Improvement of the Polaris FST:

Fueling Performance through Innovation

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ABSTRACT

From 2001 to 2006, the Michigan Technological University Clean Snowmobile Team successfully implemented high-performance four-cycle internal combustion engines into an existing snowmobile chassis. The team's complications in past years did not rise from using a 4-stroke engine in a snowmobile. The problems arose from the simple fact that all the previous engines were originally motorcycle engines which did not have dimensions or configurations consistent with that of a snowmobile engine. This led to difficulties in packaging, drive train modifications, and additional weight. In 2007, the team decided to take a completely different approach in building a snowmobile for the competition. Instead of spending significant engineering effort on engineering the cohesion between engine and chassis the team decided to start with a stock snowmobile engine and chassis. Our OEM snowmobile choice was the Polaris FST Classic, which will be used again as the 2008 entry. This selection allowed more time to be spent engineering improvements in emissions and noise beyond the OEM implementation and less time on packaging and drive train modifications. The above decision combined with a team-designed exhaust and intake systems, alongside custom fuel mapping have made significant reductions in emissions and noise possible. The net result is a snowmobile that is not only environmentally friendly, but also a pleasure to ride.

INTRODUCTION

Due to rising environmental concerns regarding the use of snowmobiles in Yellowstone National Park, the Clean Snowmobile Challenge was introduced in the winter of 2000 in Jackson Hole, Wyoming. This event was sponsored by the Society of Automotive Engineers (SAE), and consisted of universities from across the United States and Canada, all of which arrived with snowmobiles that they had designed and built. The snowmobiles were evaluated in several static and dynamic events, including acceleration, handling, and hill climb events. In 2003, the competition moved to the Upper Peninsula of Michigan and was hosted by the Keweenaw Research Center (KRC) just north of Michigan Technological University's (MTU's) campus. For 2008, the competition remains at the KRC and runs from March 10^{th} to the 15^{th}, it will feature snowmobiles propelled by internal combustion engines, gas-electric hybrids and zero-emissions electric motors.

Michigan Tech's team is comprised of 53 members from diverse educational disciplines. The team includes members pursuing degrees in Mechanical Engineering, Mechanical Engineering Technology, Electrical Engineering, Electrical Engineering Technology, and Business. The team is divided into four sub-teams: engine, chassis, drivetrain, and business. The first three of these teams are focused primarily on the design and fabrication of the snowmobile. The business team is dedicated to public and sponsor relations as well as team dynamics.

For 2008, the team has focused on refining the 2007 entry. Improvements to the snowmobile's reliability, fuel economy, ridability, and overall weight were all addressed. The team's 2007 entry showed great potential with impressive emissions numbers and an overall appealing package with very good fit and finish. Refer to Table 1 below for a comprehensive analysis of the 2007 MTU competition results.

Table 1: 2007 Clean Snowmobile Competition Results for MTU

Event	Score	Place (Out of 10)
Design Paper	86.6/100	2
Static Display	50/50	Pass
MSRP	3.9/50	6
Subjective Handling	34.1/50	6
Fuel Economy	0/200	6
Oral Presentation	63.8/100	4
Noise	0/300	8

Acceleration	77.3/100	5
Rider Comfort	56.6/75	3
Emissions	258.9/300	2
Cold Start	50/50	Pass
Objective Handling	42/75	5
Penalties/Bonuses	75	
Weight	0/100	9
Overall	808/1500	6

Table 2: Michigan Tech CSC Goals

2007 Goals	2008 Goals
Achieve sufficient track/stud combination and engine power to outperform all other entrants	Increase engine power output from the 2007 design to better replicate the stock FST
Pass 2012 EPA Emissions Regulations while running E-85 as well as surpassing previous designs and entrants to the CSC	Pass 2012 EPA Emissions Regulations while using E-85, as well as surpassing the 2007 entry's emissions
Achieve a sound pressure level lower than 76 dBA per SAE J192 Specification and significant improvements in Subjective Noise	Achieve a sound pressure level lower than 74 dBA per SAE J192 Specification
Increase both the subjective and objective handling points awarded by maintaining relatively stock ergonomics	Reduce overall vehicle weight as well as maintain relatively stock ergonomics

PERFORMANCE BY INNOVATION

The 2008 Michigan Tech Clean Snowmobile is a refined package that is not only clean and quiet, but is also enjoyable to ride. A list of the 2008 goals for MTU's Clean Snowmobile is listed in Table 2. The increase in popularity of four stroke snowmobiles is hard to ignore. Their increased fuel economy, reliability, and ease of use make them very attractive to consumers. This is very apparent when reviewing the amount of four stroke snowmobiles sold in the last few years.

The 2008 MTU entry very closely replicates a stock Polaris snowmobile. Through careful planning the ergonomics of the snowmobile remained similar to that of the OEM (original equipment manufacturer) model. The new technologies implemented into the 2008 entry include engine modifications, exhaust system design, tunnel design, suspension modifications, and calibration.

Table 3 is a list of components and equipment specifications used to meet the goals of the MTU Clean Snowmobile Team for 2008. Key vehicle components include chassis, engine, fuel, intake, exhaust, drivetrain, track, and suspension systems.

Table 3: Snowmobile Component Specifications

Component	Description
Chassis	2006 Polaris FST Classic
Engine	750cc Weber Parallel Twin Four-Stroke
Fuel System	AEM Fuel Management System
Intake System	**Intercooler:** Air/Water, Bell Intercoolers
	Intake Plenum: MTU Clean Snowmobile Designed and Fabricated
Exhaust System	**Turbo:** IHI RHB-5
	Exhaust Header: 304 Stainless Steel 2-1 System, MTU Clean Snowmobile Designed and Fabricated
	Catalyst: 3-way Catalyst, V-Converter
	Muffler: MTU Clean Snowmobile Designed Chamber Muffler System
Drive Train	**Primary Drive:** OEM P-85 Polaris
	Secondary Drive: OEM Team Rapid Reaction Roller Secondary
Suspension	**Front Suspension:** MTU Designed and Fabricated Aluminum A-arm, with Ryde FX Air 2.0 Shocks
	Rear Suspension: MTU Clean Snowmobile Shortened Arctic Cat Pro-Mountain 153 with Fox Float
Track	137"x1.25"x15" Camoplast Ripsaw

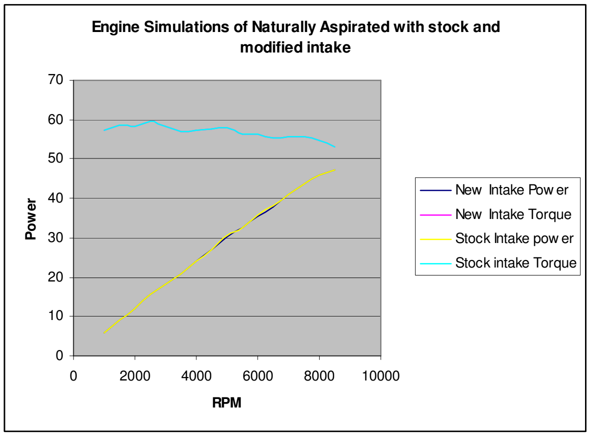
ENGINE

Engine Simulation

Lotus Engine Simulation Software was used to establish baseline numbers, for engine configurations.

