Refinement of a High-Performance Four- Cycle Internal Combustion Engine Powered Snowmobile

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ABSTRACT

For 2006, the Michigan Technological University (MTU) Clean Snowmobile Team has successfully implemented a high-performance four-cycle internal combustion engine into an existing snowmobile chassis. This year, the team has refined the 2005 design which featured a 954cc inline 4-cylinder fuel-injected four-stroke engine incorporated into a consumer snowmobile chassis. The incorporation of this engine package, along with a custom 3-way catalyst, team-designed exhaust system, and custom EFI mapping has resulted in exhaust tailpipe emissions well below industry standards, with significant reductions in CO, HC, and NOx emissions. Key areas were addressed in 2006, specifically targeting vehicle reliability and noise output. The net result is a snowmobile that is environmentally friendly and more enjoyable to ride for a wider range of operators.

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 organized by the Society of Automotive Engineers (SAE), and hosted seven universities from across the U.S. and Canada, all of which arrived with snowmobiles that they had designed and built. The machines themselves were evaluated in several static and dynamic areas, 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 MTU's campus. In 2006, the competition remains at the KRC March 13th – 18th, and will feature snowmobiles not only propelled by internal combustion engines, but gas-electric hybrids as well as zero-emission electric motors.

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

For competition year 2005, the team focused on the implementation of a new high-performance 4-cycle engine package into a new snowmobile chassis. Much time and effort was spent integrating the powertrain and chassis, which resulted in limited time for package refinement and testing, namely in the areas of noise output and vehicle reliability. Overall, the team's 2005 effort displayed tremendous potential, placing 2nd in the coveted emissions event, despite being the largest displacement engine at the competition. See Table 1 for a comprehensive results analysis from the 2005 Clean Snowmobile Competition. For 2006, the MTU team has chosen to return with the same platform used in 2005, but to focus on refinements in all aspects of the snowmobile. With these refinements, the MTU Clean Snowmobile Team expects a significant improvement in the satisfaction of the snowmobile riding experience.

Table 1: 2005 Clean Snowmobile Competition Results for MTU

Event	MTU Score	Place (out of 13)
Emissions Reduction	93.6% CO 99.2% UHC 70.8% NOx	2nd
Noise	109 dBA	**Failed**
Acceleration	83.6 points	4th
Endurance Test	0 points	**Failed**
Objective Handling	68.9 points	4th
Subjective Handling	34.0 points	11th
Cold Start	Pass	Pass
Rider Comfort	69.6 points	5th
Oral Presentation	68.0 points	6th
Static Display	44.3 points	1st
Design Paper	85.8 points	3rd
Cost	15.3 points	6th
Overall	816 points	6th

One significant change in the 2006 rules is the absence of a control sled, that is, a sled by which performance and emissions are compared against. This year, each team is required to “beat the standards” that are currently imposed on the snowmobile industry. This shift in design evaluation criteria necessitates a change in the goals for our team. Table 2 is a comparison that was drawn between the goals from 2005 and 2006.

Table 2: MTU Clean Snowmobile Team Goals

2005 Goal	2006 Goal
600 cc two-stroke equivalent performance	Accelerate a distance of 152.4 meters in under 8 seconds
Emissions passing 2012 EPA Regulations as well as surpassing previous designs and entrants to the CSC	Emissions passing 2012 EPA Regulations (see Table 3) as well as surpassing previous designs and entrants to the CSC
Noise output lower than that of any production snowmobile, 105 dBa Sound Power Level	Sound Pressure Level lower than 78dBA per SAE J192 Specification
Easy maneuvering, rider comfort and ergonomics matching that of manufacturer’s snowmobiles	Improve chassis ergonomics and increase test time to improve handling as much as possible

As shown in Table 2, all 2005 goals were easily met. Problems stemmed from a limited amount of testing, and thus it was decided to return to competition in 2006 with a refined version of the 2005 snowmobile.

BACKGROUND

Since the late 1960’s, most snowmobile manufacturers have utilized a two-stroke, spark-ignited engine as the primary power source. The two-stroke engine provides a large power output in a compact, lightweight, low cost design. The inherent disadvantage of the two-stroke engine is its poor control over the gas exchange process, as both the exhaust and intake ports are open simultaneously, allowing intake charge, consisting of air, fuel, and oil, to pass directly through the combustion chamber into the exhaust without being ignited [1]. On average, 20-33 percent of the intake charge is allowed to pass through the exhaust port without being ignited. Another disadvantage of the two-stroke engine is the fact that both oil and gasoline are burned during the combustion process. These operational characteristics lead to high engine-out levels of hydrocarbon (HC) and carbon monoxide (CO) emissions [2].

In recent years manufactures have addressed these emission concerns and have incorporated innovative technology into two-stroke engines. Such innovations include new intake processes, new injector styles, and the inclusion of direct fuel injection to eliminate short-circuiting. This involves injecting a precise amount of fuel into the combustion chamber in contrast to having "approximately" the correct amount of fuel being drawn in along with the air flow. Also, with direct injection, the fuel is better atomized than with standard two-stroke engines, resulting in a cleaner and more complete burning of the fuel. On average, the fuel efficiency of direct-injection two-stroke engines is 30 percent better than conventional carbureted engines [3].

High levels of emissions produced from two-stroke snowmobiles have caused concern among several key environmental groups. In 1997, several of these groups filed suit against the National Park Service, requiring them to conduct an Environmental Impact Study (EIS). This study was titled, “Winter Use Plans Final Environmental Impact Statement for Yellowstone and Grand Teton National Parks, and the John D. Rockefeller Jr., Memorial Parkway” [4]. The EIS has been followed by proposed EPA emissions regulations for off-highway vehicles, including snowmobiles.

The EPA released regulations for snowmobile emissions in September of 2002 [5]. The three-phase reduction calls for a 30% reduction in emissions by 2006, and even larger reductions by 2010 and 2012. Table 3 outlines these regulations.

Table 3: EPA Snowmobile Emissions Regulations

Year of effectiveness	Maximum HC g/kW-hr	Maximum CO g/kW-hr
2006	100	275
2010	75	275
2012	75	200

STRATEGY OVERVIEW

Table 4 is a list of components and equipment specifications used to meet the goals of the MTU Clean Snowmobile Team for 2006. Key vehicle components include chassis, engine, fuel, intake, exhaust, drivetrain, track, and suspension systems.

Table 4: Snowmobile Component Specifications

Component	Description
Chassis	2004 Polaris ProX 800
Engine	Honda CBR 954cc RR, inline 4-cylinder, 4-stroke, dual overhead cam, spark-ignited, liquid cooled
Fuel System	Stock Honda CBR954RR PGM-FI (Programmed Fuel Injection w/modified fuel and ignition mapping), Walbro Inline Fuel Pump
Intake System	Modified Honda CBR954RR Intake System, naturally aspirated, sound-dampened
Exhaust System	Exhaust Headers: Stainless Steel, MTU Clean Snowmobile Team Designed and Fabricated 4-2-1 System, Thermal Barrier Coating and Wrap Catalyst: 500cpsi TS Catalyst Muffler: MTU Clean Snowmobile Designed Super-Critical Dual Muffler System
Drivetrain	Primary Drive: Micro Belmont Reactor Four Tower Secondary Drive: TEAM Fast Reaction, Totally Encapsulated Roller Helix Semi-Direct Drive System incorporating MTU Clean Snowmobile Team Designed Helical Gearbox and Gears Final Reduction: 1.6:1
Suspension	Front suspension: Polaris trailing arm with Fox FLOAT Shocks Rear suspension: Polaris, equipped with Ryde FX shocks with adjustable compression damping
Track	121” x 1.0” x 15” Camoplast Ripsaw Bump Track with 96 Woody’s studs

This paper presents a detailed overview of MTU’s entry for the 2006 Clean Snowmobile Competition. Information regarding the conceptual design, detailed design analysis, manufacturing, and execution of multiple enhancements included on this year’s snowmobile will be included. These enhancements can be separated into three main areas: performance, emissions, and consumer acceptability.

