Development of an Electric Conversion for Modern Snowmobiles

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ABSTRACT

The 2013 Alternative Fuel Vehicle Team at the South Dakota School of Mines & Technology is focusing on improving the 2012 electric snowmobile in several ways. Primary improvements include changes to the Electro-Mechanical Continuously Variable Transmission (EM-CVT), upgraded electrical safety features and improved battery box design. The EM-CVT in past years has utilized two linear actuators acting simultaneously on the primary sheaves. This year, the EM-CVT is redesigned to utilize one actuator and a lever arm. Upgraded electrical safety features include a galvanically isolated DC-DC converter, an isolated low voltage system, and a master kill switch at the rear of the snowmobile. While the battery box on the rear of the snowmobile holds to the 2012 design, the battery box under the hood is modified to accommodate the placement of the single linear actuator.

INTRODUCTION

The Society of Automotive Engineers (SAE) sponsors the Clean Snowmobile Challenge (CSC) as part of their Collegiate Design Series. When first introduced, the goal of the CSC was to modify existing snowmobiles to reduce noise and emissions. Eventually the competition was split into two categories: Internal Combustion and Zero Emissions. The Alternative Fuel Vehicle team (AFV) at the South Dakota School of Mines & Technology (SDSM&T) chooses to compete in the Zero Emissions category. The goal of the Zero Emissions category is to produce a snowmobile that is 100% electric. This snowmobile is then put to use at Summit Station, Greenland, to transport researchers. Since the "Greenland Ice Cap acts like a sponge, absorbing atmospheric chemicals produced naturally, or via anthropogenic activities," [3] and many of the collection sites are remote, accessible only by foot, a zero emissions solution is necessary for transportation of equipment and personnel.

DESIGN OVERVIEW

This year the SDSM&T AFV team chooses to focus on making the 2012 design functional while maintaining the CSC goals. The team's goals which correspond with CSC goals are as follows:

- Range – 15 miles or greater
- Handling – rides like a stock snowmobile
- Noise – less than 65dB
- Towing – up to 600lb_f
- Weight – 750lb or less
- Maintenance – easy to work on

To meet these goals the team addressed issues of rules compliance and completed calculations to support the designs.

Electrical Systems

This year's electric system has been updated for rule compliance. Previous failures of rule compliance have been: an un-isolated low voltage system, a insulating monitoring device (IMD) that was not rated for automotive use, no maintenance plug, and a non-functional battery monitoring system (BMS). These rules are in place for safety reasons on behalf of those who work on and operate the snowmobile. Because the snowmobile runs at 80V and a continuous 100A, safety is of utmost importance.

In addition to rule compliance, care was taken to continue the team philosophy of an easy to maintain system. There are two battery boxes that are designed for easy removability, all wires are clearly labeled and access to many of the systems is not restricted.

Motor

In 2009, an AC-20 motor was purchased as part of a package containing the motor, a 1238 Curtis Motor Controller and a Spyglass 840 display that can be seen in Figure 1. The AC-20 is an induction alternating current (AC) motor that is powered by a three-phase AC voltage provided by the motor controller. This motor weighs approximately 48lbs, is about seven inches in diameter and fourteen inches long. It is rated for a continuous 10HP and has a peak of 50HP. [6] In the Appendix, testing data for horsepower and torque curves based on gear ratios and motor RPM can be seen. From these graphs, the peak efficiency is shown to be achieved at 1900 RPM's.

Figure 1: AC20 Motor Package - AC20 Motor, Curtis 1238 Motor Controller, and Spyglass 840 Display

Motor Controller

The Curtis 1238 motor controller inverts the direct current potential from the battery packs into the three-phase AC potential that drives the motor. This controller has a voltage rating of 80-96VDC and current rating of 550-650 Amps, making it ideal for the electric conversion. The Curtis 1238 also provides a digital output to the Spyglass display of the motor revolutions per minutes (RPM), motor temperature and the voltage level as well as current output. Additionally, a 1311 Curtis Programmer was provided with the purchase of the package and can be used to adjust the parameters for controlling the motor's output so that different operating modes can be selected depending on the needs of the operator. For example, the speed or torque range can be adjusted for different power output curves.

Displays

The dashboard area contains two displays viewable by the snowmobile operator. First, the stock display provides the instantaneous speed of the snowmobile via the stock speed sensor and display system. It was decided to keep the stock display and speed system because of their ease of use and the avoidance of accumulating additional costs by buying a new system.

The secondary display, the Spyglass 840, displays the motor RPM, motor temperature, and the system voltage received from the motor controller. Between these two displays, all the information needed to safely operate the snowmobile can be easily seen.

Microcontroller

This microcontroller system is used to control the EM-CVT and has two components, a Seeeduino Mega and an actuator controller. The Seeeduino Mega is used to read in the RPM of the motor through a Hall Effect sensor, monitor the actuator controller and tell the actuator controller when to move the actuator position based on the motor RPM. The actuator controller commands the position of the actuator arm.

This design currently provides the best performance for the EM-CVT. Fine tuning is easily accomplished because no changes to the physical EM-CVT are necessary, as everything is controlled by the Seeeduino. The Seeeduino has shift points programmed in to maximize the efficiency of the EM-CVT. The shift points are determined by the motor's torque curve. As seen in the Appendix, Figure A1, the peak efficiency for torque and horsepower is achieved at 1900 RPMs and so the most efficient gear ratio is necessary to transmit the most torque to the system. From the calculations that can be seen in the Appendix, Table A2, a gear ratio of 3.5:1 is the most efficient at 1900RPMs to transmit the torque to the drive train while also maintaining a reasonable speed.

Batteries

Batteries for electric or hybrid vehicles exist in many chemical compositions. The most common are: Lead Acid (PB), Nickel-Metal Hydride (NiMH), and a wide range of Lithium based batteries [2]. For high power, small range applications, PB batteries are most commonly used. Lithium based batteries are most often used for electric vehicles because of their high energy density. Lithium-Ion (Li-ion) batteries are commonly used but can be very dangerous. The damage of these batteries (via puncture, rapid heating or impact) has a high potential to result in an explosion due to the leak of hydrogen gas [5]. Lithium Iron Phosphate (LiFe-Po4) batteries are a safer source of energy because they are more stable and will not leak hydrogen or explode if damaged. Due to their stability, the SDSM&T AFV team chooses to use the LiFe-Po4 batteries. Another desirable feature of LiFe-Po4 batteries is that they will hold a steady voltage until the end of the life cycle (approximately 2000 cycles), even in extreme temperatures. One disadvantage of these batteries is that they are not a deep cycle battery. They can only discharge to 2.0V before damage occurs. [4]

In 2009, the SDSM&T AFV team purchased Tenergy 3.2V, 100A-h, LiFe-Po4 batteries for use in the 2010 competition. These batteries remain in use today because of their stability and team funding. There are a total of 25 batteries on the snowmobile, separated into two packs. The front box (housed under the hood) holds eight batteries and the back box (housed above the tunnel) holds seventeen batteries. They are combined in series to produce 80V and 100A-h, meeting the 8 kW-h energy limit set forth in the rules.