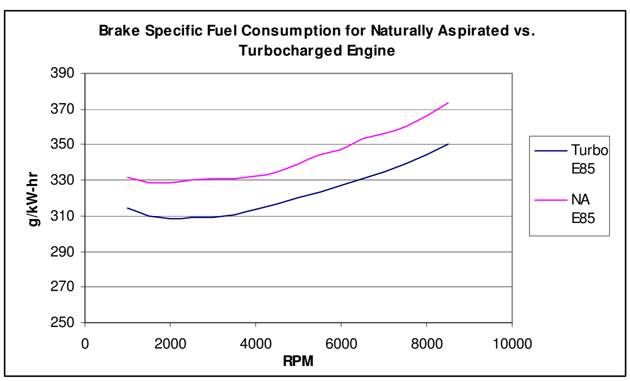
The first step of the simulation was to get a base naturally aspirated version of the engine that was representative of the amount of power and torque produced and physical dimensions. This model was then evaluated with both gasoline and E85. The same model was then used to compare the stock intake to the modified intake plenum. The results can be seen below in Figure 1.

Figure 1: Naturally Aspirated Engine Simulation



As can be seen in Figure 1, the purpose of the naturally aspirated model was to get an accurate representation of the engine before adding the complications of turbo charging. From the naturally aspirated engine model, the turbocharged model was created along with the addition of the modifications to the exhaust and intake systems. The modifications included changes to intake charge pipes, exhaust, intake plenum, turbocharger and intercoolers. This allowed us to see the effects of the proposed configurations compared to stock. Once both models were running on E85, their brake specific fuel consumptions were computed and compared as seen in Figure 2.

Figure 2: Fuel Consumption for Naturally Aspirated vs. Turbocharged Engine



From this data, the turbocharged engine is shown to consume less fuel per kilowatt. This validated the decision to implement a turbocharger on the 2008 CSC entry.

Head Rotation

The Weber 750 multi-purpose engine has a symmetrical design that allows the head to be rotated 180° and allow the engine to still run correctly. This reverses the location of the intake and exhaust ports. The rotation is made possible due to the design of the Weber engine using a central timing chain located between the PTO and MAG cylinders along with a symmetrical cylinder head design. To reverse the head a different camshaft and water pump housing is required. In the stock Polaris configuration, the intake ports face the gas tank while the exhaust is routed forward under the hood. The configuration used in the MTU 2008 entry is rotated 180° from this stock orientation, as well as it was in the MTU 2007 entry. This reduces under hood heat and allows sealing of the hood for improved noise performance.

Air Box

In order to further increase engine performance the air box of the 2007 snowmobile was redesigned. Volume was a very important factor driving the redesign. An increase in volume, approximately 4.5 L from 2007 to 2008, provides more fresh air available to be drawn into the engine. This excess of air provides the necessary volume needed for quick engine speed increases; in which the engine very quickly needs to draw a large amount of air. Noise reduction is another aspect in which volume plays a role. By having more volume in the air box there is more room for noise cancellation design elements. In the 2008 these design elements include dividing baffles that create different sized chambers throughout the air box. As intake noise is forced out through the baffled volumes, the differing volumes cancel out different frequencies of noise. Moreover the redesign of the air box focused mainly on reduction of engine intake noise. It is important in noise cancellation to not have a line of sight from the inlet to the outlet of the noise reduction device. The 2007 air box was designed with the inlet nearly on top of the outlet providing an almost direct line of sight as seen in Figure 3.

Figure 3: 2007 Air box – 16.1 L Absorption Style Muffler

The 2008 air box however, was designed with three main volume chambers in the main portion of the air box and a downward velocity stack leading into the chambers. The velocity stack and outlet of the air box can be seen in Figure 3.

Figure 3: 2008 Air box – 20.8 L Chambered Style Muffler

In short this design increases the volume by 30% from 2007 and also provides increased noise reduction making it far superior.

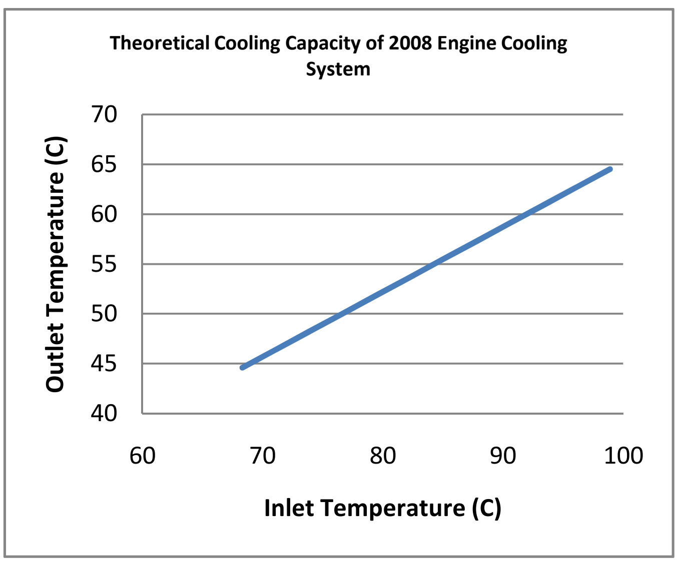
Intake

With the implementation of the head rotation, new intake runners and plenum had to be designed and fabricated to fit under the unmodified stock hood. The new runners were fabricated to match the stock length of 7.6cm and were directed down instead of the stock configuration which pointed them up. This was done to keep the intake from penetrating the hood. This new configuration placed the intake plenum above the front shock towers.

Turbocharger
The stock turbocharger from the Polaris could not be used because it has a cast turbo header. A turbocharger from IHI was selected which allowed for flexible mounting positions for the turbocharger. The turbo chosen is an IHI RHB51 which is similar in size, shape and performance to the stock turbocharger. The IHI turbo features an internal waste gate. The header is fabricated with 304 stainless steel for long term durability against dynamic and thermal loading. The down pipe and oxygen sensor housing were manufactured with 304 stainless steel to resist corrosion.

Engine Cooling System
Through testing and competition in 2007 it was found that the engine cooling system was more than adequate for the conditions the snowmobile would see. Therefore it was downsized to allow the engine to operate at a slightly higher temperature. By having a smaller cooling system there is less volume of coolant that affects the engine. This decrease in volume leads to faster response time, giving a much more dynamic cooling system that very quickly responds to changing engine conditions. In order to ensure that the new cooling system was adequate for providing enough cooling for the engine, simple calculations were made. Figure 4 displays the results of the calculations.

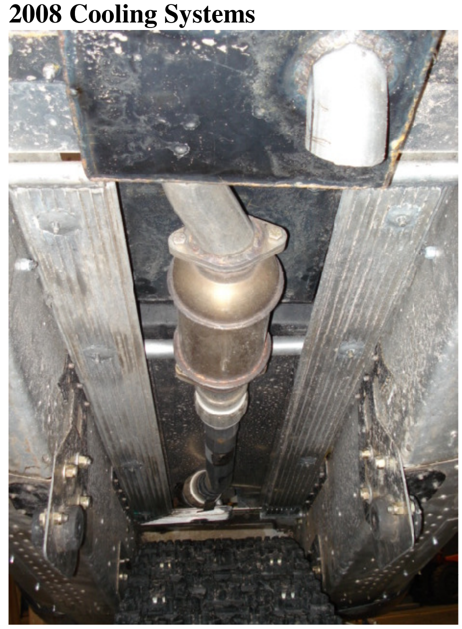
Figure 4: Theoretical Cooling Capacity of 2008 Engine Cooling System



The temperature curve seen in Figure 4 was calculated using approximate values for cooling system operating temperatures. The thermostat on the engine opens at approximately 70° C and an overheat condition for the snowmobile is when coolant temperatures exceed 99° C. A range from 70° C to 90° C was then used to calculate theoretical outlet temperatures.