PERFORMANCE

In order for the team to accomplish their performance strategy goals, team efforts were focused on four main areas. These include power adaptation from the engine to a Continuously Variable Transmission (CVT), incorporation of a semi-direct drive system, modification of the chassis structure, and packaging all components in such a manner that would allow the center of mass to be as low as possible while maintaining rider comfort.

POWER TRANSMISSION

For 2006, the team drew upon its previous experience with high-performance four-cycle engines. In 2005, the team used a Honda CBR 954RR engine. This engine has a displacement of 954cc, is spark ignited, and naturally aspirated. The motor is rated 114.8 kW (154 hp) at 11,500rpm. The larger displacement engine was chosen due to its high peak power and torque output which allows the motor to operate in a lower rpm range while exceeding the performance of a smaller displacement engine. This choice benefits the design in many ways, including the advantage of better fuel economy, lower emissions output, and lower noise output, while still achieving high performance capabilities.

In order to fully utilize the motorcycle engine, modifications had to be made to transmit power from the engine to the snow. These modifications include the Power Take Off (PTO) adapter and the semi-direct drive system.

PTO Adapter

CSC rule 4.3.2 states “The snowmobile must be propelled with a variable ratio belt transmission” [6]. The stock Honda CBR 954RR is equipped with a manually-shifted six-speed wet-clutch transmission. In 2005, the team designed and manufactured a PTO adaptation system that eliminated the manual transmission, and facilitated the installation of a conventional CVT system found on all snowmobiles today.

The conversion of the power transmission type was accomplished via the use of a two-piece adapter. The first half of the adapter, the coupler, was machined from 7075 Aluminum, and had a taper that matched that of the magneto end of the crankshaft. The second half of the adapter bolted to the first half, and was machined from 4140 heat treated steel. This half was machined down to a long slender shaft that supports the CVT clutch. The first half is fastened onto the crankshaft, and the second half attached to the first half via six 3/8” Grade 8 bolts and two dowel pins to ensure proper assembly. Figure 1 is a Pro/Engineer solid model of both halves of the adapter. The coupler is installed onto the crankshaft in Figure 2, and the complete assembly can be seen in Figure 3.

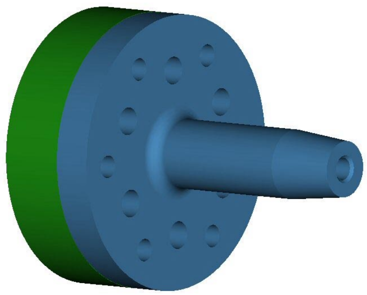

Figure 1: PTO Adapter Model

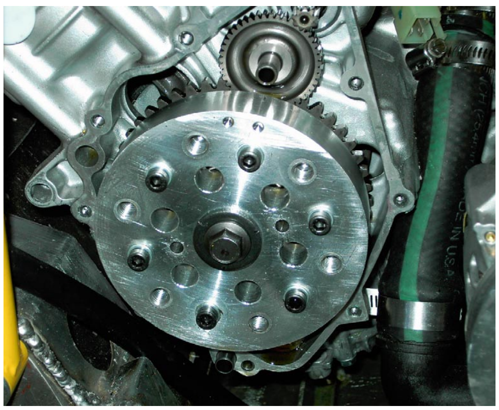

Figure 2: Coupler Portion Installed

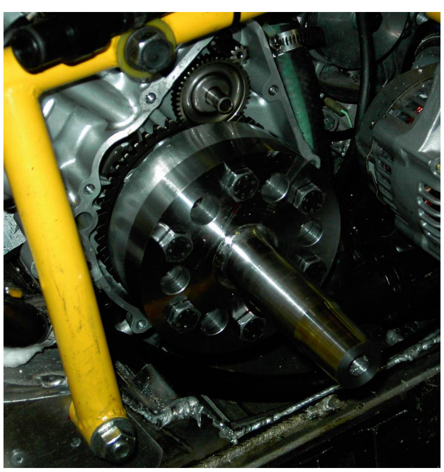

Figure 3: Complete Adapter Assembly

Worst-case belt force loads were calculated given the peak horsepower output and impact loading characteristics of the engine. . Loads calculated were a 1780N force on the end of the shaft in the radial direction due to belt forces seen by the primary pulley, and a pure torsion force of 136 N-m due to the torque produced by the engine. The PTO system was designed for infinite life with these loads applied to the end of the shaft and the torque applied by the engine. Pro/Engineer modeling was done for visualization and interference checking before machining the parts. Both portions were machined from billet using a Computer-Numerically Controlled (CNC) lathe and mill.

The completed analysis for the coupler/shaft assembly includes estimated life due to a fluctuating moment on the portion of the shaft extending out of the cover, as well as a Finite Element Analysis (FEA) of the complete assembly. For the fatigue calculations, infinite life was desired and a safety factor of 1.5 was built into the calculations. The minimum shaft diameter of 32mm was then determined. The FEA analysis was done using the solid model and computer software. The FEA results can be seen in Figure 4.

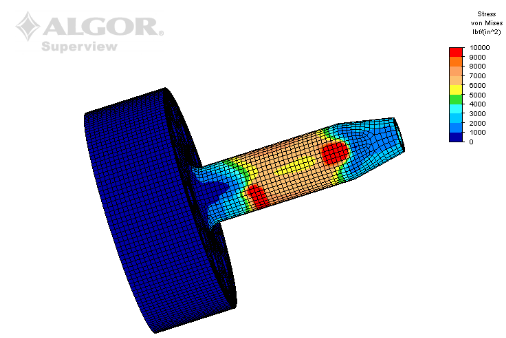

Figure 4: FEA Results of PTO Adapter

<u>Support Cover</u>

The second component involved in the transmission adaptation is a support cover which incorporates a bearing that supports the adapter shaft. The design from 2005 was utilized due to its proven performance both before competition during testing, and during competition. The cover was designed to replace the OEM Honda alternator cover, and support the radial load imposed by belt forces generated by the CVT transmission system. The cover was machined from 6061-T6 aluminum, and has features that retain the starting gear used on the original Honda engine. The cover was machine on a HAAS vertical CNC mill. An NTN 62/32ZZ/2A bearing was pressed into support cover, and features steel shields and self-contained lubrication, facilitating engine speeds up to 11,000 rpm if desired. Bearing load and life calculations were performed under worst case loading conditions resolved from forces calculated for the PTO adaptation system to ensure that no issues occurred. A photo of the completed support cover can be seen in Figure 5.

Figure 5: Completed Support Cover

In ensure structural integrity of the support cover, IDEAS structural Finite Element Analysis was again utilized. For the boundary conditions in the model, the radial input load at the bearing surface was 3 kN. This loading condition is a worst-possible-scenario condition, that is, the existing bearing just inside the support cover carries the entire moment caused by the belt tension. It was assumed that there would be no axial forces at any time during operation. The bolt holes were fixed (no displacement allowed), but rotation was permitted. FEA results can be seen in Figure 6.