Battery Monitoring System

The battery monitoring system (BMS) in use is the Lithiumate Pro, manufactured by Elithion. The BMS is comprised of cell boards that are connected between the positive and negative terminals of each battery and the master controller. This BMS provides many important safety features, such as voltage monitoring, temperature monitoring, cell balancing and the ability to isolate a battery box in the event of a major failure. Additional features are off the shelf plug-and-play, commercial grade quality, and cell state reporting when connected to a computer. [1] At the start of this year, it was discovered that the BMS was not functioning and the communication harness was incorrectly wired. The BMS main unit was sent in for repairs and now functions correctly. The communication harness was rewired correctly; It now communicates with the computer and will shut down the system when an unsafe condition occurs.

Charging System

A Zivan NG-1 charger was selected as the charger of choice because the programmed charging curve of the Zivan matches well with the charging cycle of the LiFe-Po4 batteries. The LiFe-Po4 batteries have a deep charging cycle, so the charger was programmed by the United States' Zivan distributor, Elcon, for the 80V and 100A-h system in use. The charger can be powered by 120V/60Hz or 240V/50Hz outlets, making it usable in the United States, Canada and Europe.

Low Voltage System

The low voltage system has two main functions. The primary function is the operation and power of the safety systems, and the secondary function is the operation of the CVT and actuator system. The low voltage supply is a LiFe-PO4 AA Portable Power Corp. 12.8 Volt battery with 20Ah rating. The safety system consists of four main battery isolation relays (BIRs) to cut power to the high current path of the tractive system. These BIRs are operated by the shutdown circuit which consists of the key switch, shutdown button, tether, IMD, and BMS. There are indicator lights on the snowmobile dashboard to show when the vehicle is ready to drive, when the tractive system is active, and to indicate whether the BMS or IMD is activating the shutdown circuit. When the IMD or BMS detects a fault in the system, a pushbutton under the hood will need to be pushed to reset the system. This eliminates the possibility of the system being reset while the driver is in operating position.

The low voltage system also powers on the linear actuator and adjusts the EM-CVT's effective gear ratio depending on the desired RPM efficiency. A Hall Effect sensor and magnet are used to detect the instantaneous RPM value. These variables are processed by the Seeeduino Mega, which controls the actuator's position using a Pololu MD03A DC switch. All of the GLV wires are fused using automotive blade fuses rated at 32VDC and the appropriate current ratings for the systems they protect.

High Voltage System

The high voltage system consists of 25 Tenergy 3.2V, 100A-h cells to create an 80VDC system. These are wired using 3/0AWG, 1/0AWG and 2AWG wire in the high current path. The Curtis 1238 motor controller controls the AC-20 induction motor which supplies torque to the CVT and track of the sled. A Cooper Bussmann 250A fuse rated at 150VDC is used in each battery container to protect the wiring and other electrical components. An Elithion Lithiumate Pro is used to monitor the cells' temperatures, voltages, and discharging/charging currents to protect the batteries. The IMD is a Bender IR155-3204 and monitors the insulation resistance between the tractive system and chassis ground. This is set to trip at 500Ohm/Volt as per SAE rules [3]. The batteries are charged using a Zivan NG1 charger that was customized for the snowmobile's specific cell chemistry and voltage. The BMS also monitors the cells' conditions during charging to ensure no cells overcharge or overheat while charging. A tractive system master switch is also implemented at the rear of the sled as well as measuring points for additional safety and inspection purposes.

Some connections to the high voltage system are used for pre-charging, IMD sensing, discharging the tractive system, and charging the batteries. These connections are fused where they are connected to the tractive system and contained inside insulating conduit to prevent damage to the wires or system components. IT was also discovered that the Curtis 1238 does not provide isolation from the pre-charge lead to the rest of its connections so the display wires and final contactor control wires must also be insulated from the GLV wiring.

Mechanical Systems

With the conversion of a stock internal combustion (IC) snowmobile to a full electric snowmobile, many parts need to be removed, changed or added for safety and mounting purposes. All parts dealing with the IC engine are removed and replaced with the necessary mounting fixtures for the new conversion parts. In addition, battery boxes and other containers must be manufactured to fit in the constraints of the chassis while maintaining a high level of safety.

Battery Box Design

As the energy storage containers (battery boxes) contain a large amount of energy potential, safety is the key factor in the design of the boxes. They are designed to be electrically insulated (to prevent electrical arcs), mechanically robust (to withstand 20g of force in the horizontal plane and 10g of force in the vertical plane), watertight (to prevent electrical shorts), fireproof (to contain any fires that may occur due to failures) and transparent on at least one outer face (to provide easy visual inspection).

The back battery box mounts underneath the operator in a tunnel that provides extra protection to the battery box. This box has 17 of the 25 LiFePO4 battery cells, two contactors and the master kill switch. This container is manufactured from 5052 aluminum and Lexan. These materials are mechanically robust to withstand the applied forces and are fire retardant. In Figure 2 a SolidWorks finite element analysis was performed and small deflections can be seen.

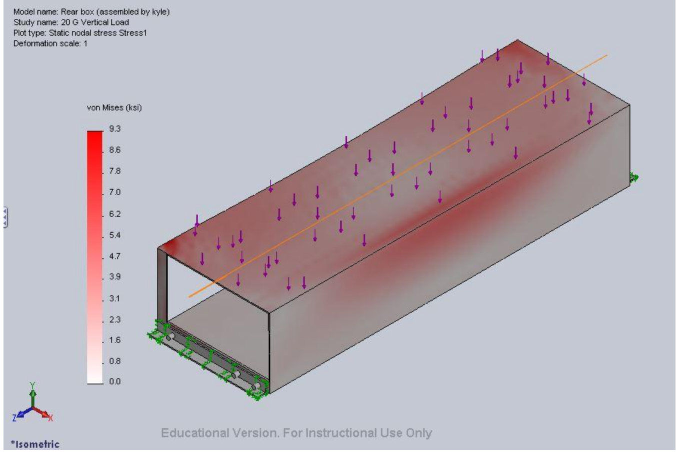


Figure 2: Back Battery Box Finite Element Analysis

The front battery box mounts beneath the hood, above the motor and beside the linear actuator. This box has the remaining 8 of 25 LiFePO4 cells and two contactors. This box is made of aluminum and Lexan for the same reasons as stated for the back battery box. The SolidWorks finite element analysis performed on this battery box also produced small deflections, as seen in Figure 3.