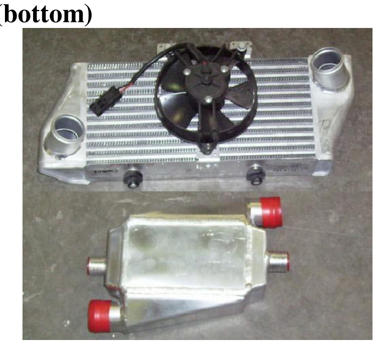
Cooling System Redesign
In both 2007 and 2008 two independent cooling systems were used for the engine and intercooler. In 2007 the engine cooling system extended through running board perimeter coolers and around the underside of the tunnel in a U-shape. The intercooler cooling system was simply a straight cooling extrusion that the coolant passed through twice in different directions. For 2008 the engine cooling system was reduced to simply an L-shape on the underside of the tunnel, while the intercooler was rerouted to be a straight run on the underside of the tunnel opposite of the L-shaped engine cooler. Both the engine and intercooler cooling systems also utilized the running board perimeter cooling on their respective sides. Figure 5 shows the cooling system as mounted in the tunnel.

Figure 5: 2008 Cooling Systems



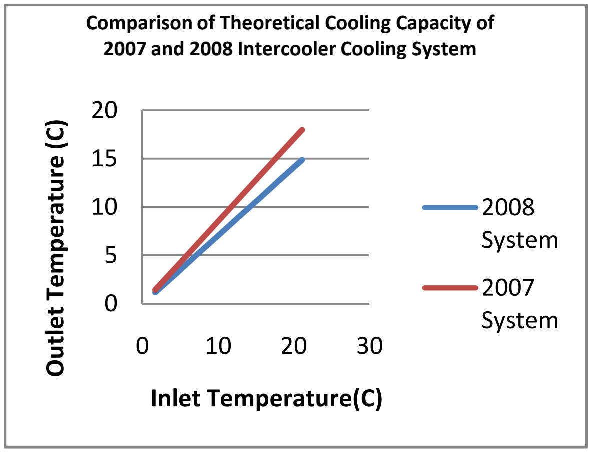
Intercooler Cooling System
In order to achieve a more efficient engine it is essential to provide a maximum amount of air. This is accomplished on the snowmobile first through the use of a turbocharger but also an intercooler. The same air to water intercooler as used in 2007 is used on the 2008 snowmobile shown in Figure 6.

Figure 6 Stock Intercooler (top) Compared to MTU's Bell Intercooler (bottom)



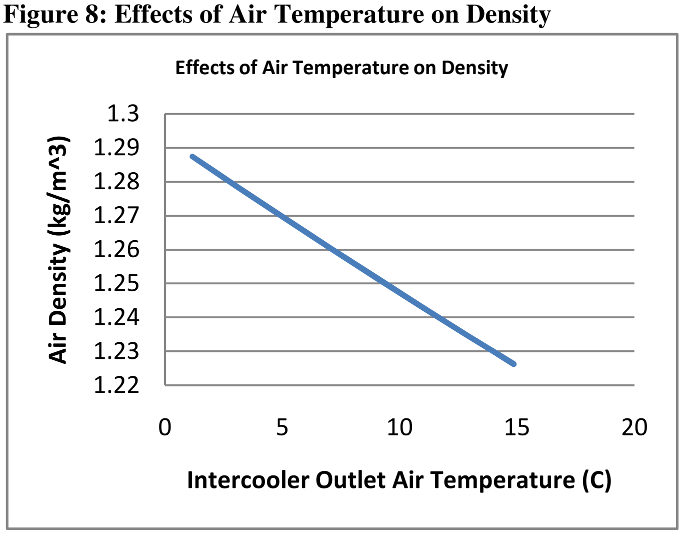
However to increase the effectiveness of the intercooler, the cooling system capacity was increased. The cooler surface area for the cooling system was doubled from 2007 to 2008 with the results of this effect shown in Figure 7.

Figure 7: Comparison of Theoretical Cooling Capacity of 2007 and 2008 Intercooler Cooling System



From the graph it can be seen that as inlet temperature increases the outlet temperatures does as well. At the upper limit of the intercooler inlet temperatures, 21° C, the temperature difference was approximately 3°C proving that the new system is a much better choice. It is also important to note that the running board perimeter cooling was not included in the calculations implying that the cooling capacity of the 2008 system has more than doubled from 2007. By having an increased cooling capacity air temperature after the intercooler will drop dramatically, increasing the density of the air. This effect can be seen in Figure 6.0.

Figure 8: Effects of Air Temperature on Density



This increase in density means that there is a higher mass of air per unit volume which means that more air can be drawn into the engine. With the increase in the amount of air in the engine the volumetric efficiency of the engine will increase as well which can be seen below in Equation 1.

Equation 1

$$n_v = \frac{m_a}{\rho_{a,i} \cdot V_d}$$

Where: n_v= Volumetric Efficiency
m_a=mass of air
$\rho_{a,i}$=Density of Air
V_d=Displaced Volume

In short, the cooling systems have been redesigned with performance in mind. The engine cooling capacity was reduced to provide a more dynamic yet still adequate cooling system. While the intercooler cooling capacity was increased to raise the density of the intake air and similarly boost the mass flow rate of the engine.

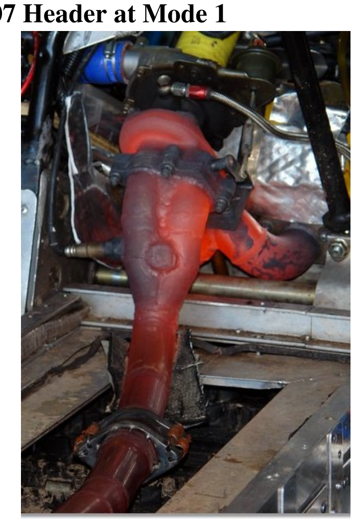
Emissions

The main goal of 2008 is an improvement in performance with little to no degradation in emissions output. This could be accomplished in three different ways; a different catalyst, specific engine tuning, or a combination of the two. While the catalyst and associated engine tuning in 2007 proved to be very effective, (2nd place) for emissions, alternatives needed to be evaluated for improved performance. It was decided that through a comprehensive re-mapping of the engine with the 2007 catalyst that the performance could be dramatically improved without sacrificing emissions output levels.

