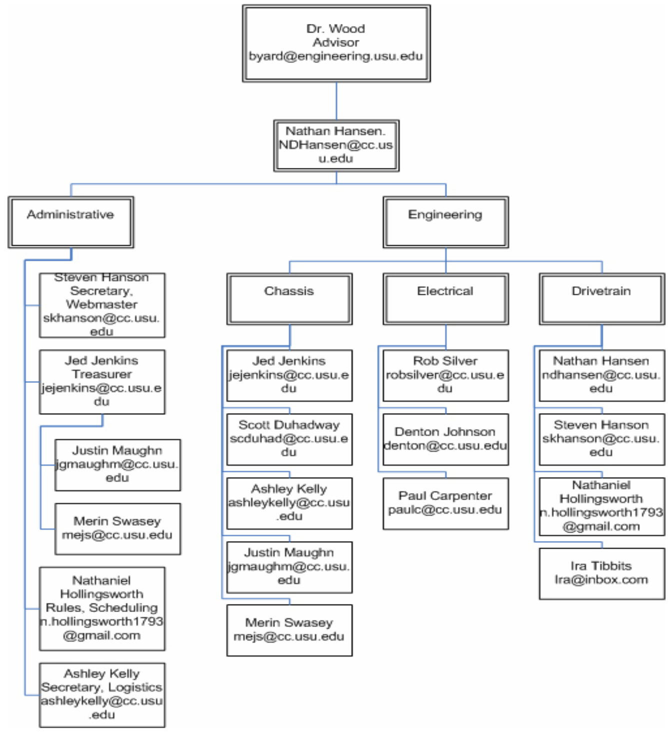

FIGURE 3: TEAM STRUCTURE OF USU ELECTRIC SNOWMOBILE TEAM, 2006.

DRIVETRAIN DESIGN

PERFORMANCE CONSIDERATIONS

Range

The main goal in drive train design was to implement the most efficient system possible that would still be robust enough for the Draw bar pull test. Our first design utilized a standard Continuously Variable (CVT) snowmobile transmission. This transmission served well for the initial experimental aspects of the project. The springs and weight in the clutches were modified to be more appropriate to the operating characteristics of the electric motor. However, further study of the CVT operating characteristics showed that a directly driven gear ratio (similar to a timing belt) would be more efficient. The two options were field tested against each other. This data is given in the Testing section below.

Highest design priority was given towards making the transmission as efficient as possible at speeds around 32 kph (20 mph). Weight was reduced wherever possible.

The reverse gear was removed from the chain case, and the gearing interior to the chain case was replaced with a more narrow chain and sprockets. This resulted in a reduction of 2.4 kg (5.2 lb) of spinning mass, and 0.6 kg (1.4 lb) of dead mass. Reverse can still be installed, mechanically or electrically. Both options impose a similar weight penalty; however, the electrical option adds non-spinning mass. As reverse is not required for the Clean Snowmobile Challenge, it was removed completely for competition purposes.

Draw Bar Pull Test

The transmission was designed to withstand the requirements of the draw bar pull test. Analysis of this capability is given in the Modeling and Testing section, below.

Cost

The CVT transmission came as part of the snowmobile, and the cost of weights and springs for tuning purposes was marginal. The retail cost of the direct drive toothed belt system used in the final design is $273.18, as quoted from the distributor [3].

Noise

A virtually silent motor is implemented in the electric snowmobile, so the great majority of the noise that is created by the sled is drive train and chassis related. These two are by far the largest factors in reducing noise relative to internal combustion engine snowmobile technology.

The drive train noise is therefore in the transmission, jackshaft, and chain case. The CVT used in standard snowmobiles is relatively quiet. The direct drive system we implemented was perceptibly quieter than the CVT transmission. The chain case had also received little attention over its lifespan, and was observed to emit a high "whining" noise in testing. This noise was the most audible, at the furthest distance. The next loudest found was the track noise, which will be discussed in the Chassis section. The chain case was rebuilt, and the reverse gearing was removed. Both of these factors were major contributors to lowering chain case noise. The chain was also shortened to reduce chain wrap and further lower noise emission.

Other Factors

Acceleration

In designing a zero emissions sled for the Clean Snowmobile Challenge, range was always chosen as the most important factor. This led to some compromises in the acceleration performance of the snowmobile. Electric motors create an incredible amount of torque, and a snowmobile could easily be built that would be very competitive with internal combustion designs. However, the acceleration performance of the sled would require a much higher discharge rate and electrical operating profile than is necessary in other events, which would ultimately compromise range. Thus, the choice was made to compromise acceleration performance in favor of range. This is not to say that acceleration performance is poor, as the snowmobile has a sporty feel and is quite powerful across all speeds. However, in terms of the CSC, maximum acceleration possibilities have been governed in favor of range. The snowmobile should still perform quite well in the acceleration event, as shown in the predictive analysis given in the Drive Train Modeling and Testing section, below. The snowmobile is just a few simple adjustments away from being programmed for a higher performance operation profile.

Cold Start

The operating temperature range of the belt drive transmission is -54 ˚C to 85 ˚C (-65 ˚F to 185 ˚F) [4]. The chain case and jackshaft are stock snowmobile parts, and are assumed to be capable of satisfactory cold weather operation. The range of operation of the motor was not available, but the typical range for electric motors extends to -40 ˚C (-40 ˚F) or below.

Rider Comfort and Feel

To increase user acceptance, it is often desirable to make new technologies "feel" similar to existing technologies. For this reason, the CVT was used in early designs. The CVT also helped remove questions of durability in our initial electric motor tests. One advantage of a CVT over direct drive systems is that the continuous transmission provides more range in gearing and flexibility of operation. As the operating characteristics of the motor and transmission were further understood, it was realized that a direct drive system would deliver a better feel than the CVT transmission. Electric motors deliver maximum torque at start up, and the CVT operated in such manner that it did not engage until the motor was actually decreasing in torque with higher motor speed. The motor would then continue to decrease in torque with increasing motor speed, which is an opposite behavior to the IC engine that the CVT was designed for. The use of direct gearing takes better advantage of the motor operating characteristics, and consistently delivers torque to the rider regardless of rpm. The response of the snowmobile is much more instantaneous as well, due to the "always engaged" state of the transmission.