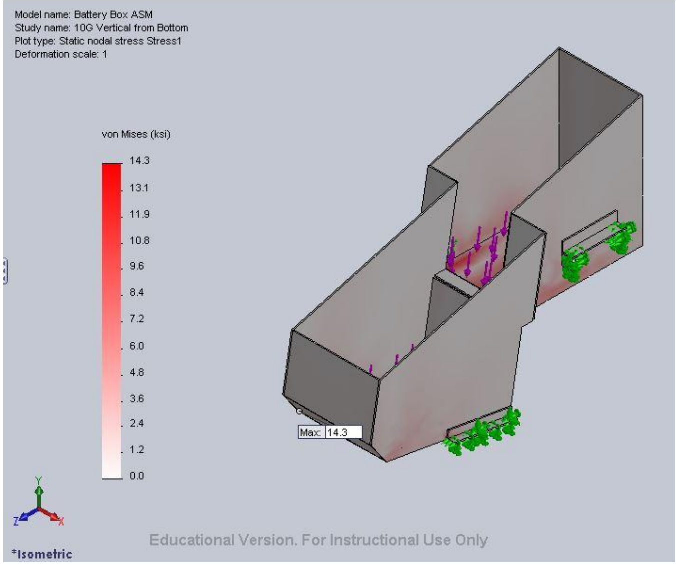


Figure 3: Front Battery Box Finite Element Analysis

Headlight Box Design

The headlight box contains several important components to the functionality of the snowmobile. It houses the headlight, Seeeduino Mega, low voltage system fuses and the DC switch. For durability and ease of visual inspection, it is made of Lexan and aluminum angle. Figure 4 gives a rough model of the box.

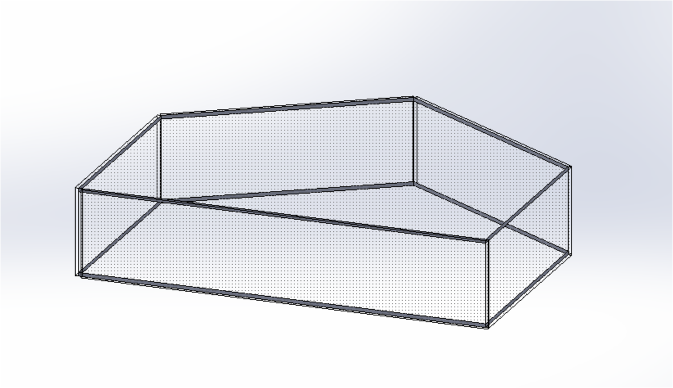


Figure 4: Headlight Box Design

Mounting Systems

Space is at a premium in the front of the snowmobile, where the majority of the components are housed. This creates a challenge for designing robust, compact, multi-purpose mounting systems. The components that need mounting systems are the AC20 motor, the linear actuator, the front battery box, the DC-DC converter and the headlight box containing the Seeeduino Mega microcontroller.

The motor mount is machined from a ½ inch, 7075 aluminum plate and is bolted to the chassis using six grade eight 3/8 inch bolts. This mount also provides support for the linear actuator, the front battery box and the displaced support.

Supporting the rest of the front battery box is 1” aluminum tubing that has welded tabs. The battery box is then bolted to the tabs, providing several mounting points that distribute the forces from the battery box.

The headlight box is mounted in the same area a standard headlight assembly would be in a stock snowmobile. It is secured with aluminum angle at the back and sits snugly fits where the standard headlight assembly would be.

Driveline Coupling

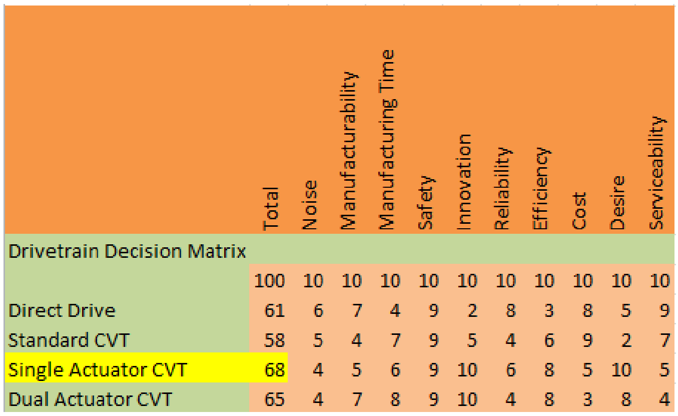
A coupling was manufactured to connect the motor to the Polaris CVT. This coupling, seen in Figure 5, must meet several requirements. It must have an interference fit (to allow high torque transfer), the Polaris driveshaft taper (to fit any Polaris CVT) and a 7/8 inch keyway (to connect to the motor shaft). Additionally, a sleeve was manufactured to fit over the shaft and retain the key. This sleeve is necessary due to the limited manufacturing capabilities of the team.

Figure 5: Motor to CVT Coupling

Drivetrain

There are many options available for the drive train of a snowmobile. Options such as direct drive, conventional CVT, and EM-CVT each have their disadvantages, advantages and challenges that need to be analyzed carefully before a final decision is made. A direct drive system is easy to implement and light but has only one gear ratio and creates efficiency losses. A rear drive is difficult to implement due to the amount of vibration caused by the interaction with the ground and the track. The design would have to be very robust to compensate for the reaction forces of the track system. A CVT is also easy to implement but it is heavy, and it does not utilize the instant torque provided by an electric motor. The EM-CVT in development by the team is challenging to implement due to space constraints but the efficiency gained from utilizing the instant torque is an advantage. The decision matrix, Table 1, shows the team decided that, even with the challenges, continuing the EM-CVT development is the best option.