Exhaust Header Redesign

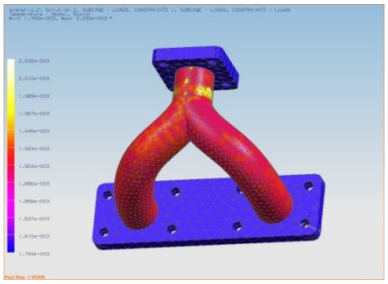
From extensive testing and operation of the 2007 snowmobile many flaws were found in the design of the exhaust header. The exhaust header is subject to both a dynamic load as well as a thermal load. Dynamically, the header is subject to a direct force from the weight of the turbocharger sitting on top of the header. Thermally, the header, at Mode 1 dynamometer testing, is subject to extremely high temperatures, upwards of 1000 degrees Celsius. A picture of the 2007 header when the engine is operating at Mode 1 is shown in Figure 9. It can be clearly seen due to the color of the header that it is experiencing extreme thermal loading.

Figure 9: 2007 Header at Mode 1



From 2007 the team learned that the dynamic and static loads from the turbocharger movement caused the header to creep. This similarly cracked several headers in 2007. Finite Element model results of this loading condition can be seen in Figure 10.

Figure 10: FEA of Header



To reduce this loading on the header, a 304 Stainless Steel bracket was fabricated to help carry the load of the turbocharger. The bracket attaches to the top of the valve cover and extends out to be bolted between the header and turbo charger. Figure 11 shows the bracket fabricated for the 2008 snowmobile.

Figure 11: Turbo Bracket

This bracket allows the engine and the turbocharger to move as one single unit.

Because the exhaust header being subjected to very high temperatures. Due, in part, to the engine operating parameters that cause exhaust gas to be hotter than normal, a change in the header material was made. The exhaust header was fabricated with Schedule 40 Weld L's of 304 Stainless Steel. While 304 Stainless Steel is not rated for the temperatures seen by the header, a wall thickness of .145 compensates for this deficiency. The design table below gives more insight into the decisions made when redesigning the exhaust header.

Table 4: Design Decisions for the Exhaust Header

Design Decision	Identification and Analysis
1. Material Selection	2007 – 321 Stainless Steel 2008 – 304 Stainless Steel 304 Stainless Steel was chosen due to its availability in the desired thickness.
2. Header Wall Thickness	2007 – 0.065 Wall Thickness 2008 – 0.145 Wall Thickness The wall thickness was increased to avoid fatigue cracking. It was found that the 0.065 wall material could not handle the combination of the dynamic and thermal load.

In short, the new exhaust header was designed with respect to durability and reliability. By increasing the thickness of the material and adding the support bracket the exhaust header was strengthened to withstand both the thermal and dynamic loadings. This makes for a more reliable design that in theory should withstand a load of a much greater magnitude as compared to the 2007 exhaust header.

<u>Increased Compression Ratio</u>

For 2008, the compression ratio of the engine was increased from 9.5:1 to 11:1. This was accomplished through the use of different pistons. In 2007 dished pistons from a stock turbocharged engine were used, while in 2008 flat-top pistons from a stock naturally-aspirated engine were used. By eliminating the dish in the piston the clearance volume was decreased which in turn increased the compression ratio. This relationship can be seen below in Equation 2.

$$CR = \frac{V_d + V_c}{V_c}$$

Where: CR=Compression Ratio
V_d=Displaced Volume
V_c=Clearance Volume

Based on information from the book <u>Internal Combustion Engine Fundamentals</u> by John B. Heywood; efficiency and exhaust temperature are positively influenced by increasing the compression ratio. From researched information, the relative efficiency of the engine is expected to improve between 3 and 6 percent overall. Exhaust temperature is also known to decrease as compression ratio and efficiency increase. It has also been shown that heat losses to the combustion chambers walls, as a function of the fuel's energy, also decrease as the compression ratio and efficiency increase.

TUNNEL DESIGN

With the center of the tunnel removed, structural changes were necessary to replace the rigidity of the center section. For the 2007 Clean Snowmobile Challenge, c-channel measuring 2.5 cm by 3.8 cm was attached to the perimeter of the tunnel to provide structure. Along with the c-channel a top plate having an identical thickness to the original tunnel was added. Not only did this top plate replace the majority of the original tunnel material removed but also added a heat barrier between the exhaust and gas tank. A Finite Element Analysis (FEA) was used to verify that the modified tunnel was stronger than the original tunnel. Figures 12, 13, and 14 display the tunnel loading, constraint, and deflection conditions used for the FEA analysis of the 2007 tunnel modifications.

Figure 12: Tunnel Loading and Constraints

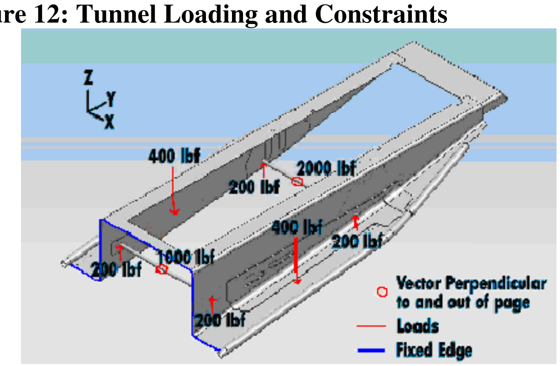


Figure 13: Stock Tunnel FEA Indicating Maximum Displacement of 3.3cm

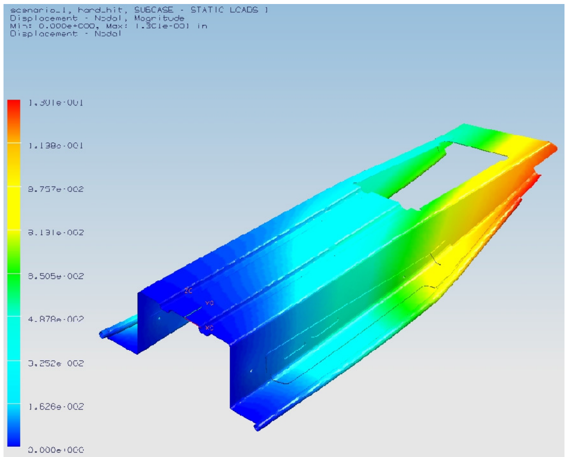
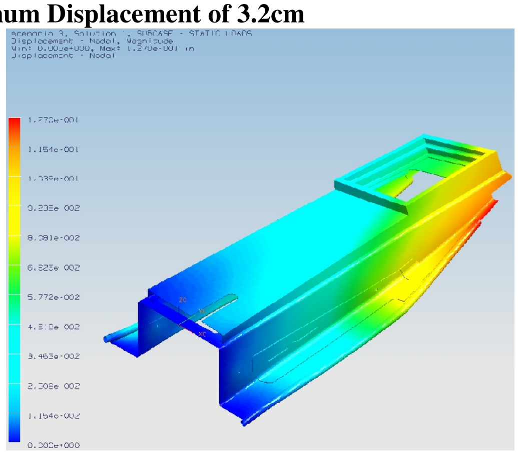


Figure 14: Modified Tunnel FEA Result Indicating Maximum Displacement of 3.2cm



In an effort to reduce weight and improve aesthetics, the c-channel type tunnel modifications were removed and replaced for the 2008 competition, seen in Figure 15.