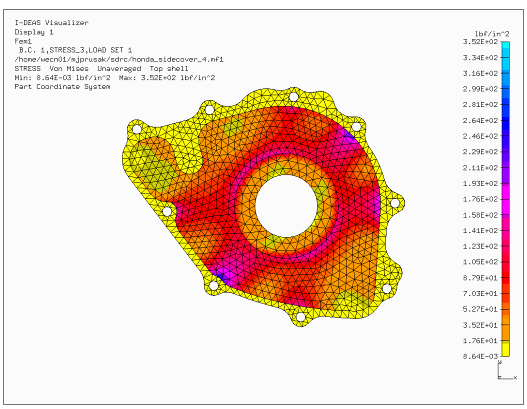

Figure 6: FEA Results of Support Cover

FEA results for every component can be found below in Table 5. The values shown are Von Mises stresses and represent the average stresses on the component.

Table 5: Results of Power Transmission FEA Analysis

Setup	Material	Max Stress (MPa)	Mass (Kg)	Safety Factor
Shaft Assembly	ASTM 4140 + AL7075	215.81	3.04	2.08
Support Cover	AL6061 T6	2.43	3.0	105

Semi-Direct Drive System

A team-designed gearbox and gears were used to transfer power from the secondary clutch to the driveshaft. In 2005, a FAST Industries gearbox featuring straight spur-style gears in a two-gear mesh was used, but generated excessive noise. For 2006, the gearbox again utilizes a two gear mesh which reverses the rotation of the driveshaft from the secondary clutch, but now features helical gears, which are considered a quieter means by which to transfer power between parallel shafts [7]. The reversal of rotation is necessary due to the rotation of the output shaft of the Honda CBR 954RR motor in its mounting configuration being opposite that of a conventional snowmobile engine. The gears were designed to handle loads produced by the engine and to be as quiet as possible. In order to achieve minimum possible noise levels for the gearbox system, several design constraints were necessary. First, the gears were designed with an axial overlap of two, that is, the number of teeth in contact at a given time, which is a minimum standard for proper helical action between the gears [8]. Second, the pitch size of the gears, that is, the size of the teeth, was minimized while ensuring adequate strength properties [7]. Third, the helix angle of the gears was maximized while ensuring that the gearbox bearings could support the increase in axial thrust [7]. For adequate strength properties, AISI 4130 was selected for the gear material and AISI 6150 was selected for the pinion. For sufficient wear resistance and strength characteristics, the pinion was heat-treated to HRC50, and the gear to HRC45. The gear design is set to provide a gear reduction of 1.6:1, creating a mechanical torque advantage at the driveshaft. Structural analysis was performed to determine if weight could be removed from the gears, but the modification would result in lower than acceptable safety factors. It was decided that the small weight advantage was not worth compromising the reliability of the snowmobile drive train system. The completed gear/pinion combination is shown in Figure 7.

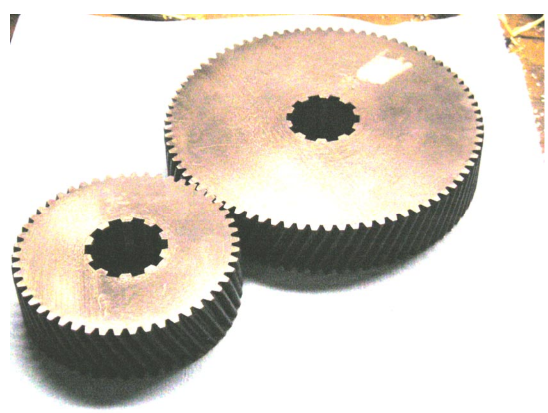

Figure 7: Team-Designed Helical Gear Pair

With the drastic change in gear type for the 2006 design, a new gearbox was designed to ensure drive system integrity. An exploded diagram of the team-designed gearbox can be seen in Figure 8. The gearbox utilizes angular contact ball bearings, two oil seals, and spacers to ensure proper bearing preloading.

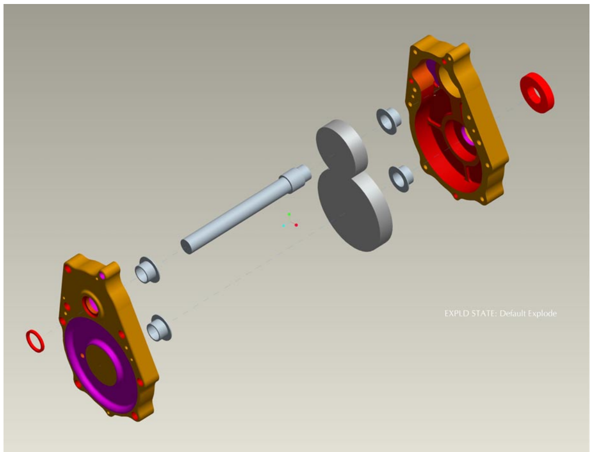

Figure 8: Exploded Model of Team-Designed Helical Gearbox

In order to assure the structural integrity of the gearbox, IDEAS structural Finite Element Analysis was again utilized. Worst-case loads were determined based on the geometry of the gears, along with the peak power and torque output data from the engine in the expected operating range. Maximum radial, tangential and axial loads were determined and resolved onto the surfaces of the gearbox. FEA results can be seen for the both the cover (Figure 9) and the case (Figure 10) below. Table 6 is a tabulation of FEA results.

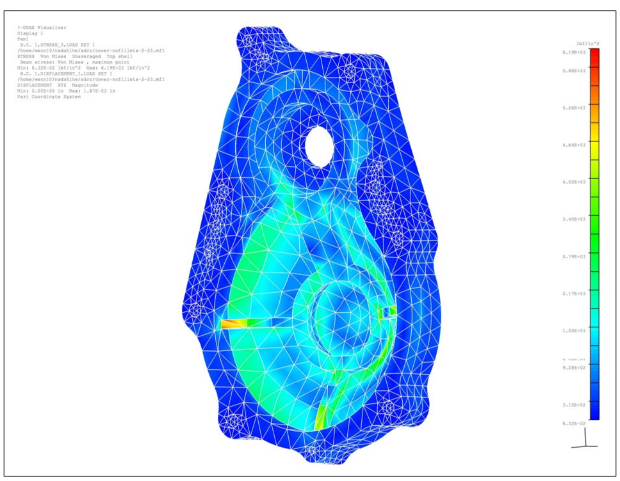

Figure 9: FEA Results of Gearbox Cover

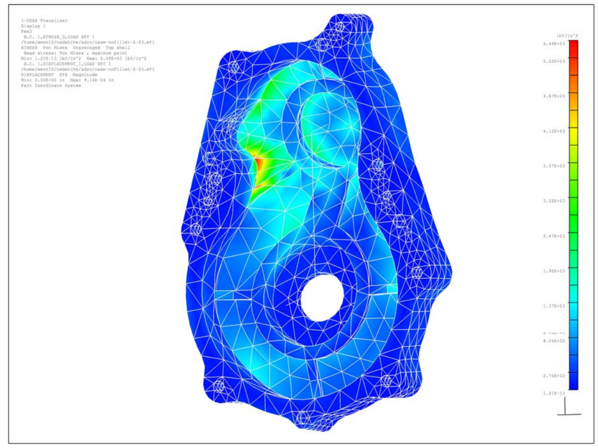

Figure 10: FEA Results of Gearbox Case

Table 6: Results of Gearbox FEA Analysis

Setup	Max Displacement (mm)	Max Stress (MPa)	Safety Factor
Cover	.0475	42.68	6.46
Case	.0232	37.85	7.29

The FEA results clearly show that the team-designed gearbox will withstand loads generated by the engine, and meet all expectations of the snowmobile operator.