Table 1: Drivetrain Decision Matrix



	Total	Noise	Manufacturability	Manufacturing Time	Safety	Innovation	Reliability	Efficiency	Cost	Desire	Serviceability
Drivetrain Decision Matrix											
	100	10	10	10	10	10	10	10	10	10	10
Direct Drive	61	6	7	4	9	2	8	3	8	5	9
Standard CVT	58	5	4	7	9	5	4	6	9	2	7
Single Actuator CVT	68	4	5	6	9	10	6	8	5	10	5
Dual Actuator CVT	65	4	7	8	9	10	4	8	3	8	4

Electro-Mechanical Continuously Variable Transmission

A standard CVT is designed to take advantage of torque at higher RPM’s, which makes it ideal for use with an IC engine. However, with the conversion to an electric motor, there is a near instant torque applied to the drivetrain at low RPM’s, which a standard CVT cannot fully utilize.

The original EM-CVT design incorporated two linear actuators and a push arm with a bearing inset, see Figure 6, instead of weights to control the position of the sheaves on the primary clutch. By controlling the outside sheaves’ position with the linear actuators, the appropriate gear ratio can be obtained to make full use of the torque applied at low RPM’s. The linear actuators were controlled by a Seeeduino Mega microcontroller, which read in motor RPM and actuator positions via Sensofoil. However, it was difficult to keep the actuators in sync due to manufacturing differences in the actuation mechanism and inaccuracies using the Sensofoil.

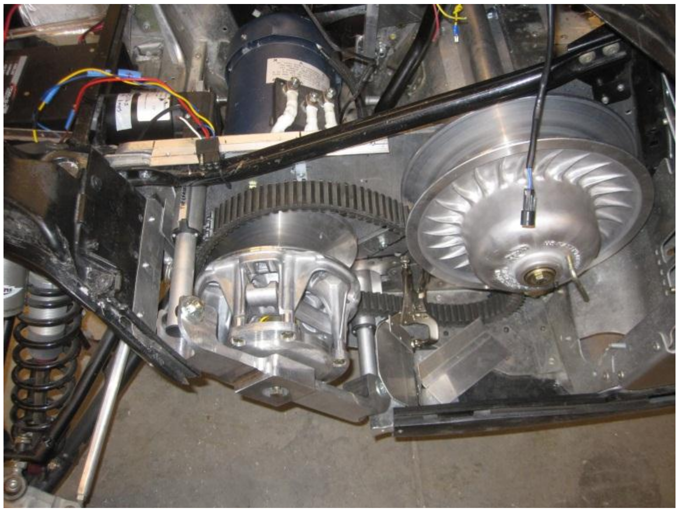


Figure 6: 2012 EM-CVT Design

To avoid the control issues of two actuators, this year's design utilize one linear actuator. Figure 7 shows the complete assembly of the EM-CVT while it is connected to the motor. The actuator is mounted above the motor and is connected to a class two lever arm that transfers the motion of the actuator to the CVT. Connected to the lever arm is the bearing housing that allows the CVT to spin independent to the lever arm. The linear actuator has a maximum axial force of 400lb_f, which is less than the previously accepted force of 800lb_f necessary to move the CVT. However, the lever arm magnifies the force using Equation 1 so that the maximum applied force is approximately 1000lb_f. Using the calculations shown in the Appendix, it is calculated that at peak efficiency, the EM-CVT produces the same speed as a direct drive at maximum RPM's. Additionally, the CVT will output 153ft-lbs of torque while a direct drive outputs 90ft-lbs. With these advantages, the EM-CVT has a 50mph increase at the high end and a 300ft-lbs torque gain at the low end.

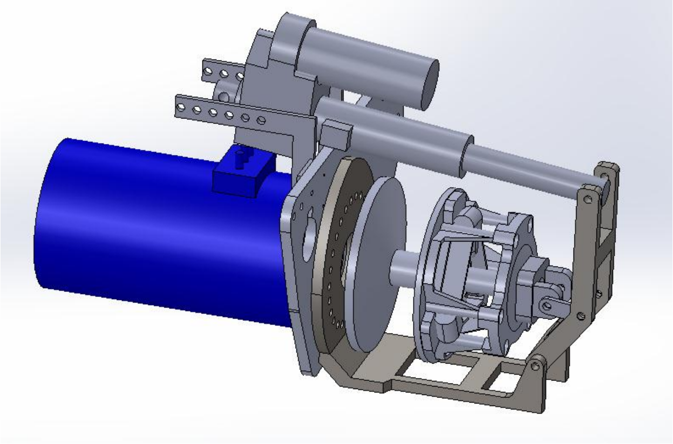


Figure 7: 2013 EM-CVT Design

$$F2 = F1 * \frac{L1}{L2} \qquad (1)$$

An additional challenge with this design is that the actuator interferes with the left side frame tube support. A finite element analysis of the original tube was done to determine where the stresses are concentrated with a 50lb_f from the front of the snowmobile and are shown in Figure 8. The decision to move the support is support by the finite element analysis done on a shortened column attached to the motor mount, as seen in Figure 9.

