# Improvement of the Polaris FST Classic: For a Cleaner and Quieter Tomorrow

**Wesley S. Barrett, Travis D. Turner, Russell P. Jungnitsch,**
**Michael A. Ryba, Dustin S. Lindstrom, Dr. Jason R. Blough**
Michigan Technological University

## 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, drivetrain modifications, and additional weight. For 2007, the team has 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. This selection allowed more time to be spent engineering improvements in emissions and noise beyond the OEM implementation and less time on packaging and drivetrain modifications. The above decision combined with a team-designed exhaust and intake system, along side 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 [8], the Clean Snowmobile Challenge (CSC) 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 designed and built. The snowmobiles were evaluated in several static and dynamic events, including acceleration, handling, and hill climb. 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 2007, the competition remains at the KRC and runs from March 19th to the 24th, and will feature snowmobiles propelled by internal combustion engines, gas-electric hybrids and zero-emission electric motors.

Michigan Tech's team is comprised of 45 members from various educational disciplines. The team includes members pursuing degrees in Mechanical Engineering, Mechanical Engineering Technology, Electrical Engineering, Electrical Engineering Technology, Scientific and Technical Communication, Accounting, and Business. The team is divided into 5 groups, with four product development teams (Engine, Chassis, Drivetrain, and Noise) along side a Business team that is dedicated to sponsor development, team image enhancement, and long-term team strategy development.

For the 2006 competition, the team focused on refining the 2005 entry. Refinements were centered on lowering overall noise output and increasing reliability. The team's 2006 efforts displayed tremendous potential in both areas passing the SAE J-192 noise test and finishing the 90-mile endurance event for the first time in 3 years. See Table 1 below for a comprehensive analysis of the 2006 MTU competition results.

**Table 1: 2006 Clean Snowmobile Competition Results for MTU**

| Event | MTU Score | Place (out of 13) |
|---|---|---|
| Emissions | 286/300 | 4 |
| Noise | 164/300 | 7 |
| | 14/150 | |
| Acceleration | 79.7/100 | 6 |
| Endurance | 123/200 | 6 |
| Objective Handling | 63.7/75 | 2 |
| Subjective Handling | 35/50 | 8 |
| Cold Start | 0 | Fail |
| Rider Comfort | 14.8/75 | 9 |
| Oral Presentation | 72.3/100 | 2 |
| Static Display | 39.8/50 | 2 |

| | | |
|---|---|---|
| Design paper | 83/100 | 3 |
| Cost | 20.7/50 | 8 |
| Penalty | -100 | Fail |
| Overall | 892/1200 | 6 |

There are several changes to the 2007 CSC rule book, one of which pertains to 2008. These rule changes did not make a significant impact in the team's goals between 2006 and 2007. One rule change, which was an addition to the rules, is a 100 point bonus for finishing the endurance event while burning E-85 fuel this year instead of E-10, 2008 E-85 is mandatory. Table 2 is a comparison between the team's goals for 2006 and 2007.

**Table 2: Michigan Tech CSC Goals**

| 2006 Goals | 2007 Goals |
|---|---|
| Accelerate a distance of 152.4 meters in under 8 seconds | Achieve sufficient track/stud combination and engine power to out perform all other entrants |
| Pass 2012 EPA Emissions Regulations (see Table 3) as well as surpassing previous designs and entrants to the CSC | Pass 2012 EPA Emissions Regulations while running E-85 as well as surpassing previous designs and entrants to the CSC |
| Achieve a sound pressure level lower than 78 dBA per SAE J192 Specification | Achieve a sound power level lower than 76 dBA per SAE J192 Specification and significant improvements in Subjective Noise |
| Improve chassis ergonomics and increase test time to improve handling as much as possible | Improve both the subjective and objective handling points awarded by maintaining relatively stock ergonomics |

Table 2 also presents a few goal changes for the MTU team this year. The two major goal changes pertain to rider ergonomics and subjective noise reduction.

This paper presents a detailed overview of Michigan Technological University's entry into the CSC for 2007. Information regarding the conceptual design, detailed design analysis, manufacturing, and execution of multiple enhancements implemented into this year's snowmobile will be included. These enhancements can be separated into three sections including performance by innovation, Emissions, and Noise.

## PERFORMANCE BY INNOVATION

The snowmobile designed for the 2007 CSC is not only clean and quiet, but also very performance oriented. Four-stroke snowmobiles will be better accepted by the snowmobile community when they possess equal or higher performance qualities then the two-stroke machines that made snowmobiling the popular sport that it is today. This is indeed happening in the marketplace today as evidenced by the market share growth of Yamaha which produces only four-stroke snowmobiles.

The 2007 Michigan Tech entry in the CSC is able to do this by incorporating new innovations in technology. The new innovations implemented into the 2007 entry include engine modifications, exhaust system routing, tunnel venturi, tunnel design, suspension/rear skid isolation, power transmission, and testing and calibration.

Table 3 is a list of components and equipment specifications used to meet the goals of the MTU Clean Snowmobile Team for 2007. Key vehicle components include chassis, engine, fuel, intake, exhaust, drivetrain, track, and suspension systems.