Figure 15: 2008 Tunnel Modifications Including Tubing Supports and Aluminum Shielding

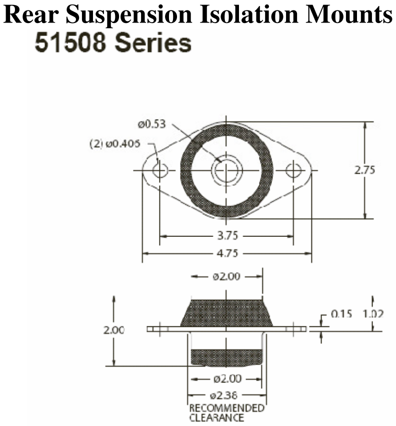
In place of the c-channel, two 2.5 cm diameter aluminum tubes were welded to the tunnel near the steering hoop with a third bridging the tunnel at the rear of the fuel tank. Combined, the three tubes support the weight of the fuel tank and reinforce the modified tunnel. To create a heat barrier between the exhaust and the fuel tank, and to close up the exposed tunnel area, a sheet of aluminum approximately 1 mm thick was bent and attached underneath the still existing tunnel area and is also seen in Figure 15. The front of this sheet was cut out to allow clearance for the exhaust downpipe and for the coolant line heat shield under the steering hoop.

SUSPENSION

<u>Rear Skid</u>

The rear skid mount design for the 2007 competition was a radical new innovation never before implemented in a snowmobile to our knowledge. For structure born noise to be generated, large flat areas must be excited by vibrational energy. The flat sides of the tunnel provide an excellent area for this to occur. Vibrations in the suspension are caused by impulses generated by track lugs striking the ground or an idler wheel passing over a rod in the track. These impulses propagate through the suspension and are transferred to the sides of the tunnel. By isolating the suspension at its attachment points, the amount of energy transmitted to the tunnel sides is reduced, therefore reducing the noise generated. These isolation mounts, shown in Figure 16 are an ideal design for the desired application [1].

Figure 16: Rear Suspension Isolation Mounts



After estimating the suspension loading, the 51508 series mount was selected for the 2007 snowmobile based on the following analysis.

The snowmobile weighs approximately 320kg itself. When this is coupled with an 80kg rider the total snowmobile/rider mass is 400kg. This total mass was then divided by two, 1/2 to each the front and rear suspension. The rear suspension portion was then divided by four, since there are four suspension mounting points. This resulted in a 50kg static, radial weight on each mount. Each mount chosen is rated for 100kg, a safety factor of 2 was allowed for impact loads, with a realization that the suspension shocks and springs would dissipate some energy before it reached the mounting locations.

This analysis was assumed to hold true for the 2008 snowmobile as the chassis is the same. The problem with this mount was that it needed to protrude between 2.5cm to 3cm inside the tunnel based on its axial length. Therefore, an Arctic Cat Firecat suspension was installed in the Polaris IQ chassis. The Firecat skid measures 34.3cm wide and easily fits inside the 38cm wide tunnel, providing the perfect amount of space for the isolation mounts. After extensive testing, approximately 250km, these mounts were removed and inspected for wear. Before removal it was noted that the front mounts seemed to be “front loaded” where the force of the track had pulled the center of the mount into a forward stance, while the back mounts appeared normal. Upon removal of the mounts, the rear mounts showed very little deterioration, while the front mounts seemed to be very near separation. Although catastrophic failure isn’t possible due to the design of both the mount itself and the implementation, it was deemed undesirable for this to occur, as it could lead to the failure of its isolation properties. A new mount was chosen with a radial rating of 145kg which provides a safety factor of 2.9 instead of the original 2 and an additional 50% increase in radial strength.

Although this isolation mounted Firecat skid frame performed great in respects to handling and noise, an Arctic Cat Float Skid was selected for the 2008 competition. This new Arctic Cat skid frame is claimed to be nearly 3.6 kg lighter than previous mountain rear suspensions and utilizes a Fox Float shock. This air shock is lighter and has been theorized to produce less noise than conventional shock/spring combinations. One problem with the Float Skid is that the shortest length produced by Arctic Cat is for a 153” track. After many measurements were taken from the skid frame, it was disassembled and the rails were cut shorter in order to accommodate a 137” track. Material was removed from the middle area of the rails and then after the two ends of the rail were butted together thick plates of aluminum were welded to either side of the joint for extra strength as seen in Figure 1.

Figure 17: Plates Added To Strengthen Shortened Rail Joint

Figures 18 and 19 show the Float Skid in its original 153” configuration and after the modifications to accommodate a 137” track respectively. After measurement of the weights of the Firecat suspension and the Float Skid it was determined that using the Float Skid saves approximately 1.36 kg.

Figure 18: Arctic Cat Float Skid In Its Original 153 Inch Configuration

Figure 19: Arctic Cat Float Skid After Being Shortened For A 137 Inch Track

A 137” track was chosen because it was available in a single-ply configuration which not only reduces its weight but also increases the efficiency of the snowmobile, this track is used by Bombardier and manufactured by Camoplast.

Front A-Arms

The stock Polaris front suspension consists of two unequal length, non-parallel A-arms with a coil-over shock mounted to the lower control arm on each side. In a further effort to reduce the overall weight of the 2008 competition snowmobile, the front suspension was redesigned using aluminum in place of the stock suspension’s steel.

The front A-arms were modeled using Catia V5 and the model was subject to a 3-G (12010 Newton) load. Based on front suspension dynamics the upper A-arm load path was directed down the length of the arm simulating a tension load. Similarly, the lower A-arm’s load paths were in the direction of the shock and simulating a front and side impact. Iterations of the design were performed until the factor of safety was above 1.5. Results of the finite element analysis can be seen in Figures 20 through 24.