To provide a means of power input and output from the gearbox, a custom input shaft and driveshaft were designed and manufactured. Fatigue life calculations were performed for both shafts to ensure adequate safety margins and maximum system reliability. Both shafts were manufactured from AISI 4140 heat-treated steel. To drive the track a set of eight-tooth drivers were installed.

To increase reliability of the semi-direct drive system, an input shaft support brace was designed and manufactured. A photo of the completed brace can be seen in Figure 11. The support spans from the end of the gearbox input shaft to the engine mount structure and to the snowmobile chassis behind the secondary clutch. The addition of this brace reduces the bending moment imposed on the input shaft, increasing the life of the upper gearbox bearings, and the input shaft itself.

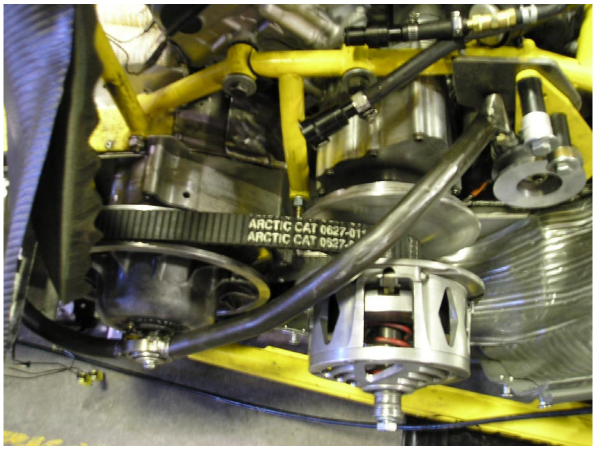

Figure 11: Photo of Team-Designed Input Shaft Brace and Complete Semi-Direct Drive System

The primary clutch was a 20.32 cm diameter Micro Belmont Reactor Four Tower. The clutch was machined from billet aluminum and is capable of handling rotational speeds up to 14,000 rpm. However, the Honda engine operates at a peak of only 10,000 rpm. Typical snowmobile clutches are rated for 9,500 rpm, so a switch to the Micro Belmont style clutch was necessary for safety and reliability of the drivetrain. In addition, the Micro Belmont clutch was tunable, with the ability to tune the vehicle's drive train for the best combination of fuel economy and high-speed performance. Tuning the primary clutch is accomplished via changes to flyweight profile, flyweight mass, and primary spring stiffness.

The secondary clutch was a TEAM Rapid Reaction Dual Roller. The clutch was 27.3 cm in diameter with a totally encapsulated helix to offer exceptional efficiency and quick back-shifting characteristics.

Overall, the semi-direct drive system from the 2006 snowmobile is a quiet, widely-tunable high performance system that will improve the performance of the snowmobile package immensely.

Braking

Slowing the snowmobile down was accomplished by mounting a brake rotor directly to the driveshaft of the snowmobile. This configuration was useful for both packaging and efficiency. With the brake mounted directly to the driveshaft, safety was increased over a more conventional snowmobile brake system using a chain case. In a conventional chain case system, if any part of the system fails, a total loss of brake control will occur due to the fact that the brake is not directly mounted to the driveshaft. In the direct mounting system if any failure occurs in the drive train system, braking is not compromised due to the independent system being mounted directly to the driveshaft. The brake caliper was manufactured by Wilwood and the brake rotor was from an Arctic Cat snowmobile. The rotor was reduced in diameter to 18.1 cm from 20.32cm, providing improved packaging. To maintain the desired braking surface, the caliper was moved closer to the centerline of the rotor and mounted directly to the tunnel. The brake controls were stock Polaris components, with a steel braided brake line connecting the system. This overall setup allows for the best performance and packaging to be achieved.

CHASSIS MODIFICATION

In 2005, the MTU Clean Snowmobile failed the 100 mile endurance event approximately 50 miles from the start. This was due to an excessive buildup of heat under the gas tank, causing the fuel to boil. One of the most time-intensive projects for the team this year was to modify the chassis structure to ensure that the exhaust system was exposed to adequate airflow, reducing the chance for a similar situation to occur this year. This was accomplished in two steps by first designing a ladder structure to retain structural integrity of the snowmobile chassis and then designing a tunnel cover to expose the entire exhaust system to a constant stream of air and snow.

Tunnel Ladder Structure

In order to expose the exhaust system to snow, the upper section of the snowmobile's tunnel was removed. In its place, an aluminum structure similar in geometry to a reinforced ladder was installed. A photo of the installed ladder can be seen in Figure 12.

Figure 12: Team-Designed Tunnel Ladder Structure

This structure was designed to support the compressive, tension, and torsional loads imposed on the snowmobile's tunnel while riding, and was fabricated from 6061-T6 aluminum. The method of direct comparison was used to assure structural integrity since the specific loads during an average trail ride are difficult to quantify. IDEAS Finite Element Analysis was again used to compare the original structure to that of the tunnel ladder. By using this method, an arbitrary input load magnitude was applied, and since the material types were the same and boundary conditions were identical, peak stresses were measured for both designs and compared. FEA plots for both the original tunnel structure and the new ladder-type structure are shown in Figures 13 and 14, respectively. The FEA results are tabulated in Table 7.

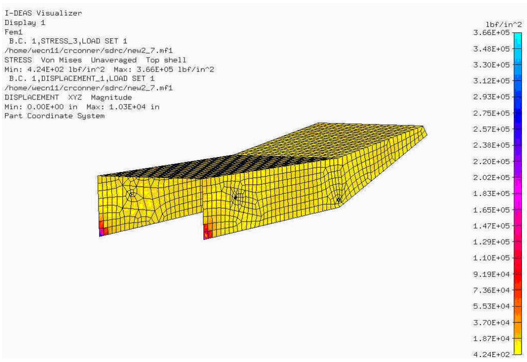

Figure 13: FEA Results of Original Tunnel Structure

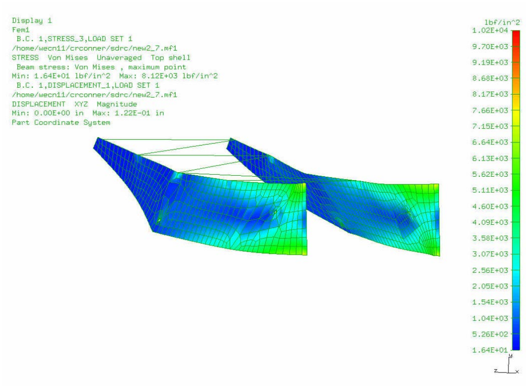

Figure 14: FEA Results of New Tunnel Ladder Structure

Table 7: Results of Tunnel Structure FEA Analysis

Setup	Material	Max Stress (MPa)	Safety Factor
Original Structure	AL6061 T6	2523.48	0.115
New Ladder Structure	AL6061 T6	55.985	5.18

As on can see, the safety factor for the original tunnel is below one, indicating that the loads used in FEA were higher than those seen in the field. Regardless, the new ladder structure yields a safety factor over 45 times that of the original tunnel structure, confirming that the ladder structure is much stronger than the material it replaces.