The direct transmission used in this year's competition machine is a single speed transmission. This system was chosen to provide maximum performance in acceleration, draw bar pull, and range at speeds up to 32 kph (20 mph). The gear ratio could have been chosen to provide top speed instead. Ideally, a two speed transmission could be used to provide both. Our team has had several ideas for how to accomplish this, however, for this year's competition sled we have focused on performance in the above mentioned events and installed a single speed direct drive transmission. Analysis was performed to choose the appropriate gear ratio, and is given in the Drive Train Modeling and Testing section, below.

DRIVE TRAIN MODELING AND TESTING

Dynamometer Testing

The manufacturer's curve for motor output characteristics was available for reference, but the actual output characteristics were also desired. The motor was removed from the snowmobile and mounted to a prony-brake style dynamometer. Two styles of dyno runs were performed: running the motor up to speed and then braking (good for measuring the top end of the motor), and then braking from a stall condition and slowly releasing the brake (good for measuring the bottom end). Data was gathered with a USB Data acquisition system. Variables measured were: torque, voltage, current, and rpm. The following figures are characteristic for the output of the motor at 120 VDC:

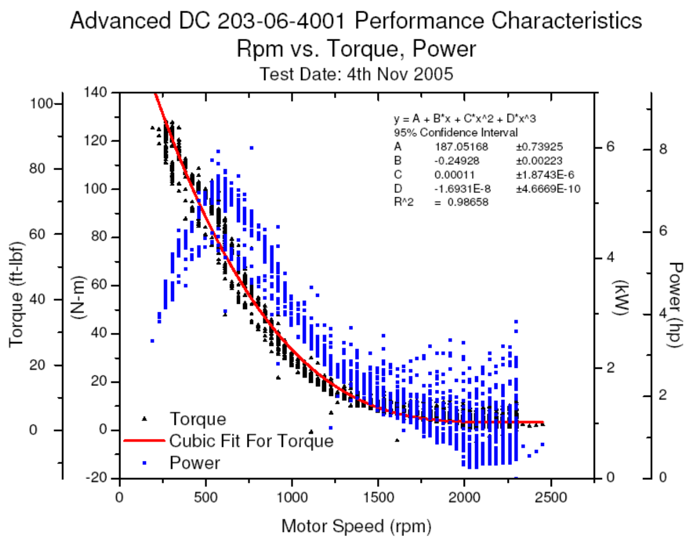

FIGURE 4: TYPICAL DYNAMOMETER PERFORMANCE CHARACTERISTICS OF ADVANCED DC 203-06-4001 MOTOR.

Notice that the torque of the motor is a maximum at start up, and then rapidly drops off with increasing speed. This behavior is consistent with the manufacturer's data. Torque was also measured as a function of current:

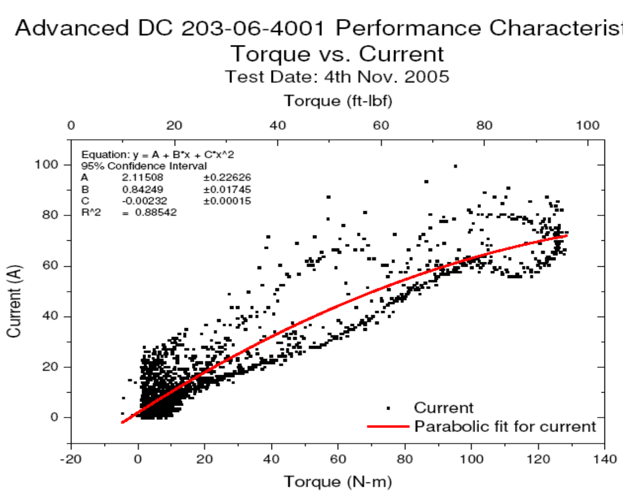

FIGURE 5: DYNAMOMETER TORQUE VS. CURRENT CHARCTERISTICS OF ADVANCED DC 203-06-4001 MOTOR.

Notice the direct relationship that current has with torque. Minimizing the torque requirement of the motor also minimizes the amount of required current. There is a tradeoff, however, in terms of the maximum velocity of the snowmobile. The gear ratio analysis below goes through this decision in more detail.

Data from these plots was used in mathematical modeling.

Drag Testing

It was desired to know the amount of force that was required to propel the snowmobile at velocities up to 48 km/hour (30 mph). This information was needed to find the energy losses and requirements of the snowmobile, gather data for mathematical model building, and design an appropriate transmission.

A load cell was attached to the back of a passenger vehicle towing hitch with non-elastic rope. This system was then attached to the snowmobile with another non-elastic rope. A velocity measuring instrument was also attached to the back of the snowmobile. Data was then acquired from the load cell and velocity system simultaneously with National Instruments LabView software and a USB Data Acquisition System. The test was performed on an asphalt parking lot, as we desired repeatability. The stock snowmobile skis were replaced with aluminum roller skis (used in snowmobile asphalt racing) to help simulate snow friction more closely and also help with steering. A rider sat on the snowmobile, and the system was gradually accelerated up to speed by the passenger vehicle. The parking lot had a slight slope, so the test was performed four times, twice in each direction across the parking lot, and the results were then averaged. The plot of these results follows:

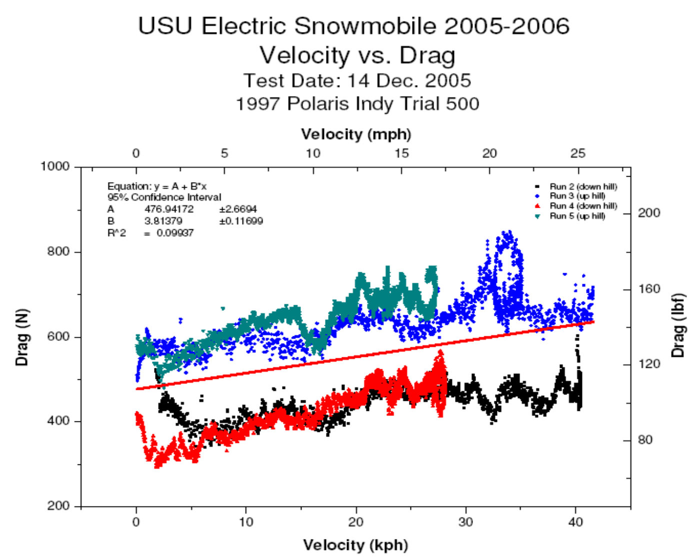

FIGURE 6: AVERAGED AND TOTAL RESULTS OF DRAG TESTING; VELOCITY VS. DRAG AT SPEEDS UP TO 40 KPH (25 MPH).