Figure 20: Finite Element Analysis of Tension Load on Upper A-arm

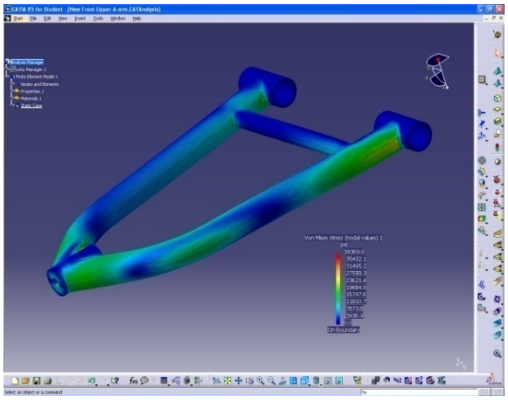


Figure 21: Finite Element Analysis of Side Impact Load on Lower A-arm

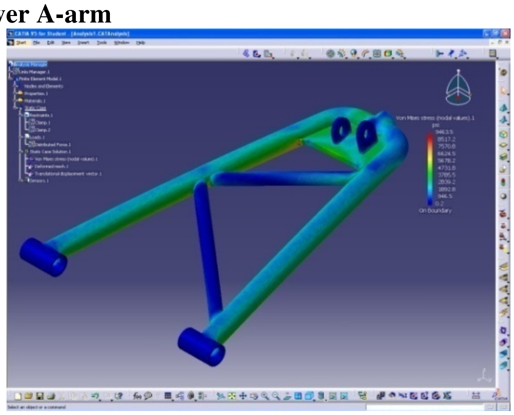


Figure 22: Finite Element Analysis of Front Impact on Lower A-arm

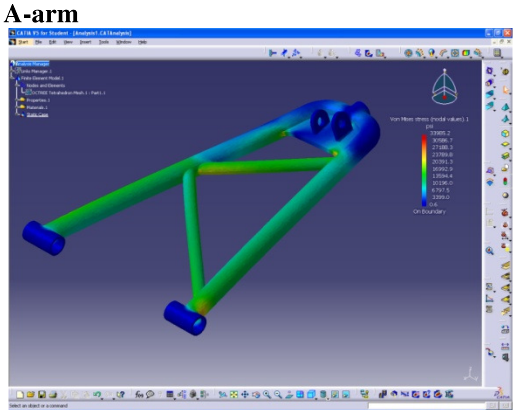


Figure 23: Finite Element Analysis of Shock Load on Lower A-arm

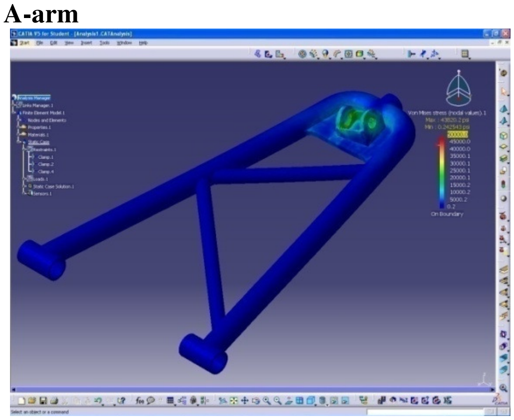
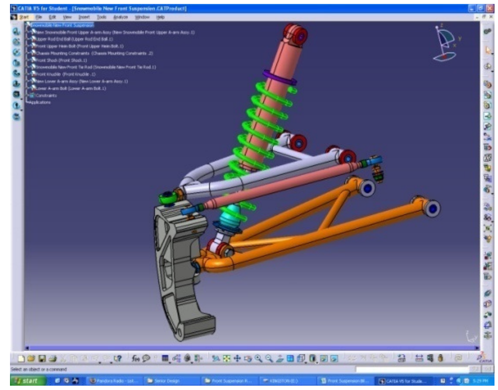


Figure 24: Complete Model of Redesigned Front Suspension



In order to avoid the necessity to verify the chassis structural integrity, the stock system geometry was not modified during the redesign. This decision meant no considerations for caster, camber, scrub, or toe were needed in the new design. For manufacturing purposes the upper and lower A-arms were built symmetrical using a specially constructed welding jig seen in Figure 25.

Figure 25: Custom Aluminum A-arm Welding Jig

The outboard shock mount of the lower control arm was relocated by 1.27 cm in order to accommodate Ryde FX Air 2.0 air shocks. In the past MTU has chosen to use Fox air shocks because of weight savings, the Air 2.0 shocks from Ryde FX were chosen because Polaris installs them of their stock 2008 snowmobiles, thus there is no effect on our calculated MSRP for the 2008 Clean Snowmobile Competition and they still offer considerable weight savings over the normal coil-over shocks.

Using aluminum in the front suspension redesign provided a 3.18 kg reduction over the stock model while the MSRP was lowered by 106 dollars. The lighter suspension is more responsive and will aid in the handling events during the 2008 Clean Snowmobile Challenge. Figures 26 and 27 show some of the redesigned suspension components during fabrication.

Figure 26: Redesigned Lower Control Arm Prior to Final Welding

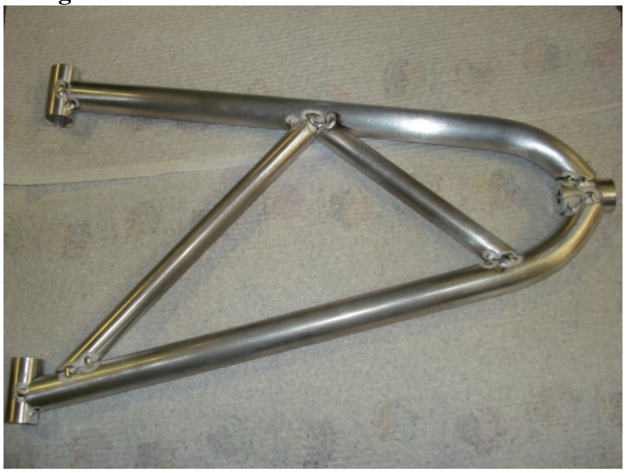
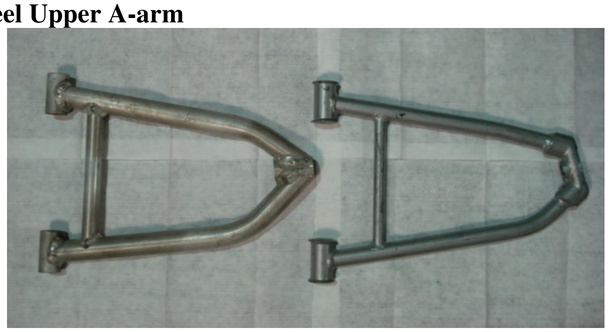


Figure 27: Finished Aluminum Upper A-arm and Stock Steel Upper A-arm



STEERING

In lieu of the "Rider Select" system that MTU ran for the 2007 competition the steering post mount has been changed to a solid mount to reduce the force required to turn the snowmobile. The "Rider Select" system was implemented by Polaris as a way for individual riders to quickly and easily select the handlebar position most comfortable for them. However, it was found by surveying members of the MTU Clean Snowmobile Enterprise Team that for the application that the competition snowmobile is meant for, it is undesirable to change the steering geometry. The ideal position to maximize comfort and steering ease during trail riding was selected and a fixed bracket was made to mount a steering post bushing similar to stock 2008 Polaris RMK snowmobiles. This bracket and bushing mount are seen in Figure 28.

Figure 28: Fixed Steering Post Mount

NOISE EMISSIONS

In 2007 the team did not compete in the J192 Noise Test due to a catastrophic engine failure. Last year's desired overall noise of the snowmobile was 76 dBA, however the goal of 2008 is an overall noise output of 74 dBA. Another goal of 2008 is even better packaging of noise control devices. The three main noise sources on a snowmobile are the engine exhaust, engine intake, and the track and rear suspension. By analyzing each source, and treating each component separately in a coherent noise reduction strategy, the team felt that the highest level of success would be achieved.

<u>Exhaust Noise Reduction</u>

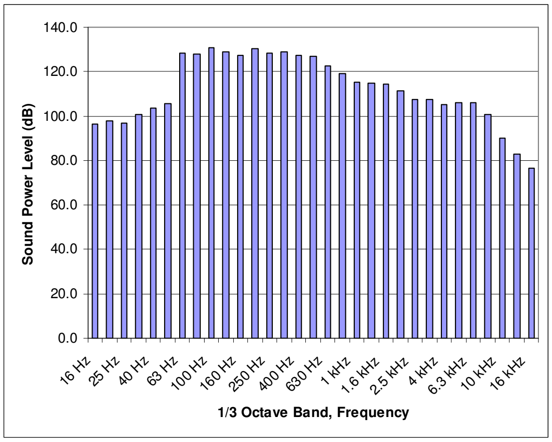
Since the exhaust layout is under the seat, the muffler is located at the rear of the snowmobile, underneath and behind the seat. Due to space limitations at this location, the team chose to use a muffler that combines the function of both a reactive and an absorptive muffler in a single package.

The use of resonators in the exhaust system is effective in removing dominant frequencies of noise produced by the combustion events of the engine. The design of the muffler chambers works to actively attenuate problematic exhaust frequencies.