**Table 3: Snowmobile Component Specifications**

| Component | Description |
|---|---|
| Chassis | 2006 FST Classic |
| Engine | 750 cc Weber Parallel Twin Four-Stroke |
| Fuel System | Mallory Competition Fuel Pump, AEM Fuel Management System |
| Intake System | **Intercooler:** Air/Water, Bell Intercoolers<br>**Intake Plenum:** MTU Clean Snowmobile Custom Designed and Fabricated |
| Exhaust System | **Turbo:** IHI RHB-5<br>**Exhaust Header:** 321 Stainless Steel, MTU Clean Snowmobile Designed and Fabricated 2-1 System<br>**Catalyst:**3-way Catalyst, V-Converter<br>**Muffler:** MTU Clean Snowmobile Designed 6 Chamber Muffler System |
| Drivetrain | **Primary Drive:** OEM P-85 Polaris Primary<br>**Secondary Drive:** OEM TEAM Rapid Reaction Roller Secondary |
| Suspension | **Front suspension:** Polaris IQ with Fox Floats<br>**Rear suspension:** Rubber Isolated Arctic Cat Fireccat w/ Standard Shocks |

| | |
|---|---|
| Track | **Track:** 128” x 1” x 13.5” Camoplast Hacksaw Silent Track<br>**Studs:** 102-1.325” Woody’s Megabites |

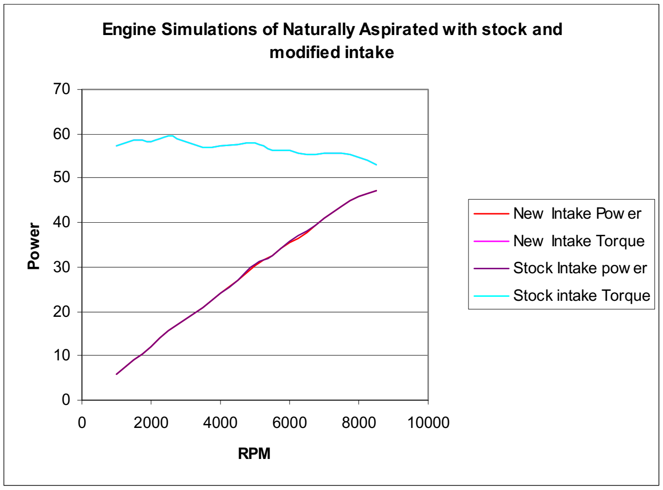
# ENGINE

## Engine Simulation

Lotus Engine Simulation was used to get base numbers for our potential engine configurations and innovations.

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.

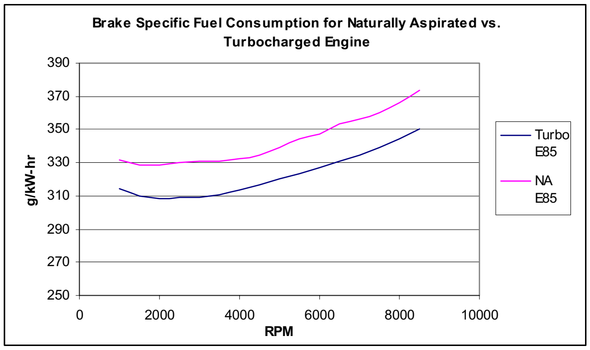
**Figure 1: Naturally Aspirated Engine Simulation**



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 2007 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 2007 entry is rotated 180° from this stock orientation. This reduces under hood heat and allows sealing of the hood for improved noise performance.

## 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 shown in Figure 3 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.

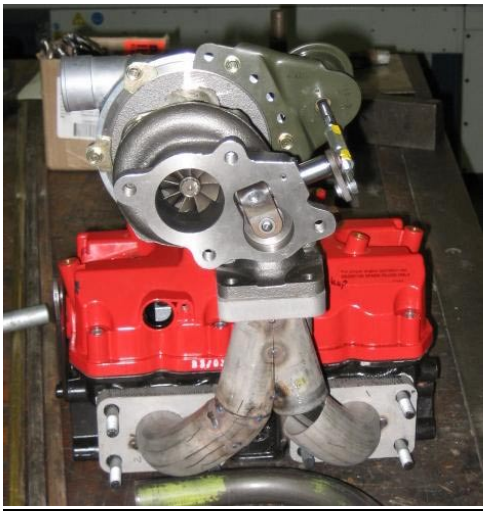
**Figure 3: MTU Custom Designed and Fabricated Intake System**

The plenum was designed by first measuring the volume of the stock intake plenum (approx. 3.5L). The new intake plenum was then fabricated from 11cm diameter 6061-T6 aluminum tubing with a goal of maintaining a similar volume. The new volume was less than the stock configuration due to space constraints and shape The use of velocity stacks inside the plenum facing the throttle bodies are used to increase throttle response and performance.