The straight red line in Figure 6 is the average of all four drag runs. This test yielded two important pieces of information. First, the energy requirements and operating characteristics of the snowmobile were obtained. Figure 6 shows that there is a large energy requirements to initiate motion, but then a relatively smaller increase to achieve higher velocities. This is consistent with the theory, as friction is independent of velocity. This test also demonstrated the actual amount of energy needed to travel at certain velocities, which was then used in mathematical models for design aspects such as range prediction and gear ratio specification.

CVT vs. Direct: Analysis and Testing

Advantages could be seen to using either a CVT or a direct drive system. Analysis from mathematical models showed both systems to be very competitive. As range was the most desired result, a range test was performed with both transmissions. Care was taken to replicate test variables as closely as possible. The following results were gathered in January 2006:

Transmission Type	Average Distance Traveled (km)	Mass (kg)
Continuously Variable Transmission	14.3 km (8.9 miles)	9.97 (22 lb)
Direct Drive (toothed belt, pulleys)	15.2 km (9.5 miles)	6.44 (14.2 lb)

FIGURE 7: COMPARISON OF RANGE AND MASS FOR DIFFERENT TRANSMISSIONS.

It should also be noted that in the direct drive system, 1.13 kg (2.5 lb) of the system is in the tensioner mount, and thus is non-spinning weight.

The difference in range is due to several factors. First, the CVT requires a higher current draw to the motor to engage the transmission. This is due to the fact that the CVT must develop enough force to clamp on to a v-belt before the power is transmitted to the drive train. This requires more torque and motor speed than a directly geared system. This higher requirement means that the motor must draw more current from the battery, which ultimately affects range. Across several miles of testing, stop-and-go behavior, and speed variation, there is a noticeable impact. Second, the CVT is also not as efficient as the direct drive gear system in that it has a lower belt tension, and is allowed to slip in-between the clutch plates. Third, the belt system uses an involute tooth profile, so the theoretical friction between the belt and the gear is zero.

It is suspected that a more-modified CVT could deliver range closer to the geared system. However, in light of the better response characteristics of the geared system and the better ultimate range, a direct drive system was chosen as the final design.

Gear Ratio Analysis, as a function of Acceleration and Range

An energy model was used to help decide the best gear ratio to satisfy both range and acceleration requirements. This analysis was based on electric vehicle theory, energy models, test data, and observed data trends. The output of this analysis is given in Figure 8, below. Another consideration was the ability of the team to implement the desired gear ratio.

	Acceleration Test			**Constant Velocity 32 kph (20mph)**			
Total Drive Ratio (x:1)	**Time (s) to 30.48m (100ft)**	**Time (s) to 152.4m (500ft)**	**Vmax (kph)**	**Motor Speed (Rpm)**	**Current (Amps)**	**Theo-retical Battery Life (min)**	**Theo-retical Range (km)**
4	2.89	10.21	65.0	3842	117.4	12.5	6.7
4.25	2.91	10.44	62.8	4083	114.2	13.0	6.9
4.5	2.93	10.66	60.7	4323	111.3	13.4	7.2
4.75	2.96	10.9	58.9	4563	108.8	13.8	7.4
5	2.98	11.13	57.2	4803	106.5	14.2	7.6
5.25	3.01	11.35	55.6	5043	104.4	14.6	7.8
5.5	3.05	11.58	54.2	5283	102.5	14.9	8.0
5.75	3.08	11.81	52.8	5523	100.7	15.3	8.2
6	3.12	12.03	51.5	5764	99.1	15.6	8.4

FIGURE 8: SUMMARY OF GEAR RATIO SELECTION ANALYSIS, AS A FUNCTION OF ACCELERATION AND RANGE.

Based on analysis, the final chosen single speed gear ratio for acceptable operation across all competition events is 4.5:1. This gear ratio should provide a good balance between low current draw (range), towing abilities, and sporty performance.

It should be noted that this analysis is based on drag test data and suspension evaluation that took place before several major improvements were made to the machine. The predicted range is consistent with the range of the snowmobile at that time. Since making the aforementioned improvements, the range has more than doubled. Likewise, acceleration has improved.

The Advanced DC 203-06-4001 has a typical maximum operating speed of 6000 rpm. At a velocity of 32 kph (20mph), the motor speed will be approximately 4400 rpm. This also allows the snowmobile the capability to safely travel at speeds above 32 kph if desired.

This gear ratio is implemented in two stages. The first stage is a timing belt style system between the motor shaft and the jack shaft. The tooth ratio in this system is 22:50, or a gear ratio of 1:2.27. The jackshaft then feeds into the chain case, where a reduction of 20:39 (1:1.95) takes place between the jack shaft and drive shaft. This yields a total gear reduction of 4.43:1 between the drive shaft and the motor.

This two stage implementation was performed due to space constraints. The initial desire of the team was to install the transmission directly between the motor shaft and track shaft. When the final gear ratio was determined, inspection revealed that space constraints would prevent installing the desired reduction in a single stage. Since two stages would be necessary, the decision was made to leave the chain case and jackshaft in, as they provide a “free” (already installed by manufacturer) 2:1 gear reduction, and no modifications to the brake would be necessary.

Draw Bar Analysis

The typical maximum output of the motor in its competition operation profile is 135.5 N-m (100 ft-lbf) of torque. The energy requirement for the snowmobile with a 1500 lb trailer is 23.3 N-m (17.2 ft-lbf). Using a gear ratio of 4.43:1 and limiting the current draw to 200 A by use of the controller limits the maximum torque to 28.20 N-m (20.8ft-lbf).