To maximize noise cancellation, the muffler was designed around the frequency output of the engine exhaust. A single muffler is used to attenuate the exhaust noise produced. This muffler is designed to incorporate the components of both a resonator and absorptive type muffler. It is designed with five chambers with varying chamber volumes to attenuate as many frequencies as possible. This represents the resonator aspect of the muffler design, which is meant to target the lower frequencies produced by the engine through the exhaust. To target the higher frequencies, a ceramic fiber muffler packing material was used to line the interior of the muffler chambers.

The first step in designing the muffler was to analyze the stock Polaris muffler. Transmission loss calculations were performed on the Polaris muffler to determine the frequencies that were targeted by Polaris when the stock muffler was originally developed. The frequencies that appeared to be targeted by Polaris are the same frequencies that were targeted when the MTU muffler was designed. Those values were used in combination with data acquired by using a Land & Sea water brake dynamometer for engine loading; the conditions that the engine will see during the noise event were simulated. A 01dB microphone and Symphonie data acquisition software were used to analyze the sound output of the engine. Each reading was taken during a simulated pass-by, in which the speed of the engine, and the load applied to the engine was varied to simulate the testing conditions experienced during the noise event. Testing was performed in the near-field, with the microphone 10cm from the exit of the exhaust, and positioned out of the exhaust flow. All noise, other than exhaust noise, was isolated and not taken into account in these tests. A third-octave band frequency analysis was recorded. The configuration was an "open" pipe, with no muffler installed The results of the frequency analysis can be seen in Figure 29.

Figure 29: Third Octave Band Frequency Analysis, No Muffler



The absorptive muffler portion, incorporates MTU CSC designed and built expanded steel tubes with Kaowool KT (X) ceramic fiber blanket packing lining the inside of each chamber. The Kaowool KT packing is rated to be used at a temperature up to 1260˚C and has a noise reduction coefficient of 0.80. The reactive aspect of the muffler involves a series of six various sized chambers with a combination of 90 degree bends and perforated expanded steel tubing directing the exhaust gases through and between each chamber. Using this setup, the perforated tubes, and the 90° tube bends, enabled the muffler to achieve minimal restriction; all while still maintaining better packaging characteristics than 2008 as can be seen in Figure 30.

Figure 30: 2008 MTU Designed Exhaust Muffler

Chassis Noise Reduction

With the structural portion of the chassis resolved by the various tunnel modifications, focus on the chassis shifted to noise. Before the 2007 competition a SAE J-192 test was held to compare the MTU custom isolated Firecat skid to a stock Polaris M-10. In the test the stock M-10 suspension measured 1dBA quieter than the isolated suspension. This seemed unlikely therefore several bystanders of the test were questioned and they revealed that the isolated suspension seemed much quieter than the standard M-10 suspension and that in their opinions the isolated suspension was louder due to track slip. The Firecat skid frame uses a track that is only 34.29 cm wide where as the standard track is 38.1 cm wide. With the Firecat track there is approximately 200 cm^2 less track on the snow, contributing to more potential track slip. Track slip was addressed in last year's testing by adding two studs per bar to the Firecat track as allowed by the CSC rules[2] which resulted in a 7dB reduction in noise. Track slip is being addressed for the 2008 competition by using a 137 inch track with the Float Skid as compared to the 128 inch track used on the Firecat skid. The longer skid frame means that there are 822.6 cm^2 more track on the ground.

Testing in 2007 also identified that removing idler wheels from the skid-frame, except for those on the rear axle, resulted in an additional two dBA reduction in noise. Bystanders also commented that the setup with wheels removed sounded subjectively much quieter than the same setup with idler wheels installed.

The stock Polaris skis, found on a FST snowmobile, are lightweight plastic with dual carbides on each ski. These skis are flimsy so a lightweight plastic ski made of a material having a greater density than stock. C & A pro 3 skis were selected because of their dense plastic construction and their use of only one carbide per ski. The material causes the ski to produce less noise than the stock skis from flexing and the single carbide creates less scratching noise on hard packed snow and ice.

The 2007 competition snowmobile used the stock FST hood but due to the unique nature of the MTU team's application most of the hood air vents were closed off to prevent noise transmission from the engine compartment. For 2008 the stock FST hood was replaced by a Polaris IQ hood found on a 2-stroke platform. The 2-stroke hood had fewer vents than the 4-stroke and gives the snowmobile a cleaner look. All but one of the few vents on the new hood were covered using ABS plastic. ABS plastic is a light, cost-effective way to close off the vents as compared to the carbon fiber used during past competitions. The inside of the hood was then covered with sound damping acoustical foam made by the Soundown company. This foil-faced material was used in two forms; one with a rubber barrier layer, and one without. After some preliminary testing it was found that the material utilizing the rubber barrier absorbed more noise but the weight of this type of material is significantly greater than that without the barrier so it was not used in all areas of the engine compartment. The foam works in absorbing noise from the engine while still being fire and heat resistant. By closing as many vents as possible and adding noise absorbing material an anechoic environment is created in the engine bay and noise is prevented from escaping the engine compartment.

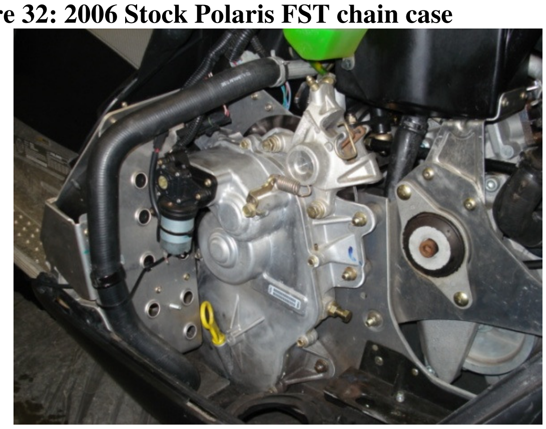
DRIVETRAIN

For the 2008 Michigan Tech Clean Snowmobile, the majority of the drivetrain components were replaced from stock. The main focus was to reduce overall weight and to improve the drive efficiency while maintaining performance.

The two components within the drive system left stock were the drive and driven clutches, neglecting spring, weights, etc. The Polaris P-85 was used as the primary clutch to transfer the power of the engine to the belt. A 100/340 pressure spring and 11 series 66 gram weights were used as the primary clutching set-up. A stationary sheave from a Ski-doo TRA primary clutch was machined to fit the taper of the crankshaft, but the decision to run a TRA was over ruled in favor of the P-85. From experience within the Clean Snowmobile Team from testing and overall knowledge, the P-85 was best suited for the application. A TEAM Industries Rapid Reaction secondary clutch was chosen to deliver the power from the belt to the jackshaft because of its reliable, proven design. Three secondary springs were chosen to be tested because on average a snowmobile comes out of the factory with 30% more belt pressure than needed [6]. This causes a loss in belt efficiency, which decreases the amount of power delivered to the track and reduces overall drive efficiency. A 100/240 (Red/Black) spring and 64/38/.65 helix angle track was used as the secondary clutch set-up. The stock jackshaft was replaced with a shorter 2008 Polaris Dragon IQ jackshaft to fit the replacement chain case. The new chain case installed was also a 2008 Dragon IQ component as shown in Figure 31. This chain case allowed for easier access and an overall more simple system. It eliminated the reverse mechanism and complicated gear case cover as seen in Figure 32, this lead to more packaging options for the air intake system. The gearing consisted of a 21 tooth top gear and a 40 tooth bottom gear for a 1.90 to 1 ratio.