Turbocharger

The stock turbocharger from the Polaris could not be used because it has a cast turbo header. A turbocharger from IHI shown in Figure 4 below was selected which allowed flexible locating positions for the turbocharger. The header was fabricated using 321 stainless steel for long term durability against heat and vibrations. The down pipe and $O_2$ sensor housing were manufactured with 304 stainless steel to resist corrosion. The turbo chosen is an IHI RHB51 which is similar in size, shape and performance to the stock turbo. The IHI turbo features an internal waste gate.

**Figure 4: IHI RHB-5 Turbocharger implemented on the 2007 MTU Entry**



Intercooler

The intercooler selection was made in cooperation with Bell Intercoolers. This enabled the use of the custom air to water intercooler shown in Figure 5 below. An air to water intercooler was chosen because the amount of airflow under a snowmobile hood is minimal. The FST's hood will be closed off to reduce sound emissions, making it even more critical to run the air to water intercooler. A small electric water pump feeds the intercooler. The pump is controlled by the ECM and flows 10.9 L/min at a max current of 7.5 amps. The coolant is pumped to a heat exchanger on the running board where it is cooled by the snow.

**Figure 5: Stock Intercooler (top) Compared to MTU's Bell Intercooler (bottom)**

During mode 1, 7500 RPM under full load, testing at 60 kPa the turbo outlet air temperature was measured to be 87°C, while the air temperature in the intake plenum was 37°C meaning a reduction of 50°C was achieved. The inlet water temperature was 15°C. With an efficiency of nearly 100%, the outlet water temperature was 37°C. The physical size of the Bell intercooler is smaller than the stock air to air intercooler allowing for improved engine compartment packaging.

Engine Control Module

A different engine control module (ECM) was required to allow the use of E85 fuel. This meant that the following engine maps had to be developed: the fuel map, ignition timing map, and various other enrichment maps. The ECM selected is produced by Advanced Engine Management (AEM). This ECM is very similar to the stock Bosch ECM as they both have wide band oxygen sensor feedback, auto fuel mapping, knock detection, fully sequential fuel injection and coil on plug ignition.

The ECM is currently configured with speed density. This means that the ECM relies on a manifold absolute pressure (MAP) reading and engine speed (RPM). This was done for simplicity, as less calibration is necessary when compared to a mass air flow configuration. Future iterations may include mass air flow as it is more accurate.

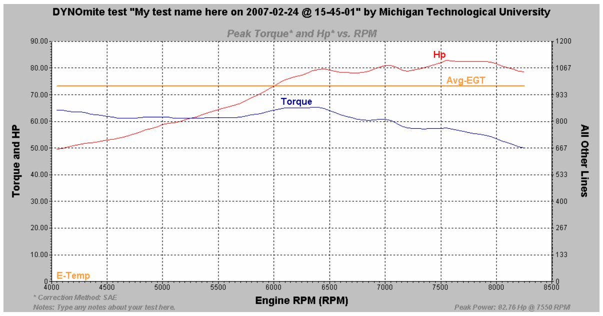
During testing, the MAP readings tended to be inconsistent and with a wide range of oscillation. Further testing revealed this was due to the sensor being on only one of the intake runners. This is the stock configuration and was used as a starting point. It was attempted to dampen these fluctuations by altering the sampling rate of the sensor using the AEM software, but this did not stabilize the readings. This isolation was most apparent at idle as the intake valve would open and close.

The solution was to link the two intake runners together to average the apparent pressure reading and install a dampener inline on the vacuum hose to the map sensor. The dampener was a small piece of aluminum with a small passageway through it. While this slowed the reaction time of the sensor, no ill effect has been seen, as the enrichments were slightly adjusted to correct for the delay.

The auto-mapping function of the AEM ECM was used to improve the base map calibration. The auto-mapping functions by setting a target lambda reading which causes the ECM to adjust the fuel within a given set of parameters. After the fuel map was calibrated, the $O_2$ sensor feedback was activated to maintain the fuel mixture at a target lambda without changing the fuel map. This allows for variations in fuel quality and air density.

Calibration results using the AEM ECM can be seen in figure 6 below.

**Figure 6: Power and Torque Curves**



This figure was generated with the engine running 60 kPa of boost.

## EXHAUST

The stock exhaust system implemented on the FST uses an under hood exhaust pipe, coupled to a muffler located on the drivers' right hand side of the under hood compartment. This year, following similar concepts utilized in MTU CSC teams of the past, an under-seat exhaust system was developed.

This under seat exhaust system is beneficial in three distinct ways. First, it reduces the amount of weight and volume in the engine compartment. Many four stroke snowmobiles are known for their heavy ski pressure due to the heavier four stroke engines. The extra space under the hood provides room for added noise absorption material. Second, re-routing the exhaust removes heat from under the hood. With the added noise absorption material and many of the hood vents sealed to keep noise from exiting the engine compartment, heat build up under the hood becomes an issue, this is solved by exiting the exhaust under the seat where snow and cold air is readily available for heat dissipation. Third, it provides greater flexibility in locating the catalytic converter and muffler.