At 32 kph (20mph), the drive belt (Gates Polychain GT 896-21) is rated to 48.7N-m (35.9 ft-lbf), yielding a safety factor of 1.7. [2] This safety factor increases as velocity is reduced, and is approximately 5.7 at startup. Using a coefficient of friction of 0.1 between the trailer and snow, the torque requirement to move the snowmobile and trailer at 32 kph (20 mph) is 25 N-m (18.45 ft-lbf), giving a safety factor of 1.94. [4]

New Motor Mount

A new motor mount was designed for the electric motor, as the previous mount was observed to deform excessively. Analysis of the designs was performed at 136 N-m (100 ft-lbf) of motor torque. The redesigned motor mount exhibits a safety factor of 3.1 for shear at the bolts. The safety factor for plastic deformation is 4. The new mount is also 0.9 kg (2 lb) lighter than the previous design. The following analysis figures demonstrate the deformation of the old and new designs:

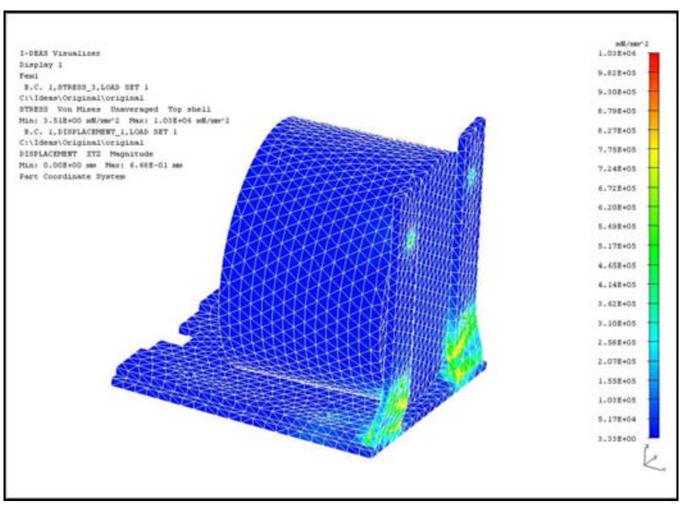

FIGURE 9: LOADING ANALYSIS OF INITIAL MOTOR MOUNT DESIGN. NOTICE THE PLASTIC DEFORMATION OF MOTOR MOUNT.

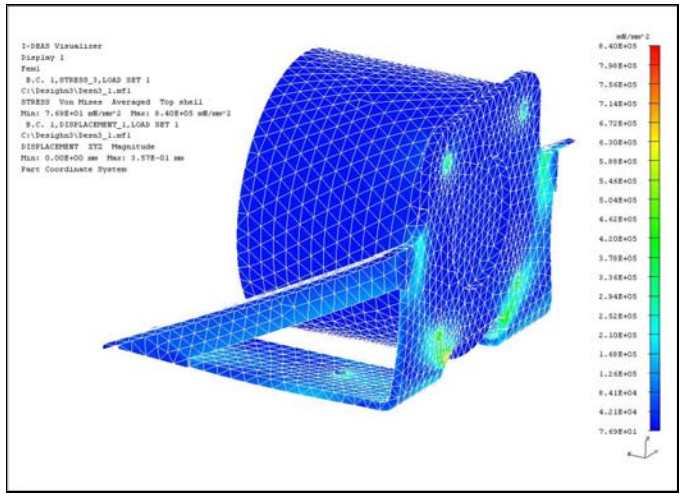

FIGURE 10: LOADING ANALYSIS OF NEW MOTOR MOUNT. NOTICE THE LOWER STRESS, GREATER STIFFNESS, AND LOWER DEFORMATION.

Both of these analysis figures use an exaggerated deformation scale. This scaling factor is used to visually expose the behavior of the material in the given loading.

ELECTRICAL DESIGN

A basic wiring diagram of the electrical system is given here to demonstrate simplicity and components:

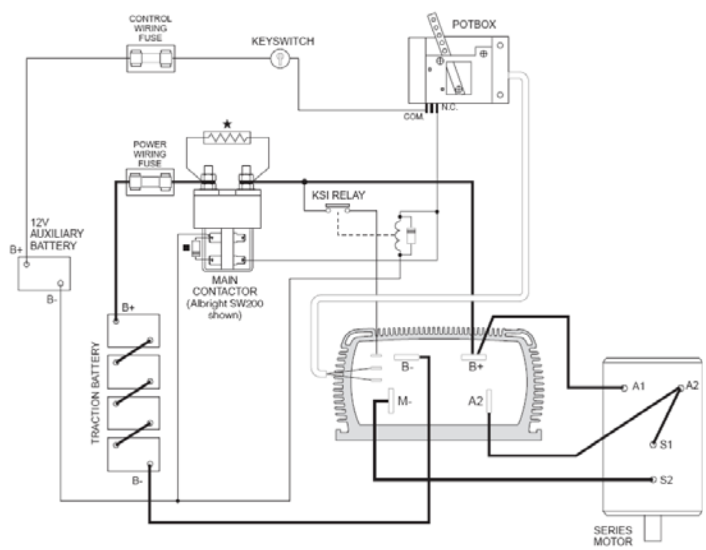

FIGURE 11: BASIC WIRING DIAGRAM OF ELECTRIC SNOWMOBILE COMPENENTS [6].

In this diagram, high voltage connections are shown by the thicker lines. The only major components are the motor, controller, and battery. The contactor and potbox (electronic throttle) are small components that cost under $100.

PERFORMANCE CONSIDERATIONS

Range

Increasing the amount of energy capacity in the battery pack was essential to increasing the range. The battery packs considered for use were several variations of lead-acid deep-cycle batteries, a Nickel Metal Hydride battery from a Toyota Prius, and building a Lithium Polymer battery pack. The chargers for the NiMH and Li-Poly batteries were found to be excessively expensive, as were the Li-Poly batteries. The USU team also investigated other possibilities, such as a hydrogen fuel cell or ultra-capacitors.

The snowmobile range will improve with an increase in motor efficiency and reduction in motor current. Alternating current motors were considered, but were rejected since the AC motor would require a DC to AC converter and a new motor. The decision was made to continue with the existing DC configuration because DC would avoid the losses in the converter, and the DC motor was very robust. The motor was re-wired by Hi-Torque Electric so that the field coils could be routed in parallel or series, as shown in Figure 11.