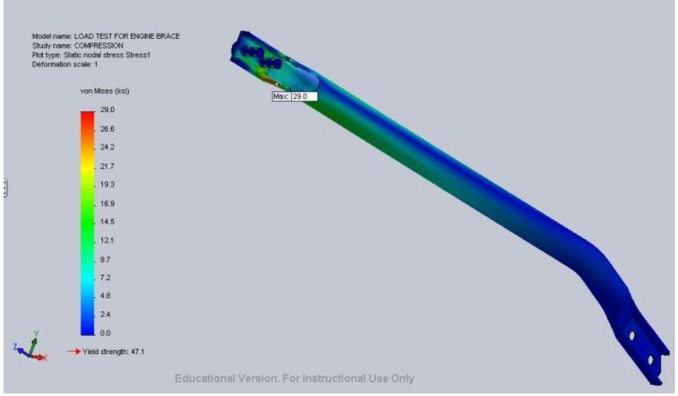


Figure 8: Stock Frame Support

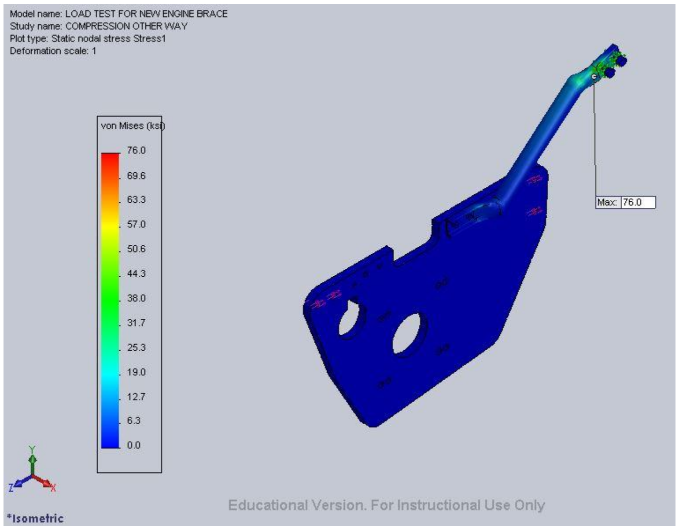


Figure 9: Modified Frame Support

SUMMARY

The 2013 electric snowmobile produced by the SDSM&T AFV team has many improvements and modifications over the 2012 snowmobile. Safety features such as a properly isolated low voltage system, and a working BMS and IMD have been designed implemented. A new EM-CVT was designed and forced change to the front battery box, creating a place for innovation.

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ACKNOWLEDGMENTS

The Alternative Fuel Vehicle team at the South Dakota School of Mines and Technology would like to thank its sponsors,

advisors and mentors. These businesses and people provide much needed resources, assistance and encouragement.

Sponsors: Polaris Industries, South Dakota School of Mines & Technology, CAMP, SolidWorks, Tenergy Battery Technologies, Thunderstruck Motors, Signs Plus+ Graphics, The National Science Foundation, Black Hills Powersports, Eric Simes, Summit Signs & Supply, Black Hills Bicycles, E&J Specialties, and The Athow Family.

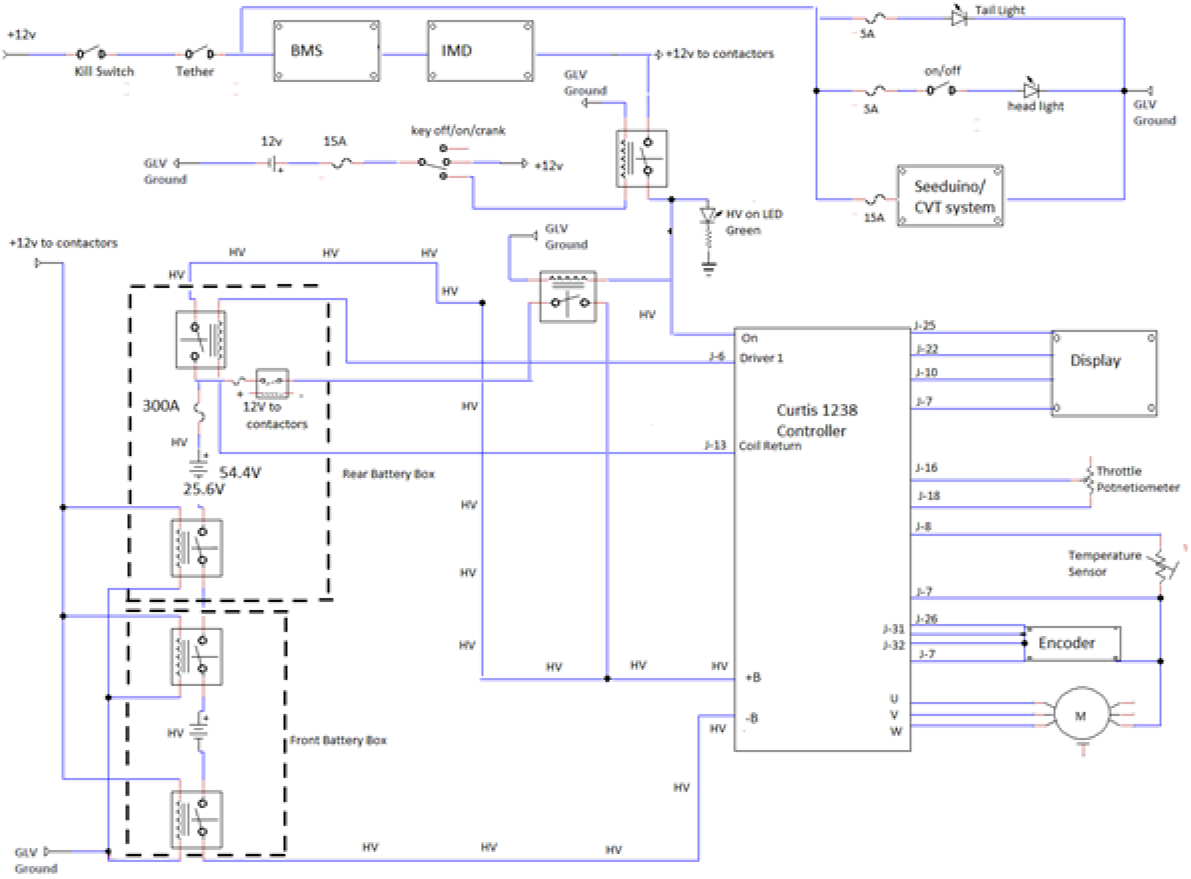
Advisors & Mentors: Fellow SDSM&T CAMP Teams, Dr. Daniel Dolan, Ralph Grahek, Dr. Marius Ellingson, Alycia Jensen and Kimberly Osberg.

DEFINITIONS/ABBREVIATIONS

AC	Alternating Current
AFV	Alternative Fuel Vehicle
BIRs	Battery Isolation Relays
BMS	battery monitoring system
CSC	Clean Snowmobile Challenge
EM-CVT	Electro-Mechanical Continuously Variable Transmission
IC	Internal Combustion
IMD	Insulation Monitoring Device
Li-ion	Lithium Ion
LiFe-Po4	Lithium Iron Phosphate
NiMH	Nickel-Metal Hydride
PB	Lead Acid
RPM	Revolutions Per Minute
SAE	Society of Automotive Engineers
SDSM&T	South Dakota School of Mines & Technology