The biggest hurdles in mounting the exhaust under the seat are similar to the issues of mounting it under the hood, lack of space and heat generation. To counter both of these problems, the center of the tunnel was removed. This allows the exhaust system to run between the fuel tank and the track, providing a consistent bath of snow dust and air for cooling. Also, with the head of the engine turned 180°, the turbo is now located between the engine and the gas tank.

## TUNNEL VENTURI

To combat excessive heat build up near the turbo, the team designed a venture pictured below in figure 7 to pull heat down in the very front of the tunnel and away from the turbo via forced convection, where the track rotation is the fan. Figure 8 shows the performance values calculated to validate the venturi design.

**Figure 7: Tunnel Venturi**

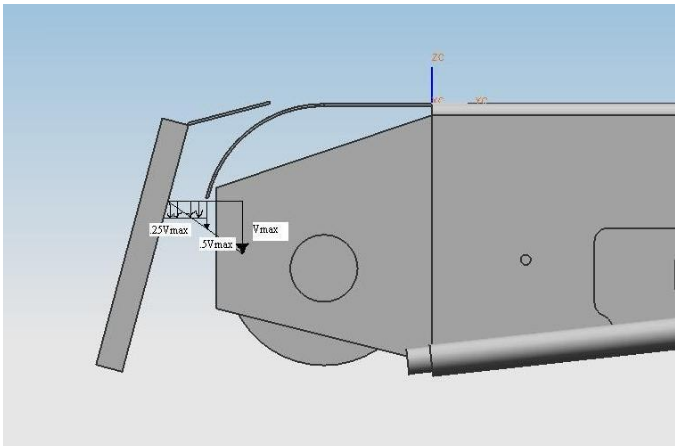
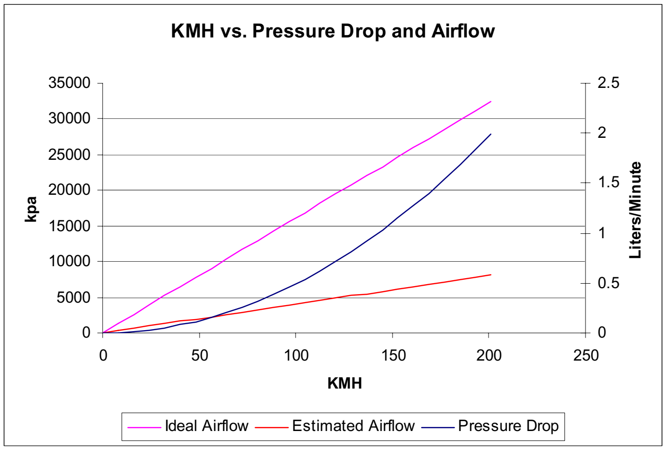


**Figure 8: Pressure Drop and Airflow of Custom Tunnel Venturi**



The estimated airflow is based on a 25% efficiency rate. This value came from the cross sectional area after the venturi doubled in size, thus the air velocity was reduced by a factor of 4. These calculations were done using Bernoulli equations of fluid dynamics. The expected results are between ideal and estimated airflow. The air velocity before the venturi was assumed to be track speed and the pressure above the tunnel was assumed to be atmospheric

## TUNNEL DESIGN

With the center of the tunnel removed, structural changes were necessary to replace the rigidity of the center section. 2.5 cm by 3.8 cm c-channel was attached to the perimeter of the current tunnel to provide structure. A top plate, with an identical thickness to the original tunnel was also added, this replaced the majority of the original tunnel material removed. A Finite Element Analysis (FEA) was used to verify that the modified tunnel is stronger than the original tunnel. Figures 9, 10, and 11 display the tunnel loading and constraint and deflection conditions used for the FEA analysis.