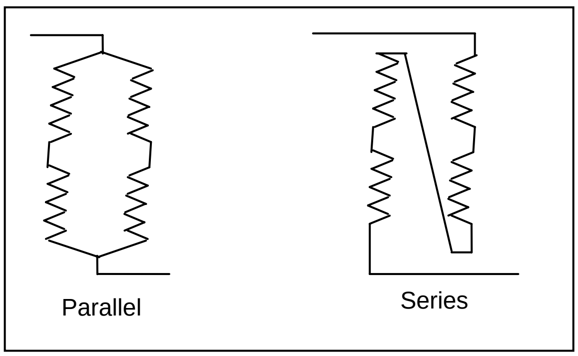

FIGURE 11: PARALLEL VERSUS SERIES WIRING IN THE USU ELECTRIC SNOWMOBILE MOTOR.

In theory, the parallel arrangement would result in a lower current draw from the battery pack and slightly lower torque. Testing verified this hypothesis, and the electrical team concluded that the parallel wiring configuration should be used for the motor coils.

Draw Bar Pull Test

Utilizing the commercially available figures for motor output, the electrical team determined that the current motor and batteries would have sufficient energy to pull a 681 kg (1500 lb) trailer.

Cost

The cost of an electrical system for the snowmobile is the major factor in the expense. In terms of additional technology cost, the only other major modification that has financial impact is the direct drive transmission system.

The motor and controller are off the shelf parts (readily available), at a combined average retail price around $2000. [6,7] In relation to other options, this is a competitive price, particularly in light of their versatility and durability. The battery pack is the next most expensive item: the 120 V 550 Ah AGM technology used comes at a cost close to $1000. [8] In relation to other possible battery technologies, this is the least expensive option.

With university pricing, the USU team obtained a new 120 V 550 Ah AGM battery pack for $500. This is in contrast to approximately $3000 for a NiMH system, and $8000-$10000 for a Li-Poly system. For this year, the better technologies were simply out of range in terms of cost (and, consequently, practicality).

The cost of battery chargers, contactors, throttle potentiometers, and other related high voltage components is close to another $1000. Clearly, the price of electric vehicle parts is what leads the electric snowmobile to cost more than its internal combustion equivalents. However, as with any new technology, an increase in market demand will lead the way to lower prices.

Noise

The electric components of the sled are not significant contributors to audible noise.

Other Factors

Acceleration

Top performance in the acceleration event requires different characteristics than the endurance event. Since the 16 km (10 mile) range was the primary concern, the electrical approach to boost performance was to make small adjustments to the sled. The controller for the sled utilizes potentiometer screws to govern acceleration performance and maximum current output. For endurance, both voltage and current are fully governed. The possibility of making these potentiometers adjustable during sled operation was investigated. Having these potentiometers be real-time adjustable by the rider would make it so one could choose between a performance profile and an endurance profile.

Cold Start

The main consideration for a cold start test on an electric snowmobile is the performance from the batteries. From the manufacturer's specifications for the AGM batteries, the temperature operating range is from -15˚C (5˚F) to 40˚C (104˚F), with the battery capacity falling with temperature [2]. The anticipated overnight low temperature for Houghton, MI during the competition is -15˚C (10˚F), which is within the operating limits of the battery.

ELECTRICAL MODELING AND TESTING

Data Acquisition System

Data from snowmobile tests was gathered using a USB data acquisition system (DAQ). Since electric vehicle performance is characterized with voltage and current, these two variables were required to be measured accurately. Motor RPM was also a desired variable.

The DAQ consisted of transducers, analog to digital converters, and a sampling card with a USB interface. The tests also included gathering temperature data.

During testing, the electrical team observed that when the DAQ system was powered by the main battery pack, the output data was very noisy. This is because the controller varied the voltage and current running through the system, and this was seen in the supply to the sampling equipment. Also, as the main battery pack discharged, data acquisition capabilities were adversely affected. This problem was solved by utilizing two NiMH batteries on a separate circuit from the main high voltage battery pack. Using a separate battery for instrumentation nearly eliminated all noise in the readings. The DAQ was also utilized for dyno testing and drag testing of the snowmobile, as discussed in the Drive Train section above.

Series vs. Parallel Testing

The theory that a parallel field would require less current than a series one was tested by performing a field comparison test. Care was taken to replicate test variables as closely as possible. The electrical team used data acquisition equipment to measure current, motor rpm, and temperatures during testing.

The figure below shows the current drawn through the motor, versus rpm. The test shows that the motor is approximately 9-16% more efficient in parallel than it is in series. Therefore, the parallel motor wiring scheme was selected as the most efficient solution to increasing snowmobile range.

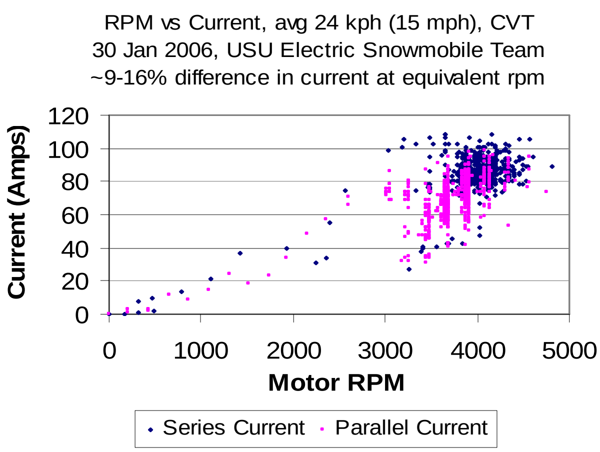

FIGURE 12: CURRENT DRAW AS A FUNCTION OF MOTOR SPEED IN SERIES VS. PARALLEL TESTING.

The grouping behavior of the data in Figure 12 is due to the resolution of the RPM sensing system used.

CHASSIS DESIGN

PERFORMANCE CONSIDERATIONS

Range

The chassis, track, and suspension were designed to require as little energy as possible. Track tension was reduced to the lowest acceptable level, and the suspension was re-designed to reflect a relatively low speed and flat terrain riding profile. Weight was also reduced wherever possible.

Draw Bar Pull Test

The existing snowmobile chassis used already had a towing connection. This hitch system was analyzed for capability to tow 630 kg (1500 lb), and was found to be acceptable. No modifications were made.

Cost

Several ideas for how to meet the performance demands of a much-heavier electric snowmobile were possible. The most attractive in terms of cost was to modify the existing suspension. Other chassis modifications were made with minimizing cost in mind.