Tunnel Cover

Since the top of the tunnel had been removed to expose the exhaust to snow, a tunnel cover was designed and fabricated to prevent snow from entering the engine cavity or contacting the driver. In order to manufacture the complex geometry, the rear section of the snowmobile chassis was solid-modeled in Pro/Engineer, and the tunnel cover was designed to cover the entire exhaust system. Figure 15 shows the solid model of the tunnel cover attached to the chassis.

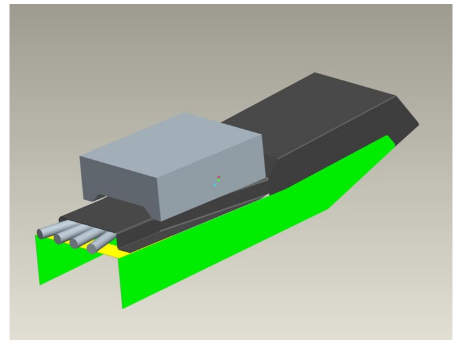

Figure 15: Tunnel Cover Attached to Chassis

Due to the elevated temperature of the nearby exhaust system, it was necessary to find the best possible way to greatly reduce heat transfer to the gas tank and seat. An analysis was done on the exhaust system using RadTherm to determine how the heat was transferred to the tunnel and surrounding parts. RadTherm is a computer program which is used to model heat transfer paths and rates [9]. The first analysis was performed using the 2005 exhaust system and heat shielding. Figure 16 shows a peak temperature on the gas tank surface of 142 °C.

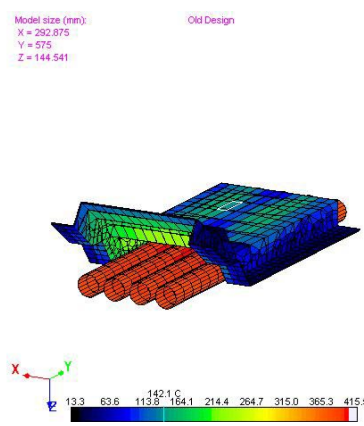

Figure 16: Radtherm Results for 2005 Exhaust System Design

A second RadTherm analysis was performed with the new tunnel cover design. The peak temperature recorded on the gas tank surface was 31 °C, a reduction of 111 °C, or 78%. The results of the second RadTherm analysis are shown in Figure 17. Additionally, extensive testing with the new design has proven that under-tank heat buildup is no longer a concern.

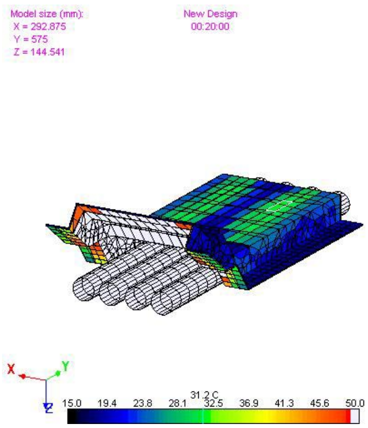

Figure 17: Radtherm Results for 2006 Exhaust System Design

PACKAGING/MASS CENTERING

Modifications to the engine were required to make the larger, four-stroke engine fit in the snowmobile chassis without adversely affecting the overall vehicle handling. Keeping the engine mass as low as possible in the chassis was the primary goal. These modifications included the exhaust/seat lift, air box and remote oil filter assembly modification.

Exhaust System

The exhaust system consisted of three major components including the header, catalytic converter, and muffler. There components were completely designed and fabricated by the MTU team to assist in engine packaging and maintain vehicle performance. The headers, being a key component to engine performance, were designed using Lotus Engine software. The Lotus Engine software was used to calculate a variety of configurations. A model of the engine was created with all the CBR 954 engine specifications, including bore, stroke, cylinder phase, cam lift, cam duration, number of valves, valve area, and valve timing. This model was then used to create power and torque outputs given different header configurations. The header configuration utilized a tri-y setup with different primary and secondary pipes. The lengths of the primary and secondary pipes were altered to optimize power and torque output between 3000 and 7000 rpm. See Figure 18 for the simplified engine model used in the Lotus program. The headers were originally designed for the 2005 snowmobile and performed to the team's satisfaction. With only minor modifications they were able to be used for the 2006 vehicle design.

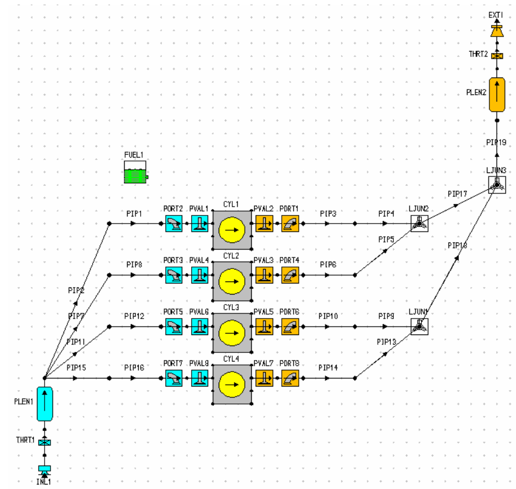

Figure 18: Engine Model Used in Lotus Engine Simulation Software

The entire exhaust system was covered in heat-insulation fiberglass wrap providing three distinct advantages. First, the wrap retained heat inside the exhaust to reduce radiant heat transfer to temperature-sensitive areas of the snowmobile. Second, it protected the headers from direct snow contact, reducing thermal stresses on the exhaust pipes. Third, the wrap maintained high internal exhaust gas temperatures to improve performance and reduce emission output after the use of a catalyst. The header wrap was made by Thermo-Tec and was capable of with standing a temperature of 816 °C. Figure 19 is a photo of the wrapped headers.

Figure 19: Wrapped Exhaust Headers

Intake

The stock Honda CBR air box is located directly on top of the engine with runners directly inline with the intake ports on the cylinder head. This places the air box in the path of the steering post. To address this problem, a set of shorter velocity stacks were purchased providing clearance to modify the air box. The top of the air box was reconstructed using carbon fiber and the volume of the airbox was held constant while a depression was created for the steering post. Figure 20 shows the completed air box with carbon fiber top.

Figure 20: Modified Air Box

Oiling System

The stock Honda CBR engine utilized an oil filter/cooler assembly located directly on the back of the engine block. Due to the installation of the engine into a snowmobile chassis, the original oil filter/cooling assembly interfered with the snowmobile chassis and driveshaft. For the 2005 design, a solid piece of billet aluminum with a press-fit threaded stud was used to relocate the filter/cooler assembly to the front of the chassis. This design proved to be difficult to install and leaked fluid. For 2006, a new, three component, oil block was designed which provided more flexibility to position the oil supply and return lines. The new design consisted of the block, a thru-bolt, and a cover. The components were made from 6061 T6 aluminum. The redesigned system also allowed the use of standard tools to install and remove the block, improving engine service and maintenance. Figure 21 is an IDEAS solid model of the 2006 oil filter relocation assembly.

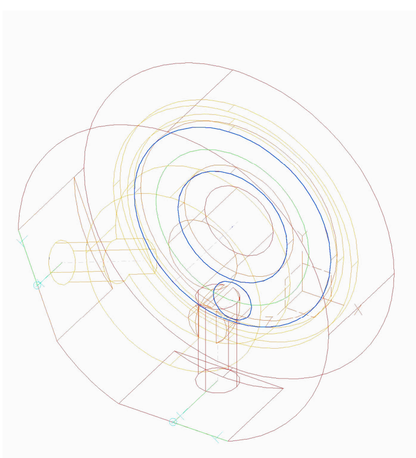

Figure 21: New 2006 Oil Filter Relocation Design

The original engine oil pan was modified to clear chassis structural members and to locate the engine lower and further back in the chassis. The sump was moved out 5.0 cm and back towards the rear of the sled by 3.8 cm.