APPENDIX

Complete Electrical Schematic



Calculations and Testing data for the motor and EM-CVT

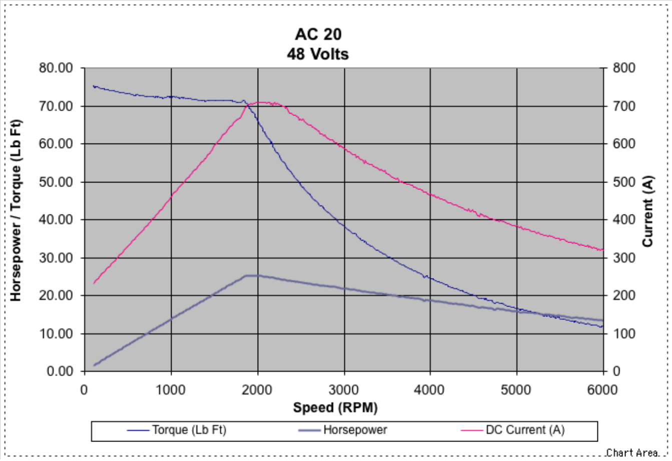
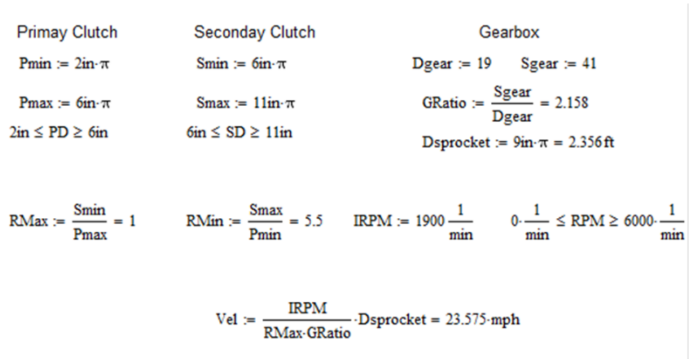


Figure A1: Calculated Torque, Horsepower and Current Curves for the AC20 Motor.



Primay Clutch

$Pmin := 2in \cdot \pi$

$Pmax := 6in \cdot \pi$

$2in \le PD \ge 6in$

Seconday Clutch

$Smin := 6in \cdot \pi$

$Smax := 11in \cdot \pi$

$6in \le SD \ge 11in$

Gearbox

$Dgear := 19 \quad Sgear := 41$

$GRatio := \frac{Sgear}{Dgear} = 2.158$

$Dsprocket := 9in \cdot \pi = 2.356 ft$

$RMax := \frac{Smin}{Pmax} = 1 \qquad RMin := \frac{Smax}{Pmin} = 5.5 \qquad IRPM := 1900 \frac{1}{min} \qquad 0 \cdot \frac{1}{min} \le RPM \ge 6000 \cdot \frac{1}{min}$