Noise

In an electric snowmobile, the main source of noise is mechanical, and the great majority of this noise is from the track. The stock track was compared to other “quiet” options on the market, and was found to be acceptable in terms of quiet performance, especially in light of additional costs. Track tension was optimized at a balance in-between low tension and noise generation. The sprung components of the suspension are relatively silent.

Other Factors

Acceleration

The track and suspension characteristics were designed to deliver maximum performance in the acceleration event.

Suspension Displacement and Loading

The present weight characteristics of an electric snowmobile are much heavier than an internal combustion snowmobile, and the suspension had to be modified to accommodate the additional weight. This extra loading also required modification to achieve the required 15.24 cm (6 in) of travel. The base snowmobile weight of 386 kg (850 lb) is equivalent to having two extra riders on a stock snowmobile chassis, therefore analysis was performed to ensure that the suspension would be able to handle the extra loading. The vast majority of this extra loading was over the rear suspension, so full analysis was only performed in this area. The rear suspension was redesigned to better support the extra load, and to improve response characteristics.

Subjective Handling

The placement of batteries underneath a custom seat also yielded a higher center of gravity and ride height. Both of these factors required the suspension and steering systems to be modified in order to feel more like a “stock” snowmobile. A higher performance ski design was incorporated to help enhance steering of the heavier design.

Rider Comfort

The heavier weight characteristics and higher ride height required the suspension and steering to be modified. Particular to this event, the rear suspension geometry was redesigned to work more in conjunction with the front suspension, and also to support the weight of the battery pack and rider.

Battery Box

All of the batteries are housed within a single battery box that also serves as the seat structure. Previous versions of this electric snowmobile have utilized a more distributed battery placement configuration, which is more desirable for weight distribution and ride performance. This single box design was chosen for simplicity and safety. The suspension was redesigned to reflect this loading. The battery box is sealed and vented, and the batteries are securely held on all sides by insulating foam, with straps and foam across the top. An AGM battery contains very little liquid, therefore an acid spill in event of an accident is minimal. The overall design of the chassis is such that any risk of high voltage contact is minimized.

Handle Bars

The handle bars needed to be raised to make the rider more comfortable and to aid in the control of the sled. A spacer was designed and installed to provide an acceptable level for the handle bars in relation to the seat level.

Hood

The two center vent banks in the hood were blanked off to reduce the amount of air forced into the motor compartment. This is done to help prevent introduction of moisture into the electrical components. It also helps keep electrical components above their minimum operating temperature. Some ventilation holes are left open to help ensure that the motor can cool itself sufficiently.

Strength

The rules of the Clean Snowmobile Challenge state that the front bumper must be strong enough to hold the weight of the snowmobile when suspended in mid air. This requirement was taken literally, and the front bumper was analyzed and found to be barely strong enough to support the full weight of the snowmobile. The bumper was modified to meet this strength requirement. All other modifications to the chassis were made with strength in mind.

CHASSIS MODELING AND TESTING

Front Bumper

Calculations were made on the tensile strength of the steel structure used in the front bumper. The calculations showed that they would not fail in tension. The aluminum rivets that connect the webbing to the bulk head were analyzed for shearing, and it was found that they would fail in shear. These rivets were replaced with steel bolts. The Mathcad analysis used for this decision is given below:

Front bumper calculations

The front bumper material properties from www.matweb.com:

material	Tensile Yield Strength	Shear Yield point
Steel (1030)	$T_s := 179 \cdot 10^6 \mathrm{Pa}$	$S_s := .5 \cdot T_s$
Aluminum (1100)	$T_a := 34 \cdot 10^6 \mathrm{Pa}$	$S_a := .5 \cdot T_a$

The area of the smallest cross section of steel webbing is analyzed as follows:

The area of the web is: $A_w := 0.375\mathrm{in}^2$

The load for yield is: $\mathrm{Yeild}_w := A_w \cdot T_s$ $\quad \mathrm{Yeild}_w = 4.331 \times 10^4\ \mathrm{N}$

The rivets are analyzed in shear as follows:

The total cross sectional area of the 3/16" rivet is: $A_r := .028\mathrm{in}^2$

Yield loads in each rivet:

Aluminum: $\mathrm{Yeild}_{ra} := A_r \cdot S_a$ $\quad \mathrm{Yeild}_{ra} = 307.1\ \mathrm{N}$

Steel: $\mathrm{Yeild}_{rs} := A_r \cdot S_s$ $\quad \mathrm{Yeild}_{rs} = 1616.77\ \mathrm{N}$

There are four rivets on each side of the bulk head, so the shear load for yielding on each side and total shear load for yielding is:

Shear for one side :

Aluminum: $S_{ay1} := 4 \cdot \mathrm{Yeild}_{ra}$ $\quad S_{ay1} = 1.228 \times 10^3\ \mathrm{N}$

Steel: $S_{sy1} := 4 \cdot \mathrm{Yeild}_{rs}$ $\quad S_{sy1} = 6.467 \times 10^3\ \mathrm{N}$

Total shear :

Aluminum: $S_{ayt} := 8 \cdot \mathrm{Yeild}_{ra}$ $\quad S_{ayt} = 2.457 \times 10^3\ \mathrm{N}$

Steel: $S_{syt} := 8 \cdot \mathrm{Yeild}_{rs}$ $\quad S_{syt} = 1.293 \times 10^4\ \mathrm{N}$

Force of Sled: $F_s := 4000\mathrm{N}$ (900 lb snowmobile)

Safety Factors: $SF_{al} := \dfrac{S_{ayt}}{F_s}$ $\quad \boxed{SF_{al} = 0.614}$ aluminum

$SF_{st} := \dfrac{S_{syt}}{F_s}$ $\quad \boxed{SF_{st} = 3.234}$ steel

FIGURE 13: MATHCAD ANALYSIS OF FRONT BUMPER STRENGTH (MATERIAL PROPERTIES FROM [9], EQUATIONS FROM [10]).

Figure 13 is also included to serve as a typical example of how engineering calculations were performed.

Front Suspension Design

In the initial electric snowmobile configuration, several batteries were located in close proximity to the front suspension. This extra weight prevented the snowmobile from exhibiting the required 15.34 cm (6 in) of travel. An analysis model (using Mathcad) was built to find the requirements of the system, and a new required spring constant was calculated. However, the battery configuration was changed, and significant weight was transferred towards the rear of the snowmobile. The model then revealed that the stock springs would give the required amount of travel. In total, no change was made to the front suspension. Performance was found to be best if the springs were adjusted to their maximum stock stiffness, and this design has been implemented.