Changes to the oil system allowed the engine to be moved 16.5 cm rearward and 7.6 cm downward. This move resulted in a much lower center of gravity and helped reduce the negative effects of the larger and heavier engine.

Engine Mounting

For 2005, new engine mounts were fabricated to install the Honda engine into the Polaris chassis. The engine mounts performed exceptionally well at competition and during testing, and were thus retained for the 2006 design. Figure 22 shows the engine mounting system and engine installed in the snowmobile chassis.

Figure 22: Engine Mounting Frame in Chassis

VEHICLE MASS REDUCTION

To improve performance, the power to weight ratio of a vehicle can be increased by either increasing power or decreasing weight. Utilizing a four-stroke engine over a two-stroke engine is a weight disadvantage. To address this concern, the team reduced weight in two main areas: the engine and the drivetrain.

Engine Mass Reduction

The conversion from a two-stroke engine to a four-stroke engine inherently results in an overall engine weight increase. In order to offset this weight increase, the OEM Honda transmission components were removed to reduce the mass of the engine. This resulted in a 62.7N reduction in total engine mass, or 15% of the total engine mass.

Drivetrain Mass Reduction

To reduce drivetrain weight, the team designed a gearbox that eliminated the jackshaft and placed the drivetrain lower in the snowmobile chassis, providing for reduced and lowered mass.

Total Vehicle Mass

Table 8 compares the weight of the 2006 Michigan Tech four-stroke snowmobile and the 2004 Michigan Tech four-stroke snowmobile to an average 600cc two-stroke snowmobile. As the table shows, the 2006 four-stroke design is superior in the area of specific power, even when compared to a production two-stroke snowmobile, and far surpasses designs from years past.

Table 8: Weight, Power and Specific Power: Comparison of Three Snowmobiles

	Dry Weight (N)	Max. Power (kW)	Specific Power (W/N)
2006 MTU 954cc four-stroke	2800	90	32.14
2004 MTU 600cc four-stroke	3247	63.4	19.52
Production 600cc two-stroke	2669	82	30.72

PERFORMANCE DEVELOPMENT

Engine Cooling System

In 2005, the team chose to incorporate an electric water pump to circulate coolant through the engine, a radiator, and one heat exchanger. The electrical demands from the pump were too high and resulted in reduced cooling system reliability. For 2006, the cooling system utilized the original mechanical Honda CBR water pump. The use of a mechanical water pump proved more reliable and lighter compared to the electric pump. To increase the cooling capacity of the engine, a radiator and three separate snow-quenched heat exchangers were utilized. Figure 23 illustrates the cooling scheme for 2006.

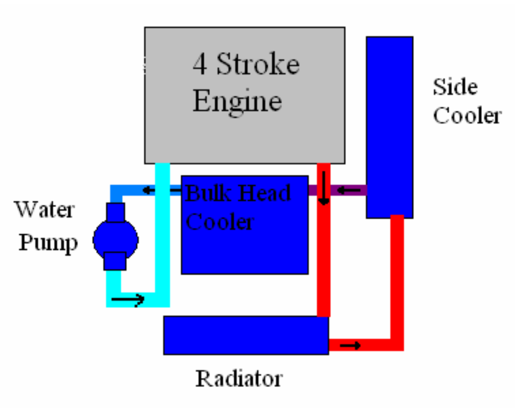

Figure 23: Engine Cooling Schematic

The radiator has a 12 VDC electric cooling fan that is thermostatically controlled to turn on around 100 °C to provide adequate air flow for the radiator.

Electrical System

Due to the CVT adaptation design in 2005, the stock flywheel/stator assembly was removed in order to provide a mounting location for the adapter shaft. This required a new means of generating electrical power. It was decided that the power would be generated from an alternator driven by a belt with a pulley attached to the primary clutch. The flywheel/stator assembly was rated 50 amps at 5,000 rpm. Due to the added current draw caused by the mounting of hand warmers and various additional electrical accessories, the stock rating was used as the minimum rating acceptable for the system. The 2005 design incorporated a 60 amp mini alternator that features a one wire connection due to its internal regulation. The alternator was designed to start charging around 2,500 rpm with an upper limit of 10,000 rpm. A drive ratio of 1:1 was appropriate given that the expected clutch engagement would be above 3,000 RPM and the maximum engine rpm for the design was 10,000 rpm. For 2006, this alternator design was again implemented.

Steering Ability

The steering system that was used in the 2005 competition proved to work sufficiently. The steering post is routed over the engine and is linked with a universal joint near the front of the snowmobile. This system utilized the stock steering rack and tie rods. The approach angle to the rider positions the handle bars in a comfortable location for the operator. Figure 24 shows the complete steering system as mounted in the snowmobile.

Figure 24: Installed Steering System

Suspension/Ride Quality

With the return of the subjective handling and human exposure to whole body vibration events for the 2006 competition, the sled is designed to handle and drive as similar to a production snowmobile as possible. This design was implemented using specific seating and handlebar locations, along with the incorporation of Fox FLOAT shocks. While providing a wide range of settings, the Fox shocks also reduce vehicle mass by incorporating an air spring and eliminating the standard steel coil spring.

EMISSIONS CONTROL

As environmental concern rises, it is becoming increasingly important to minimize both ozone-depleting exhaust gas emissions, and noise emissions. For 2006, the team targeted development in these two specific areas. Extensive testing of both the engine and the snowmobile system as a whole led to significant reductions in both forms of pollution.

EXHAUST GAS EMMISIONS

To reduce exhaust gas emissions and to meet 2012 EPA requirements, the stock Honda PGM-FI with a piggy back fuel system modifier called Power Commander, manufactured by DynoJet Research Inc. was implemented. The Power Commander allows the modification of the fuel and ignition maps via a computer while keeping the integrity and accuracy of the stock system. In order to test emissions at the specified engine operational modes, a Land-and-Sea dynamometer was used to control engine load. The tested modes can be seen in Table 9. An EMS Model 5100 five-gas analyzer was used to measure HC, CO, and NOx. A 3-way catalytic converter was utilized to further reduce exhaust emissions. The converter was supplied by Emitec.

Table 9: Mode Definition for Emissions Analysis

	Percentage of Maximum	
	RPM	**Throttle**
Mode 1	100	100
Mode 2	85	51
Mode 3	75	33
Mode 4	65	19
Mode 5	idle	0

In 2006, the team evaluated three configurations on the Honda engine in an attempt to reduce exhaust gas emissions. First, the original Honda fuel map with the original CBR muffler was tested. Second, the Emitec catalytic converter was added and run with Honda's calibration. Last, the original Honda muffler was replaced with a team-designed quiet muffler, and the fuel injection and ignition timing maps were modified to minimize emissions. Results for these tests can be seen in Figures 25, 26, and 27, and tabulated in Table 10. When comparing the results of all three tests it was easy to see the stock system is very rich with high contents of HC, CO and NOx. The addition of a catalyst brought down CO, and NOx but raised HC due to increased back pressure. The use of fuel tuning and timing adjustments significantly reduced all emissions.