$$Vel := \frac{IRPM}{RMax \cdot GRatio} \cdot Dsprocket = 23.575 \cdot mph$$

Figure A2: Calculations for Velocity at Maximum Efficiency

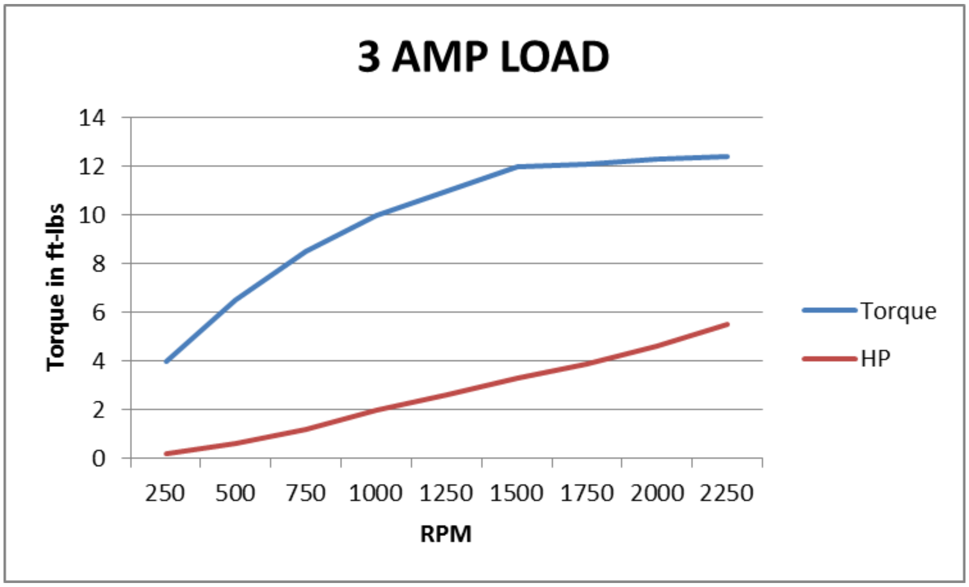


Figure A3: Recorded Values of RPM vs. Torque of the Motor with a 3A Load

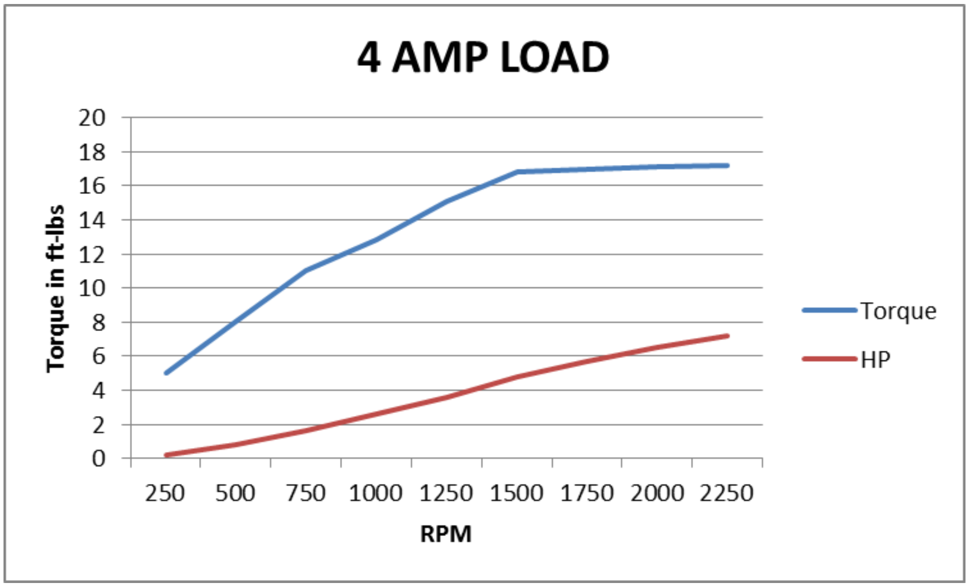
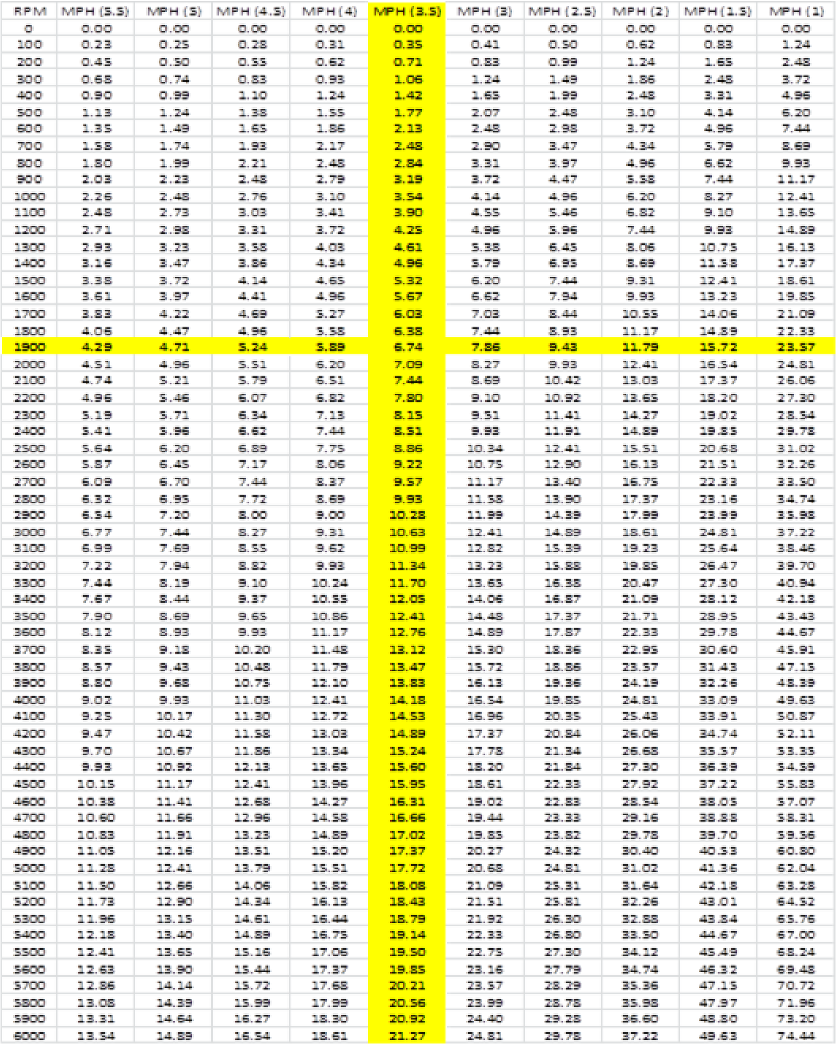


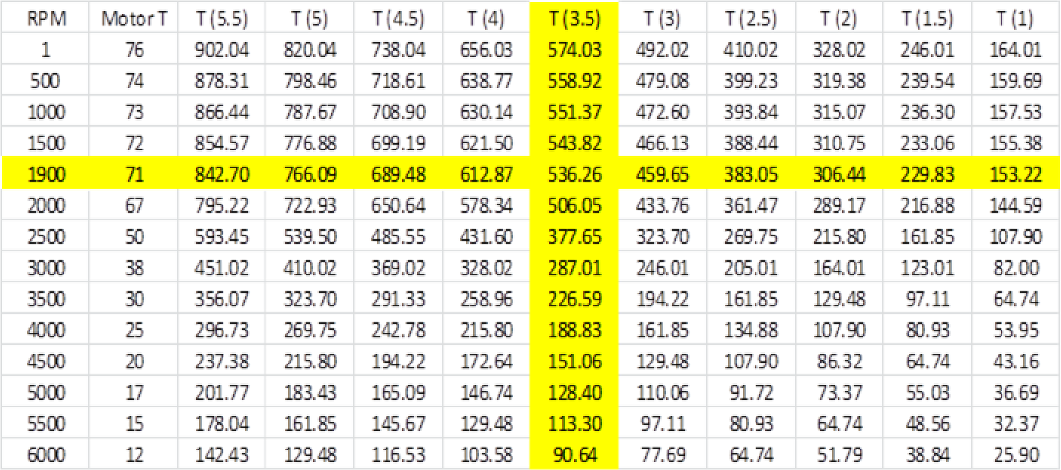
Figure A4: Recorded Values of RPM vs. Torque of the Motor with a 4A Load