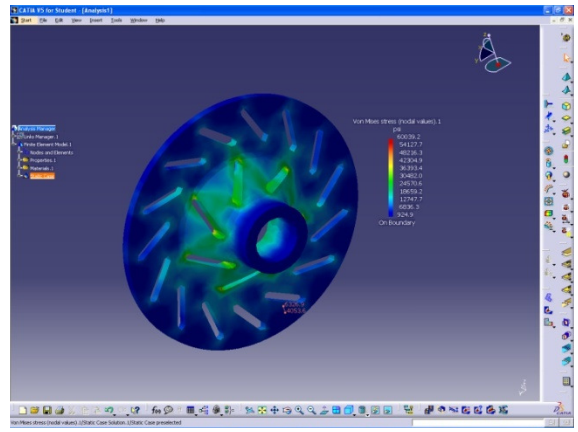
Figure 31: 2008 Dragon IQ replacement chain case

Figure 32: 2006 Stock Polaris FST chain case



The team investigated many options for reducing the rotational inertia within the drive train. The stock Polaris brake rotor was modeled in Catia V5 and per rule 4.4.6 the surface area was reduced within the allowable 15 percent by 14.9 percent. Additional material was removed and a 3000 ft lb load was applied during the FEA process to determine part integrity. The results shown in Figure 33 verify the part will remain within the elastic limit. A CNC water jet was used to cut the pattern shown in Figure 33. Testing proved that this new rotor design not only reduced rotating mass, but also provided better cooling for the rotor and better resistance to snow build up.

Figure 33: Finite Element Analysis of Brake Rotor with a 3000 ft lb load



Two different drive shafts were installed to test two different style tracks. One drive shaft was from a 2008 Dragon IQ with 2.52” pitch drivers to run a 128”x13.5”x1” Camoplast Hacksaw track. The other drive shaft was from a 2008 Polaris RMK with 2.86” pitch drivers to run a 137”x15”x1.25” Ski-doo single ply track. All the stock drive train components that were removed from the snowmobile to be replaced were weighed and compared to the new 2008 IQ Dragon components. The outcome was a weight savings of 3.098 kilograms.

Testing Procedure

A scientific clutch tuning procedure was implemented for the 2008 competition season. This procedure allowed for organization of testing results in a living Excel file. It enabled the team to refer to recorded data. This visually made it easier to decide which variables to change within the drivetrain system for fuel economy and acceleration purposes. The spreadsheet of information included examples such as temperature, snow conditions, clutch springs and weights, distance traveled, fuel consumed, etc. Prior to any testing, a procedure of how fuel economy and acceleration testing would be preformed was discussed. This helped to eliminate “on-the-fly” decisions to keep from wasting valuable testing time. This procedure included a 30 mile trail section from Houghton to Twin Lakes where fuel economy testing would take place. It was decided that the most accurate way to record fuel economy data would be to measure the amount of fuel consumed with a fuel transducer and the distance traveled with a Global Positioning System. The fuel testing would be performed at competition speeds of 30 to 40 miles per hour. The recorded data would be compared to a stock Polaris FST

Classic to get accurate data when changing variables within the drivetrain system. The stock clutching/gearing set-ups would be the first tested. Table 5 shows the results of the Fuel Economy and Acceleration data recorded with stock parameters. Changes of the drive system variables (gears, weights, springs, etc.) would be made from there one at a time to keep track of the snowmobile performance with few complications. The most time would be contributed to fuel efficiency testing. For acceleration testing it was decided that testing be performend in a field located in Dollar Bay. This location had a flat runway of 600 feet and a heated garage to make clutch changes. The most fuel-efficient drive train set-ups would be tested for the best acceleration. Eliminator 2000 photo gates would be used to record the time in between the gates for acceleration purposes. Acceleration would take place over a period of one day or night so the change in snow conditions is minimal.

Table 5: Fuel Economy Data with stock FST set-up

Test Trail	Twin Lakes	Twin Lakes
Driver's Name	Steve N	Steve N
Driver's Weight	185 lb	185 lb
Snow conditions (sugary, bumpy, hard packed, groomed etc.)	average packed, bumpy	average packed, bumpy
Ambient Temperature	22 degrees	22 degrees
Wind Conditions	5 mph	5 mph
Weather conditions (Snowing, Sunny or Overcast)	Clear, overcast	Clear, overcast
P-85	yes	yes
Primary Spring	100/340	100/340
Primary Weights	66 gram	66 gram
Secondary Spring	100/240	100/240
Secondary Helix	64/38/.65	64/38/.65
Belt	Stock	Stock
Top Gear	21T	21T
Bottom Gear	40T	40T
Tooth Driver size	2.52"	2.52"
Snowmobile Modifications/Set up	none	none
Track	1.25" Ripsaw	1.25" Ripsaw
Chassis	FST	FST
Engine	750 cc	750 cc
Peak Horsepower	140 hp	140 hp
Best BSFC/RPM	unknown	unknown
Results		
Average Test Speed	35 mph	35 mph
Miles	28	28
Gallons of fuel	2.18	2.13
Miles per Gallon	12.8	13.1
Engagement RPM	4000	4000
Shift-Speed Peak RPM	7900	7900

Malfunctions	Alternator and battery positive connections loose, Sled battery drained, had to jump battery on the trail	

CONCLUSION

The 2008 Michigan Tech Clean Snowmobile is a step away from tradition, and a step towards the future. It incorporates exciting technology that is sure to lead the future of snowmobiling. Through careful design and engineering, the fusion of performance, efficiency, low exhaust emissions, low noise operation, and alternative fuels along with practicality has become a reality.

ACKNOWLEDGMENTS

Special thanks to all of the following sponsors for making it possible for the 2008 MTU CSC snowmobile to enter competition.

- **GM**
- **3M**
- **Cummins**
- **Chrysler**
- **Oshkosh**
- **American Axle**
- **Polaris Industries Inc.**
- **Bombardier Inc.**
- **Arctic Cat Inc.**
- **Yamaha Motor Corp**
- **Camoplast**
- **Soundown**
- **IHI-Turbo**
- **AEM**
- **Castle Racing**
- **Fox**

- **Eaton**
- **Slowboy Racing**
- **V-converter**
- **Stud boy**
- **Weber Motor**
- **Redline**
- **Gauge-Tech**

REFERENCES

1. "515 Series Mounts." Novibes.com. 2008. No Vibes. 25Feb2008 <http://www.novibes.com/vibration/productinfo/515series/index.asp>.
2. Barrett, W., Turner, T., Jungnitsch, R., Ryba M., Lindstrom, D., Blough, J., "Improvement of the Polaris FST Classic: For a Cleaner and Quieter Tomorrow" 2007
3. Gillespie, Thomas D. Fundamentals of Vehicle Dynamics. SAE 1993.
4. Heywood, John B. Internal Combustion Engine Fundamentals. New York: McGraw-Hill, 1988.
5. Metz, Milliken, Milliken. Racecar Vehicle Dynamics. SAE December 1995.
6. Olav Aaen (2004). Clutch Tuning Handbook. Aaen Performance
7. "The SAE Clean Snowmobile 2008 Rules" 2007

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