**Figure 9: Tunnel Loading and Constraints**

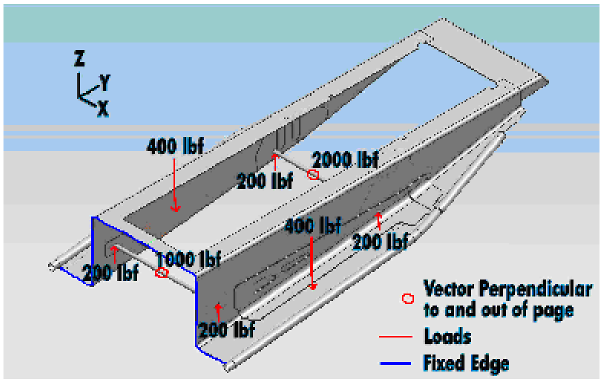


**Figure 10: Stock Tunnel FEA Indicating Maximum Displacement of 3.3cm**

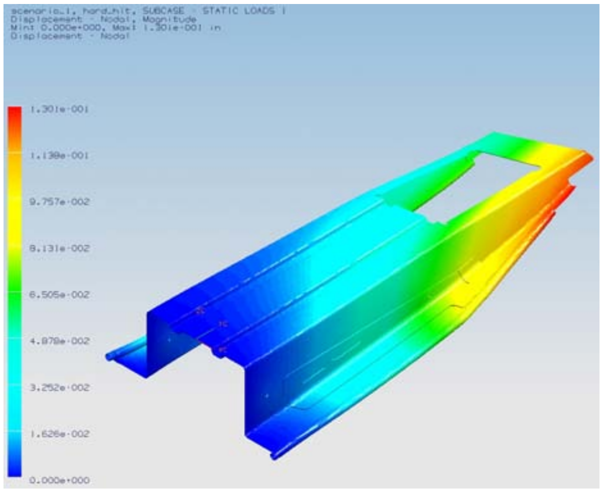
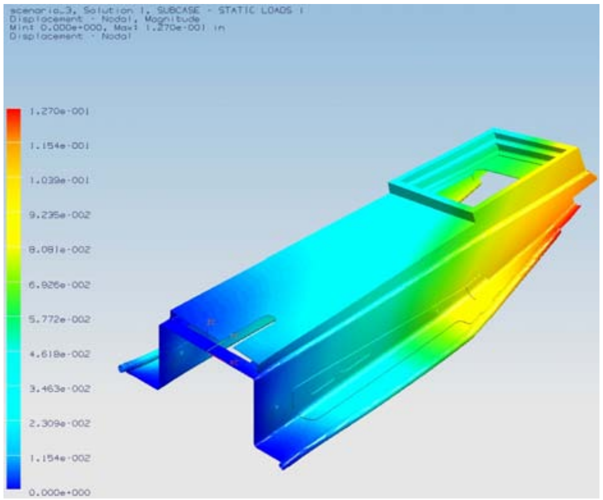
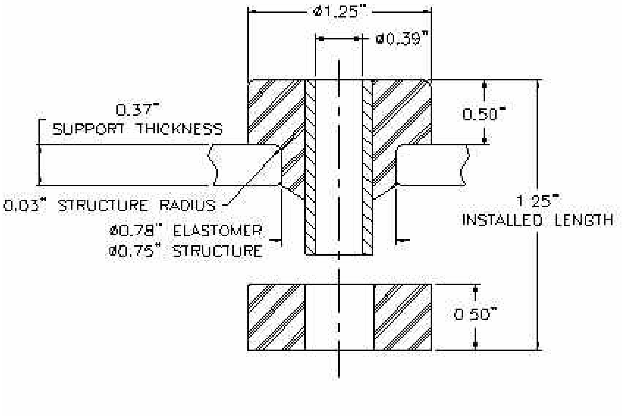


**Figure 11: Modified Tunnel FEA Result Indicating Maximum Displacement of 3.2cm**



With the tunnel sufficiently strengthened, the next step was to mount the muffler. This was accomplished by using Tech Product's universal mounts shown in Figure 12 below.

**Figure 12: Muffler Mounts**



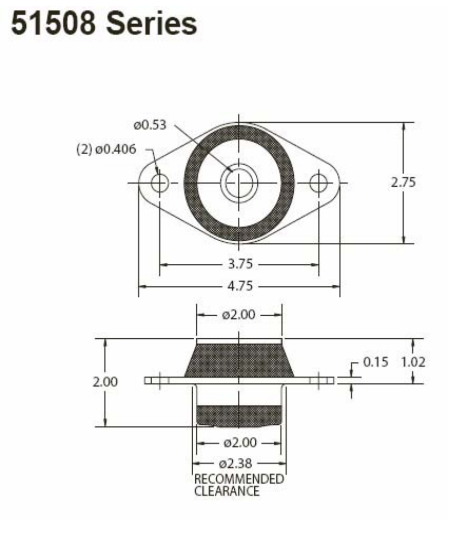
| Part No. | Color Code | Axial Load Rating (lbs.) | Radial Load Rating (lbs.) |
|---|---|---|---|
| 60011 | Yellow | 35 | 18 |

Four of these mounts connect the 11kg muffler to the chassis.

SUSPENSION/REAR SKID

The rear skid mount design this year is a radical new innovation never before implemented in a snowmobile. For structure born noise to be generated, large flat areas must be excited by the 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 13 are an ideal design for the desired application.

**Figure 13: 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. The problem with this mount was that it needed to protrude between 2.5cm to 3cm inside the tunnel based on its size. Therefore an Artic 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.

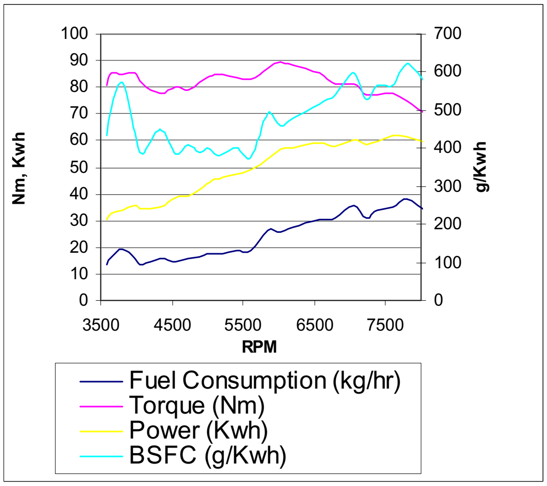
POWER TRANSMISSION

The continuously variable ratio transmission (CVT) is important in tuning for acceleration, noise, and fuel economy. How the transmission performs greatly affects noise and fuel economy. The goal for the clutch tuning was to increase fuel economy and reduce noise.