Table A1: Calculations for MPH at Various Gear Ratios & RPM’s



RPM	MPH (5.5)	MPH (5)	MPH (4.5)	MPH (4)	MPH (3.5)	MPH (3)	MPH (2.5)	MPH (2)	MPH (1.5)	MPH (1)
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
100	0.23	0.25	0.28	0.31	0.35	0.41	0.50	0.62	0.83	1.24
200	0.45	0.50	0.55	0.62	0.71	0.83	0.99	1.24	1.65	2.48
300	0.68	0.74	0.83	0.93	1.06	1.24	1.49	1.86	2.48	3.72
400	0.90	0.99	1.10	1.24	1.42	1.65	1.99	2.48	3.31	4.96
500	1.13	1.24	1.38	1.55	1.77	2.07	2.48	3.10	4.14	6.20
600	1.35	1.49	1.65	1.86	2.13	2.48	2.98	3.72	4.96	7.44
700	1.58	1.74	1.93	2.17	2.48	2.90	3.47	4.34	5.79	8.69
800	1.80	1.99	2.21	2.48	2.84	3.31	3.97	4.96	6.62	9.93
900	2.03	2.23	2.48	2.79	3.19	3.72	4.47	5.58	7.44	11.17
1000	2.26	2.48	2.76	3.10	3.54	4.14	4.96	6.20	8.27	12.41
1100	2.48	2.73	3.03	3.41	3.90	4.55	5.46	6.82	9.10	13.65
1200	2.71	2.98	3.31	3.72	4.25	4.96	5.96	7.44	9.93	14.89
1300	2.93	3.23	3.58	4.03	4.61	5.38	6.45	8.06	10.75	16.13
1400	3.16	3.47	3.86	4.34	4.96	5.79	6.95	8.69	11.58	17.37
1500	3.38	3.72	4.14	4.65	5.32	6.20	7.44	9.31	12.41	18.61
1600	3.61	3.97	4.41	4.96	5.67	6.62	7.94	9.93	13.23	19.85
1700	3.83	4.22	4.69	5.27	6.03	7.03	8.44	10.55	14.06	21.09
1800	4.06	4.47	4.96	5.58	6.38	7.44	8.93	11.17	14.89	22.33
1900	4.29	4.71	5.24	5.89	6.74	7.86	9.43	11.79	15.72	23.57
2000	4.51	4.96	5.51	6.20	7.09	8.27	9.93	12.41	16.54	24.81
2100	4.74	5.21	5.79	6.51	7.44	8.69	10.42	13.03	17.37	26.06
2200	4.96	5.46	6.07	6.82	7.80	9.10	10.92	13.65	18.20	27.30
2300	5.19	5.71	6.34	7.13	8.15	9.51	11.41	14.27	19.02	28.54
2400	5.41	5.96	6.62	7.44	8.51	9.93	11.91	14.89	19.85	29.78
2500	5.64	6.20	6.89	7.75	8.86	10.34	12.41	15.51	20.68	31.02
2600	5.87	6.45	7.17	8.06	9.22	10.75	12.90	16.13	21.51	32.26
2700	6.09	6.70	7.44	8.37	9.57	11.17	13.40	16.75	22.33	33.50
2800	6.32	6.95	7.72	8.69	9.93	11.58	13.90	17.37	23.16	34.74
2900	6.54	7.20	8.00	9.00	10.28	11.99	14.39	17.99	23.99	35.98
3000	6.77	7.44	8.27	9.31	10.63	12.41	14.89	18.61	24.81	37.22
3100	6.99	7.69	8.55	9.62	10.99	12.82	15.39	19.23	25.64	38.46
3200	7.22	7.94	8.82	9.93	11.34	13.23	15.88	19.85	26.47	39.70
3300	7.44	8.19	9.10	10.24	11.70	13.65	16.38	20.47	27.30	40.94
3400	7.67	8.44	9.37	10.55	12.05	14.06	16.87	21.09	28.12	42.18
3500	7.90	8.69	9.65	10.86	12.41	14.48	17.37	21.71	28.95	43.43
3600	8.12	8.93	9.93	11.17	12.76	14.89	17.87	22.33	29.78	44.67
3700	8.35	9.18	10.20	11.48	13.12	15.30	18.36	22.95	30.60	45.91
3800	8.57	9.43	10.48	11.79	13.47	15.72	18.86	23.57	31.43	47.15
3900	8.80	9.68	10.75	12.10	13.83	16.13	19.36	24.19	32.26	48.39
4000	9.02	9.93	11.03	12.41	14.18	16.54	19.85	24.81	33.09	49.63
4100	9.25	10.17	11.30	12.72	14.53	16.96	20.35	25.43	33.91	50.87
4200	9.47	10.42	11.58	13.03	14.89	17.37	20.84	26.06	34.74	52.11
4300	9.70	10.67	11.86	13.34	15.24	17.78	21.34	26.68	35.57	53.35
4400	9.93	10.92	12.13	13.65	15.60	18.20	21.84	27.30	36.39	54.59
4500	10.15	11.17	12.41	13.96	15.95	18.61	22.33	27.92	37.22	55.83
4600	10.38	11.41	12.68	14.27	16.31	19.02	22.83	28.54	38.05	57.07
4700	10.60	11.66	12.96	14.58	16.66	19.44	23.33	29.16	38.88	58.31
4800	10.83	11.91	13.23	14.89	17.02	19.85	23.82	29.78	39.70	59.56
4900	11.05	12.16	13.51	15.20	17.37	20.27	24.32	30.40	40.53	60.80
5000	11.28	12.41	13.79	15.51	17.72	20.68	24.81	31.02	41.36	62.04
5100	11.50	12.66	14.06	15.82	18.08	21.09	25.31	31.64	42.18	63.28
5200	11.73	12.90	14.34	16.13	18.43	21.51	25.81	32.26	43.01	64.52
5300	11.96	13.15	14.61	16.44	18.79	21.92	26.30	32.88	43.84	65.76
5400	12.18	13.40	14.89	16.75	19.14	22.33	26.80	33.50	44.67	67.00
5500	12.41	13.65	15.16	17.06	19.50	22.75	27.30	34.12	45.49	68.24
5600	12.63	13.90	15.44	17.37	19.85	23.16	27.79	34.74	46.32	69.48
5700	12.86	14.14	15.72	17.68	20.21	23.57	28.29	35.36	47.15	70.72
5800	13.08	14.39	15.99	17.99	20.56	23.99	28.78	35.98	47.97	71.96
5900	13.31	14.64	16.27	18.30	20.92	24.40	29.28	36.60	48.80	73.20
6000	13.54	14.89	16.54	18.61	21.27	24.81	29.78	37.22	49.63	74.44

Table A2: Calculations for Torque at Various Gear Ratios and RPM’s



RPM	Motor T	T (5.5)	T (5)	T (4.5)	T (4)	T (3.5)	T (3)	T (2.5)	T (2)	T (1.5)	T (1)
1	76	902.04	820.04	738.04	656.03	574.03	492.02	410.02	328.02	246.01	164.01
500	74	878.31	798.46	718.61	638.77	558.92	479.08	399.23	319.38	239.54	159.69
1000	73	866.44	787.67	708.90	630.14	551.37	472.60	393.84	315.07	236.30	157.53
1500	72	854.57	776.88	699.19	621.50	543.82	466.13	388.44	310.75	233.06	155.38
1900	71	842.70	766.09	689.48	612.87	536.26	459.65	383.05	306.44	229.83	153.22
2000	67	795.22	722.93	650.64	578.34	506.05	433.76	361.47	289.17	216.88	144.59
2500	50	593.45	539.50	485.55	431.60	377.65	323.70	269.75	215.80	161.85	107.90
3000	38	451.02	410.02	369.02	328.02	287.01	246.01	205.01	164.01	123.01	82.00
3500	30	356.07	323.70	291.33	258.96	226.59	194.22	161.85	129.48	97.11	64.74
4000	25	296.73	269.75	242.78	215.80	188.83	161.85	134.88	107.90	80.93	53.95
4500	20	237.38	215.80	194.22	172.64	151.06	129.48	107.90	86.32	64.74	43.16
5000	17	201.77	183.43	165.09	146.74	128.40	110.06	91.72	73.37	55.03	36.69
5500	15	178.04	161.85	145.67	129.48	113.30	97.11	80.93	64.74	48.56	32.37
6000	12	142.43	129.48	116.53	103.58	90.64	77.69	64.74	51.79	38.84	25.90