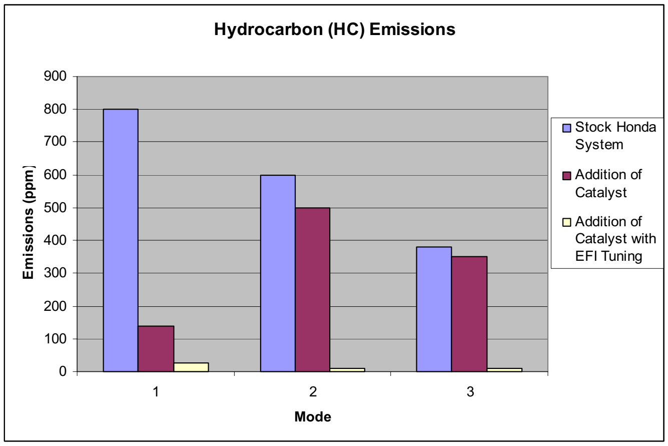

Figure 25: Hydrocarbon Emissions

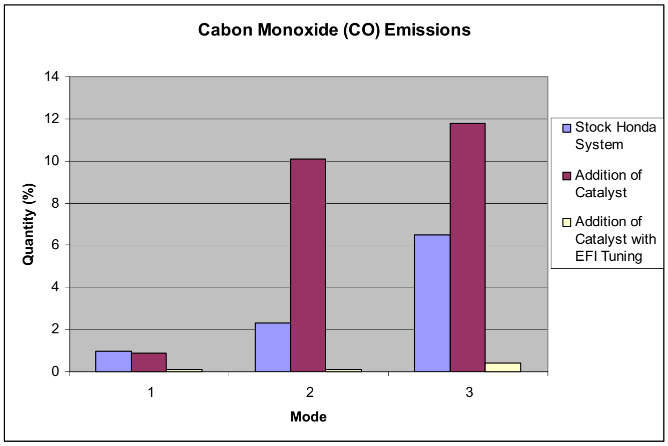

Figure 26: Carbon Monoxide Emissions

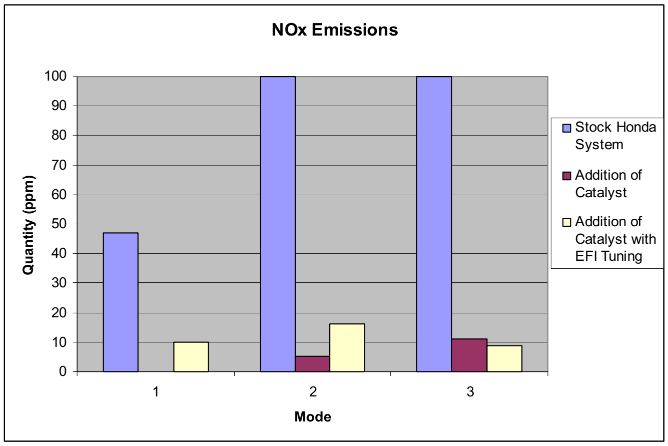

Figure 27: NOx Emissions

Table 10: Percent Reductions in Emissions from Stock Honda Engine Calibration

Percentage Reduction in Emissions	Mode	HC	CO	Nox	Average
Catalyst	1	81	11	99	64
	2	16	-354	95	-81
	3	8	-82	89	5
Catalyst w/ Tuning	**1**	**95**	**90**	**79**	**88**
	2	**99**	**91**	**84**	**91**
	3	**97**	**95**	**91**	**94**

NOISE EMMISIONS

The main focus of the noise team was to pass the SAE J192 snowmobile manufacturers noise test. To pass this test the peak sound pressure level emitted by the snowmobile had to be less than 78 dBA while passing through a noise trap. To be successful in our endeavors this year we have created a snowmobile that has been prepared to be quiet in separate packages. Once the packages are assembled we will have achieved our goal of a quiet snowmobile. To achieve this goal the team has created three packages that were concentrated on: exhaust noise, intake noise, and noise coming directly from the engine compartment. We looked at each area separately which made us focus on the particular problems of that area.

Exhaust Noise Reduction

For 2006, the MTU Clean Snowmobile Team focused on creating a quiet exhaust system, while still maximizing performance characteristics of the engine. The 2006 competition snowmobile uses a catalyst which increases the overall length of the exhaust, causing problems with packaging of the muffler under the seat area. To address this issue a muffler was designed specifically around our packaging constraints. In 2005, specific frequencies were targeted for elimination; for 2006, the team focused its efforts on producing the maximum insertion losses across the entire frequency spectrum. To do so, a two-muffler system was conceptualized, designed and manufactured. In this design, the primary muffler was designed to reduce sound pressure levels at lower frequencies (63-1000Hz) and the secondary muffler's function was to reduce levels at higher frequencies (>1000Hz). The use of two separate mufflers aided in the packaging of the entire exhaust system inside the chassis as well.

For 2006, the primary muffler of choice was that of a super-critical muffler. The advantages of a super-critical muffler are that it is designed for each application and space. A super-critical muffler is defined as having an insertion loss of 35 to 45 dB, a pipe length to diameter ratio of 10 to 16, and a muffler volume to pipe volume ratio of at least 3 [10]. The necessary inputs for the design execution of a super-critical muffler include the peak sound pressure levels, and the frequencies at which they occur. This year's engine had a max dBA of 116 over the range from 250 Hz to 500 Hz. A frequency analysis of the Honda engine under load taken in 2005 can be seen in Figure 28.

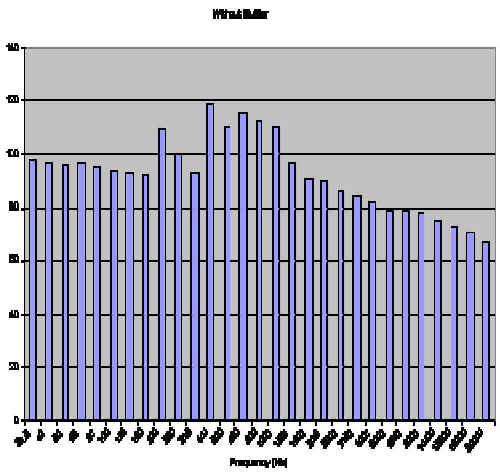

Figure 28: 2005 Honda CBR Frequency Analysis

Following the design criteria in ASHRAE's handbook, the team was able to design and fabricate a super-critical muffler that interfaced with the exhaust header system. A photo of the complete muffler system can be seen in Figure 29.

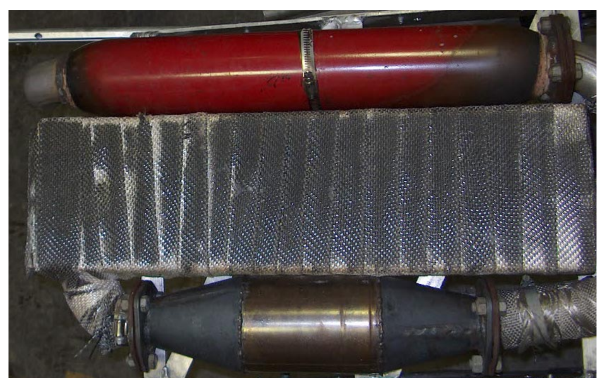

Figure 29: Photo of MTU Clean Snowmobile Exhaust System

After our super-critical muffler was fabricated, the team was able to test multiple secondary mufflers, and determine their effect on noise output and power. Sound pressure level measurements were taken for five mufflers at a distance of 15.2 meters directly behind the exhaust outlet while the engine was operating at 8500 rpm. Figure 30 illustrates the average sound pressure levels observed for each secondary muffler. As one can see, the turbo-style muffler produced the lowest average sound pressure at 82.3 dBA. This muffler reduced peak engine power levels by nearly 4kW when compared to the other four mufflers; therefore, the "Long Red GP" style secondary muffler, as seen in Figure 29, was selected for use in the 2006 exhaust system.