The CVT and drivetrain remained stock to maintain durability. A Polaris P-85 primary drive clutch was used to transfer power from the engine to the belt. The Polaris P-85 is a proven, lightweight, and durable primary drive. Originally a Pivario V-1 electronically controlled primary clutch was to be run on the 2007 Michigan Technological University Clean Snowmobile. However, due to product development issues with the Pivario V-1 the manufacturer was not able to supply a clutch. A Team Industries Rapid Reaction Roller driven clutch is being used to transfer the power from the belt to the stock Polaris jackshaft. The power is then transferred from the jackshaft to the stock chain case and driveshaft. The Polaris chain case utilizes a plastic slide chain tensioner and hyvo quiet gears, making for a very quiet chain drive. The reverse assembly was removed from the chain case to save on weight, reduce rotating mass, and to simplify access to the chain case. The lightweight stock extruded drive shaft was also utilized.

Depending on load, the CVT determines the rpm at which the engine runs. This is mainly controlled by the fly weights and the primary spring. If the rpm of the engine is too high, both the noise and fuel consumption will increase. Testing was performed to determine the best rpm range to operate the engine at with a cruising speed of 72 km/h. Using the power sweep statistics shown in Figure 14, 5600rpm was identified as the starting point for the clutch calibration as it was shown that the engine's lowest Brake Specific Fuel Consumption (BSFC) occurred at 5602 rpm. The BSFC was 376.3 g/kWh. The peak torque and local power peak occur at 5500 rpm and 5700 rpm respectively, making 5600rpm an ideal range to clutch the engine for cruising.

**Figure 14: Power Sweep Statistics**



Fuel economy was tested over one day on a 65km loop at a steady 72km/h. The test snowmobile was a stock Polaris FST. The best fuel economy achieved was with a 5600rpm engine speed, with a cruising speed of 73 km/h. Fuel economy was tested to be 7.05 km/L, as shown in Table 4. This is an 18% improvement over the stock tested fuel economy of 5.95 km/L.

**Table 4: Fuel Economy Testing**

| | Primary Spring Final/Initial (N) | RPM @72.4 km/h (rpm) | Distance Traveled (km) | Fuel Used (L) | kilometer/ liter (km/L) |
|---|---|---|---|---|---|
| Stock | 444/1512 | 5850 | 65.2 | 10.95 | 5.95 |
| #1 | 400/978 | 5600 | 64.2 | 10.44 | 6.15 |
| #2 | 222/934 | 5500 | 66.1 | 9.38 | 7.05 |
| #3 | 533/1289 | 5700 | 44.3 | 8.03 | 5.52 |

TESTING AND CALIBRATION

For the 2007 competition year, the team implemented two totally new development concepts. First being use of two snowmobiles during the build phase of the competition snowmobile. One of MTU's problems in the past has been the lack of ability to build and test simultaneously. If the engine or chassis were being modified, there could be no suspension, noise, or clutch testing. This year one snowmobile was left stock except for suspension and clutching modifications to allow for the J-192 testing on the rear skid as well as fuel mileage and clutch testing. The second snowmobile was the competition chassis which was left in the shop to allow for engine and chassis modifications to be performed. This greatly increased the amount of testing the team was able to complete, both on the noise and clutches, in addition to dynamometer testing and calibration of the competition engine configuration. Secondly, the team designed and built a dynamometer stand an accompanying computer and instrumentation cart to compartmentalize the engine dynamometer process for engine tuning. The computer cart houses three separate computers and computer monitors. Each computer has a separate function to display and run the ECM software, the dynamometer software, and the five gas analyzer software. Incorporating all three of these systems into a mobile, compact and dedicated platform provided additional simplicity to the MTU engine technicians. The dynamometer computer cart is shown in Figure 15 below.

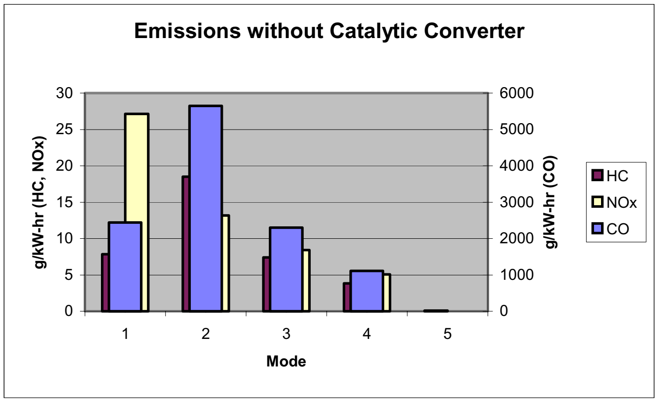
**Figure 15: MTU Clean Snowmobile Dynamometer Stand**

## EMISSIONS

The exhaust emissions were tested in three different configurations. The first configuration was without a catalytic converter, the second configuration was with a catalytic converter, and the final configuration was with a catalytic converter and engine calibration changes.