Rear Suspension Design

The rear suspension was re-designed and analyzed due to extra loading, weight, and track tension issues present in the electric snowmobile. Full analysis was performed to ensure that they design would perform as expected, and also be safe.

Suspension Change and Analysis

The suspension with the factory setup did not perform satisfactorily with the amount of weight that was on the sled, primarily due to the batteries. The original design allowed the front and back arms to move independently, which led to rough ride characteristics. The design was changed to allow both the front and the rear springs to work in tandem to supply the maximum possible force to the chassis in order to sustain the weight imposed upon it. This change also improves ride for the passenger. The suspension is designed as a four bar linkage with equal length arms and identical angles, to keep the rails at the same angle at all times. The suspension design is shown below:

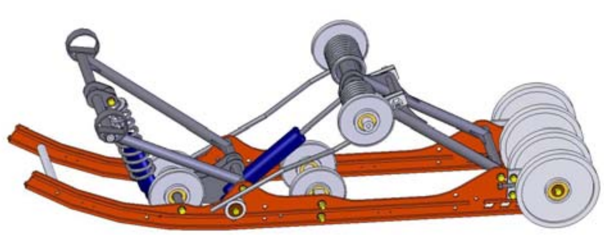

FIGURE 14: SOLID MODEL OF MODIFIED REAR SUSPENSION DESIGN.

Advantages

The first advantage of the parallelogram type suspension is that the front and back springs work together at the same time to support the chassis. If the front of the suspension encounters a bump it will compress the whole suspension. This same principle applies in reverse (see figure below).

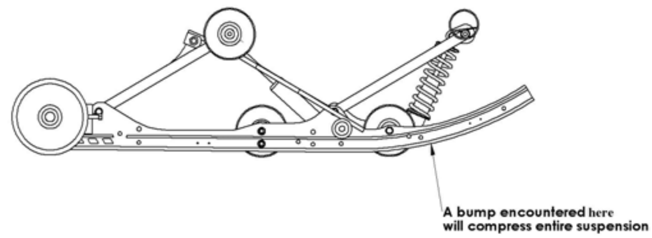

FIGURE 15: SIDE VIEW OF MODIFIED REAR SUSPENSION. A BUMP ENCOUNTERED AT THE FRONT OF THE ASSEMBLY WILL COMPRESS THE ENTIRE SUSPENSION.

This type of suspension also helps to smooth out the ride. Once the suspension encounters a bump, the suspension compresses equally across it's length. Thus, only the initial part of the bump is felt as the suspension then stays level on top of the feature. This is on contrast to the bump being transferred through the entire suspension as is the case with independent front and rear arms.

Analysis

The maximum forces from the springs were used to analyze the stresses in the suspension components. The front spring constant is 26 N/mm (150 lbf/in). The stress analysis of the front arm is given below. The loads are shown as pink arrows, and the constraints as green arrows.

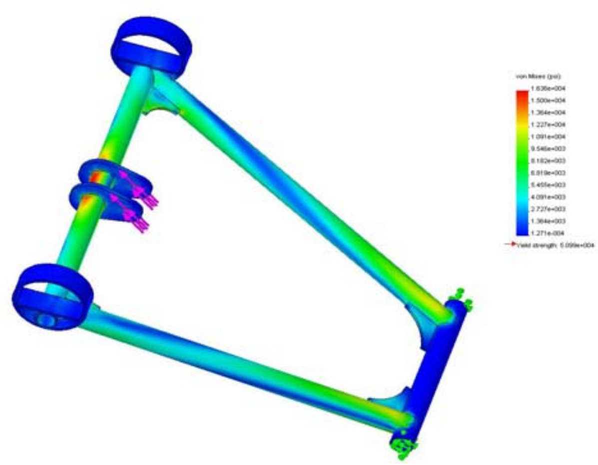

FIGURE 16: ANALYSIS OF STRESS LOADING IN FRONT SUSPENSION ARM, TOP LOADING.

The stresses are conservative because this analysis does not include the aluminum shaft that runs through the top part of the arm. This loading yields a safety factor of 3.1.

Another possible loading is from the side, such as if the snowmobile happens to land on the side of the sled, or if it gets tipped over. The load is distributed between the front and the back arms. The total side load on the suspension is 1.95 kN (440 lbf) from the batteries, 667 N (150 lbf) from the rider, and an extra 930 N (210 lbf) to account for any impact on the system. Thus, the total load used for the front arm is 3.78 kN (850 lbf). The analysis of the front arms in this loading follows:

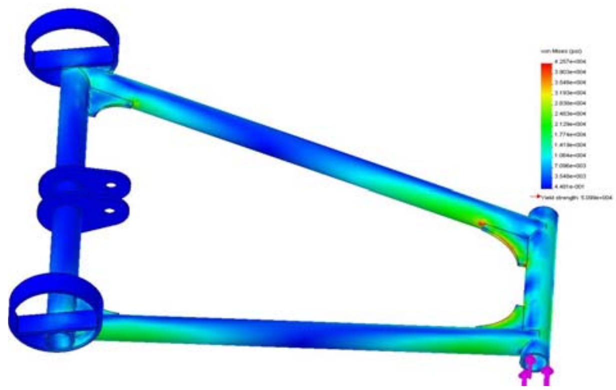

FIGURE 17: ANALYSIS OF STRESS LOADING IN FRONT SUSPENSION, SIDE LOADING.

As seen in Figure 17, the maximum stresses are near the welds of the arm. With this side loading, the front arm safety factor is 1.2.

The front lower bracket that supports the bottom of both shocks is shown below. A force of 18 kN (410 lbf) was used for the front spring and damper, and 2.7 kN (600 lbf) was used for the rear damper (to allow for quick compression of the system). The analysis of this loading follows:

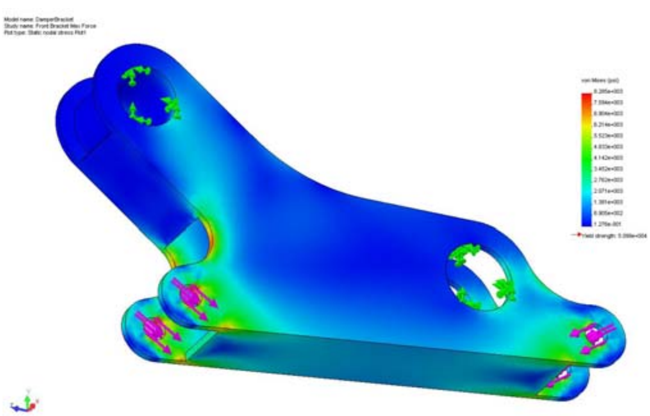

FIGURE 18: ANALYSIS OF STRESS LOADING IN SHOCK BRACKET.