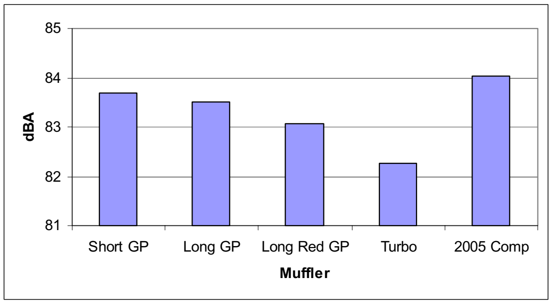

Figure 30: Secondary Muffler Sound Pressure Levels

<u>Intake Noise Reduction</u>

For 2006, the team has comprehensively investigated the effects of engine intake noise on overall vehicle noise. We focused our attention on the intake plenum that we made previous to last years competition. The use of SoundProof foam inside the plenum helped reduce the noise of air traveling through the plenum.

The team tested the intake noise using the SAE J192 as our base test. We tested various configurations with and without the foam. As can be seen in Figure 31, the quietest intake was with the SoundProof foam and the cover. Baseline snowmobiles, including a 2005 Arctic Cat Crossfire 600, and a 2005 Ski-Doo MXZ 600 Rev were compared to the 2006 MTU Clean Snowmobile. As can be seen, the MTU Snowmobile is a full 4dBA quieter than the Ski-Doo control snowmobile.

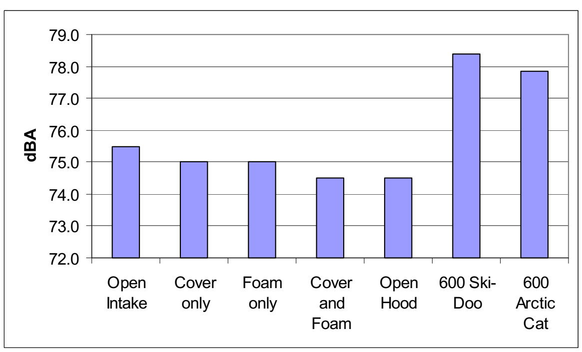

Figure 31: Intake Noise Sound Pressure Levels

<u>Engine Noise Reduction</u>

Preliminary testing on the 2006 competition snowmobile revealed a significant amount of mechanical noise being generated directly by the engine itself. Econo Barrier from American Micro Industries was applied to the engine cavity to reduce transmitted sound levels. This material has an adhesive already applied to one side so we used this to coat the belly pan of the snowmobile. Figure 32 is a photo of the acoustically treated engine compartment.

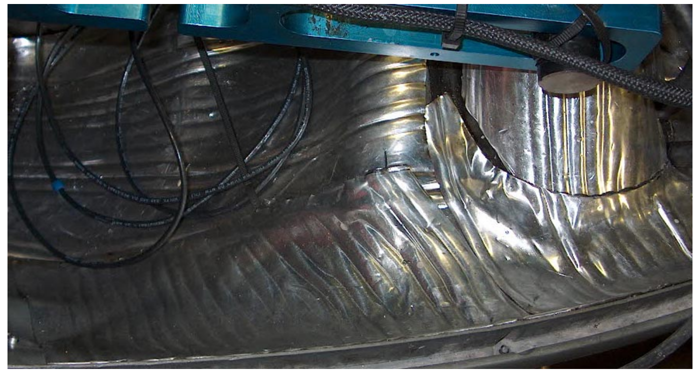

Figure 32: Photo of Acoustically Treated Engine Compartment

For 2006, the Honda engine will again be soft-mounted to the rigid motor mount structure via Urethane bushings. This reduces the amount of energy transmission from the engine to the snowmobile's chassis structure.

CONSUMER ACCEPTABILITY

While designing, fabricating, and refining the snowmobile for the 2006 Clean Snowmobile Competition, the MTU team kept the consumer in mind. The team wanted to produce a vehicle that was designed for snowmobile rental agencies and personal consumers alike. Cost, durability, fuel economy, comfort, ride, and cold engine starting were the most important characteristics for this market.

COST

The cost of the Michigan Tech snowmobile over a conventional snowmobile, as determined from the CSC 2006 Technology Implementation Cost Assessment (TICA) form, is $1346.19. This additional cost compared to current expenditures could be recouped by the rental businesses and customers from reduced maintenance costs, reduced oil consumption, higher durability and lower fuel consumption.

DURABILITY

Honda engine products are well known for their durability and reliability. The CBR954RR is no exception. This engine undergoes rigorous durability tests by the manufacturer and has also been extensively tested by the team. Upwards of 100 hours of dynamometer testing, as well as over 500 miles of actual riding have been performed to test the durability of both the engine, as well as the overall snowmobile package. While this is very limited from a production snowmobile durability test standpoint, initial results are promising.

FUEL EFFICIENCY

Electronic Fuel Injection continuously optimizes the amount fuel delivered to the engine, thus maintaining a consistent air to fuel ratio and increasing fuel economy.

By optimizing the air/fuel ratio throughout the fuel map and avoiding rich conditions, a minimal amount of fuel is used during combustion. This allows the 2006 MTU Clean Snowmobile to achieve fuel economy levels upward of 5.95 km per liter (14 miles per gallon).

COMFORT AND RIDE QUALITY

The team placed great emphasis on the overall ride quality of the snowmobile. In previous designs, ride quality was not emphasized nearly as much. The 2006 snowmobile will treat every rider to the gentlest of rides while still maintaining a high level of performance. This was accomplished through the incorporation of Fox FLOAT shocks into the tried and true Polaris front suspension. This allows the rider to adjust the damping of the suspension with a quick air pressure adjustment, making it easy to tune to varying riders and trail conditions. The rear suspension utilizes shocks with adjustable damping as well. These factors combined with design parameters that include low center of mass, and comfortable seating and steering position give the snowmobile outstanding ride quality.

PERFORMANCE

For 2006, the MTU Clean Snowmobile is not only clean and quiet, but also very performance oriented. Four-stroke snowmobiles would be better accepted by the snowmobile community if they possessed equal or better performance qualities to the two-stroke machines that made snowmobiling the popular sport that it is. The 2006 MTU Clean Snowmobile was designed and built to exceed the performance aspirations of even the most aggressive enthusiasts. Using an engine capable of producing 115 kW (154 hp), the snowmobile can be an exciting machine even to the most veteran riders. Combined with simple and fast suspension tuning, the snowmobile can easily adapt to various riding conditions.

Starting a cold snowmobile can also prove to be a challenge to riders. When a cold start test was conducted during the 2005 competition, the MTU entry fired to life after only approximately 2 seconds of cranking, and continues to start well in extremely cold conditions today.

CONCLUSIONS

The MTU designed snowmobile for the 2006 Clean Snowmobile Competition is a reliable, efficient, quiet, and excellent riding vehicle. The 2005 entry had reliability and noise issues yet showed potential to be a clean, quiet, high performance vehicle. These issues have been addressed with the 2006 design while ensuring that the machine’s inherent strengths are retained. This snowmobile represents the ultimate technology available to the modern snowmobile enthusiast, and sets an unwavering path to a cleaner, quieter, more exciting snowmobile riding experience now and into the future.

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