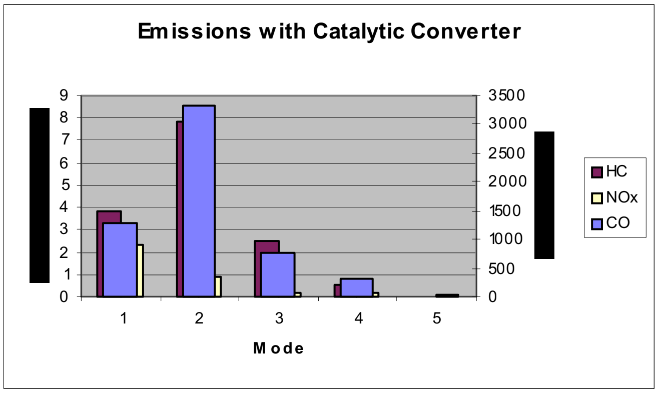
The first configuration can be seen in Figure 16. This test was performed with E85 and no catalytic converter.

**Figure 16: Emissions without Catalytic Converter**



The next configuration was tested with the catalytic converter to evaluate the effectiveness of the converter. The data from this test with the converter is shown in Figure 17.

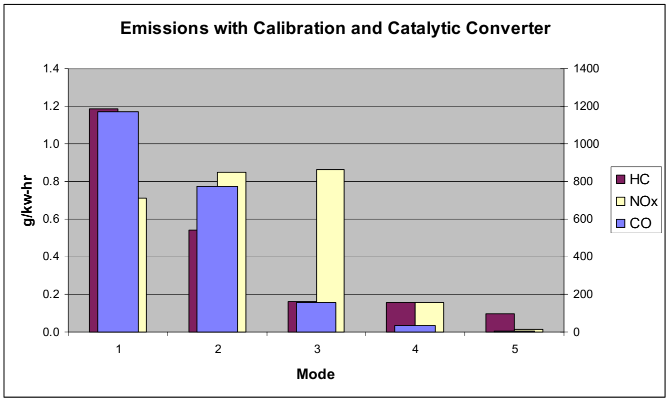
**Figure 17: Emissions with Catalytic Converter**



As seen when comparing the two graphs, there was a significant reduction in all emissions with the catalytic converter installed. Each sample was reduced by approximately 50%. Mode 2 on both tests was higher because the dynamometer was unstable at this operating point; a fix to this problem is being investigated. The instability is triggering fuel enrichments and causing higher emissions.

The final test was done with minor calibration changes. The results can be seen in Figure 18.

**Figure 18: Emissions with Calibration and Catalytic Converter**



To achieve these final results the fuel was leaned out until stoichiometry was achieved and engine ignition timing was retarded to reduce NOx emissions.

## NOISE

In the 2006 Clean Snowmobile Competition, the team goal was to build a snowmobile that had an overall noise output lower than all current production snowmobiles, achieving a sound pressure level of 78 dBA or lower. This goal of 78 dBA was reached in 2006, for 2007 the goal was set at 76 dBA. To achieve this goal for 2007, a new strategy was developed for the engine and chassis package to focus on noise control throughout the design and construction of the snowmobile. This new strategy includes targeting both airborne and structure-borne noise.

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.

### Exhaust Noise Reduction

Since the exhaust layout is under the seat, the muffler is located at the rear of the snowmobile, 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.

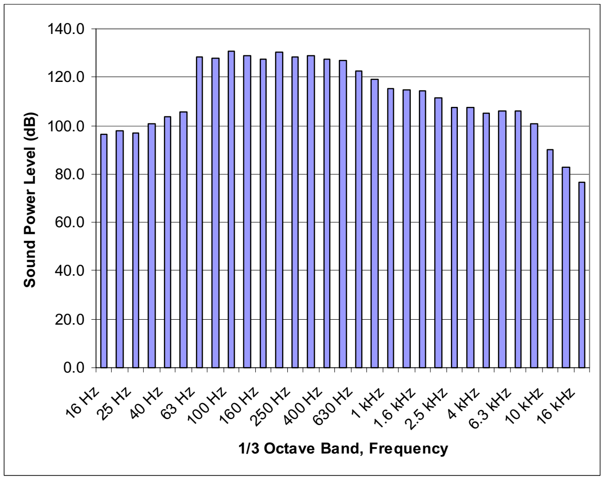
The use of resonators in the exhaust system is effective in removing dominant frequencies of noise produced by the combustion events of the engine. The design of the muffler chambers works to actively attenuate problematic exhaust frequencies.

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 six 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 competition. 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 using two different configurations. The first configuration was an "open" pipe, with no muffler installed while the second configuration tested the custom built muffler. The results of the frequency analysis can be seen in Figures 19 and 20.