This loading gives a safety factor of 6.2 against yielding.

The spring load on the rear arm is due to a torsional spring. The torsion spring constant is calculated to be 2 N-m/deg (1.5 ft-lbf/deg). The worst case scenario for stress on the rear arm is when the suspension is in complete compression. The spring has an initial rotation of 90 degrees, plus an additional rotation of 45 degrees at full compression. This gives a torque of 274.5 N-m (202.5 ft-lbf) to the rear arm. The length of the spring arm on the short side is 9.53 cm (3.75 in). This gives a load of 2.9 kN (648 lbf) to the rear arm. The stress analysis for this load follows:

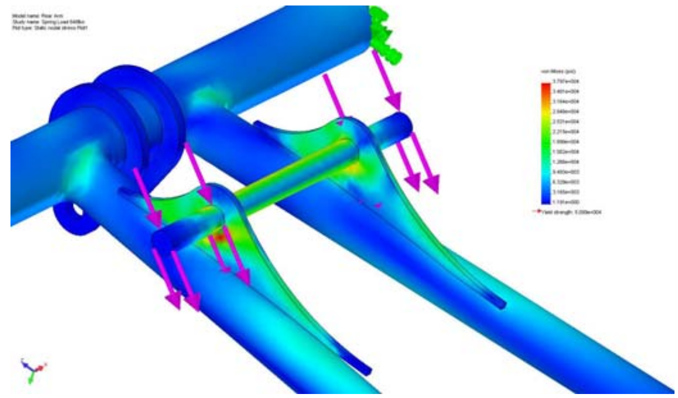

FIGURE 19: ANALYSIS OF STRESS LOADING IN REAR SUSPENSION ARM, SUSPENSION COMPRESSION.

With this loading it gives the rear arm a safety factor of 1.3 against yielding.

The side loading explained above is distributed between the front and the rear arm. The side load for the rear arm is measured to be 2.2 kN (500 lbf). The stress distribution for this side loading follows.

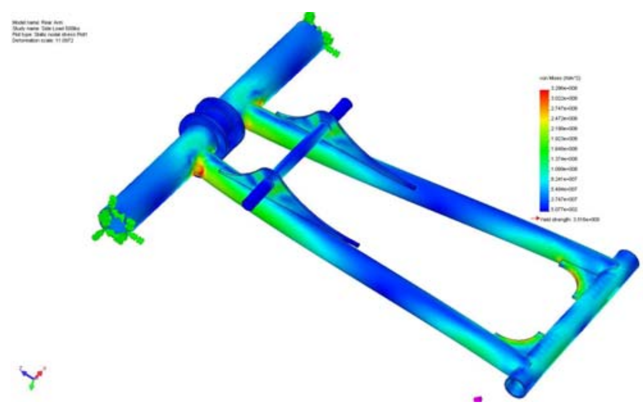

FIGURE 20: ANALYSIS OF STRESS IN REAR SUSPENSION ARM IN SIDE LOADING.

This gives a safety factor of 1.1 against yielding. This amount of side loading is not a common occurrence. The suspension was designed for trail riding: flat land with a few bumps. The suspension will not handle large jumps or extreme types of riding.

CONCLUSION

Utah State University engineering students have successfully designed, built, and tested a fully functional electric snowmobile. This snowmobile has been designed to successfully compete in all aspects of the SAE Clean Snowmobile Challenge. Efforts have been made towards cost effectiveness, safety, ease of use, practicality, and fun. Engineering analysis has been performed in all critical areas to ensure that the machine will be safe and durable. Theoretical models have been constructed to predict performance, and these models have been field tested and verified. The USU electric snowmobile is remarkably clean, exceptionally quiet, and performs nicely in range, utility, and acceleration.

The Utah State University Electric Snowmobile Team looks forward to building these electric snowmobiles for many years to come, and anticipates that improvements in energy storage technology will eventually open up a way for these machines to become a practical solution for all snowmobile users.

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Gold Level ($1000+):

- Snowlectric
- Utah State University
- National Science Foundation
- Dr. and Mrs. Byard Wood

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REFERENCES

1. http://www.evparts.com/shopping/index.php?id=536 (site accessed 1 Mar 2006)
2. Univeral Power Group, UB12550 AGM Battery data sheet. http://www.universalpowergroup.com/specs/D5825.pdf
3. Motion Industries, authorized Gates Polychain GT distributor. 390 N 1000 W, Logan, UT 84321 - 8295 (435) 753-7310
4. Gates Polychain GT Belt Drives Catalog. Gates publication 17595.
5. Curtis PMC Motor Controllers 1209B/1221B/1221C/ 1231C Manual, page 9. Curtis PMC. 6591 Sierra Lane, Dublin, CA 94568. (925) 828-5001.
6. http://www.evparts.com/shopping/product_details.php?id=536&product_id=1120 (site accessed 1 Mar 2006
7. http://www.evparts.com/shopping/product_details.php?id=277&product_id=1251 (site accessed 1 Mar 2006)
8. http://www.apexbattery.com/ub-ub12550-12v-55ah-sealed-lead-acid-battery.html (site accessed 1 Mar 2006)
9. www.matweb.com (site accessed 1 Feb 2006)
10. Norton, Robert L., Machine Design: An Integrated Approach, Second Edition, Prentice Hall Inc, Upper Saddle River, NJ, 2000.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

AC: Alternating Current
AGM: Absorbed Glass Mat
DC: Direct Current
CSC: Clean Snowmobile Challenge
CVT: Continuously Variable Transmission
IC: Internal Combustion
Li-Poly: Lithium Polymer
NiMH: Nickel Metal Hydride
SAE: Society of Automotive Engineers.
USU: Utah State University