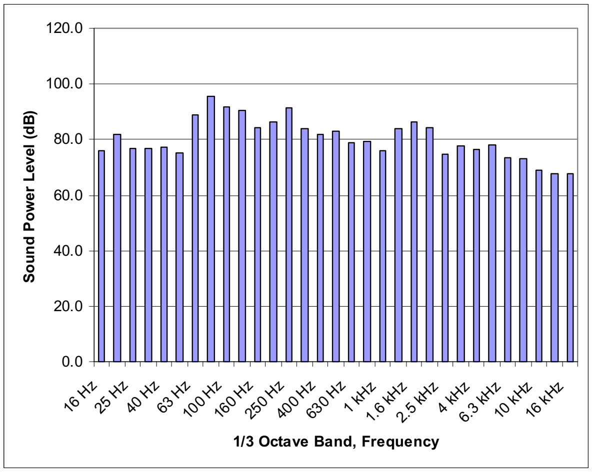
From Figure 19, the peaks in the chart represent the target frequencies. Since there is no well defined peak, the focus of the muffler design was directed towards the frequency band between 100 Hz and 1000 Hz. This range is where the muffler needs to reduce sound power levels the most.

**Figure 19: 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 of 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. The custom designed muffler only dropped the power output of the engine 1.5kW, compared to running no muffler at all. Figure 19 shows the analysis of the MTU designed and built muffler.

**Figure 20: Third Octave Band Frequency Analysis, Custom Designed and Built Muffler**



The results of the near-field noise testing show that the custom built muffler lowered the overall sound power level by 38.5 dB.

Using the temperature of the exhaust, the speed of sound, *c*, for that medium was found to be 1200 m/s. The wavelength corresponding to the dominant frequencies can be found using Equation 1.

$$Wavelenth, \lambda = \frac{c}{frequency} \quad (1)$$

Each internal tube acts as a quarter-wavelength tube so as the sound wave destructively interferes with itself after reflection. Therefore the baffle length is calculated by dividing the dominant wavelength by four. Photographs of the interior packing and chambers used for the muffler can be viewed in Figure 21 and 22.

**Figure 21: Muffler Packing and Expanded Tubes**

**Figure 22: Muffler Chambers**

Once the exhaust exits the muffler it is directed through the tunnel and towards the track of the snowmobile and the ground. This leads to additional absorption of any noise exiting the muffler by the track, snow, and ground.

Intake Noise Reduction

To gain the most intake noise reduction possible, sound absorbing material was installed in the custom made air-box shown below in figure 23, and sound-damping material utilized under the hood.

**Figure 23: MTU Custom Air-box Enclosure**

The new air-box was designed, which will also act as an intake muffler. The interior of the air-box uses sound absorbing foam and a stock air filter to absorb any engine or turbocharger noise that would otherwise escape through the engine intake.

The sound damping material used in the engine compartment is Soundown brand acoustical foam. Both foil-faced sound absorbing foam and foil-faced sound absorbing foam with a barrier layer will be used to control under-hood noise. This foam allows for maximum absorption of sound, while still being fire and heat resistant. To aid in the foam's sound absorbing ability, as many vents as possible in the hood and belly pan were closed off. This creates an anechoic environment in the engine bay and prevents noise from escaping the engine compartment.

Chassis Noise Reduction

With the structural portion of the chassis resolved by the tunnel modifications, the focus shifted to noise. In a simulated J-192 test the stock FST with the stock M-10 suspension measured 1dBA quieter then our team developed isolation system. This seemed unlikely; however, upon questioning several bystanders as to how the snowmobile sounded it was revealed that the suspension system seemed much quieter on the isolated snowmobile than on the stock snowmobile. Their opinion was that the reason the isolated snowmobile was louder was due to track slip. With the Firecat track there is approximately 200cm$^2$ less track on the snow, which contributed to track slip. With this information in hand, the problem of track slip was addressed. Given the test track conditions being a very hard packed, near ice surface, a track was then tested with the two studs per bar allowed by the CSC 07 rules [6], the result was a full 7dB reduction in noise. Once the track slip was addressed any other possible noise sources were addressed, mainly the idler wheels. With all of the idler wheels removed, except the ones on the rear axle, the snowmobile was once again run through J-192 testing. The removal of the idler wheels provided an additional 2dBA reduction in noise. However, again interviewing the panel of bystanders for their opinion they said it sounded significantly quieter then the same setup with wheels. Passing J-192 is very important; however a decrease in subjective noise is also very desirable. It would not have been possible to remove all of the idler wheels for extended periods of time on this very cold, very dry day, as the slide and track wear was just too great.

## CONCLUSION

The 2007 Michigan Tech Clean Snowmobile is an innovative exciting concept of tomorrow. It incorporates technology previously unseen in the snowmobile industry. Some of these technologies include the air to water intercooler, 3-way catalysts and an isolated rear suspension. These innovations have helped to create a snowmobile that is not only cleaner and quieter than its stock predecessor but retains its exhilarating ride characteristics.

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## CONTACT

Dr. Jason R. Blough is an Assistant Professor in the Department of Mechanical Engineering at Michigan Technological University and the faculty advisor for both the MTU Clean Snowmobile Team and the SAE Student Chapter at Michigan Technological University.

ME-EM Department
Michigan Technological University
1400 Townsend Drive
Houghton, MI 49931
Phone: (906) 487-1020 Email:jrblough@mtu.edu

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