Breaking Trail for Efficiency:

Enhancing the Polaris Switchback

Joshua B. Ball, Jeffrey C. Levine, Steven J. Nagy, Daniel D. Rahman, Michael D. Rittenour, Andrew B. Wichlacz, Dr. Jason R. Blough
Michigan Technological University

ABSTRACT

The Michigan Technological University Clean Snowmobile Team is entering the 2010 Society of Automotive Engineers Clean Snowmobile Challenge with a redesigned 2008 Polaris FST Switchback. The MTU entry uses a variety of methods engineered to increase fuel economy and rider comfort. A naturally aspirated 750cc four-stroke Weber engine coupled with an AEM engine management system and MTU designed intake and exhaust allow the snowmobile run on ethanol-based fuel while reducing engine emissions and overall snowmobile noise.

INTRODUCTION

To address concerns about the environmental impact of snowmobiles in Yellowstone National Park, the Clean Snowmobile Challenge was introduced in the winter of 2000 in Jackson Hole, Wyoming. The goal was to invite university students to design and produce a touring snowmobile to primarily be ridden on groomed snowmobile trails throughout the park. 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 they had designed and built. The snowmobiles were evaluated in several static and dynamic events, including acceleration, handling, and hill climbs. 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 2010, competition remains at the KRC and runs from March 15th to the 20th. It will feature 19 snowmobiles propelled by either internal combustion engines or zero-emissions electric motors.

In 2009, MTU proved to be a worthy competitor in the design competition with a second place finish. Table 1 shows a comprehensive analysis for MTU in the 2009 competition.

Table 1: 2009 MTU Clean Snowmobile Team Competition Results

Event	Score	Place (Out of 12)
Noise	300/300	1
In Service Emissions	50/50	1
Lab Emissions	178/300	5
Subjective Handling	22.5/50	3
Objective Handling	0/75	7
Fuel Economy	132/200	4
Acceleration	83.9/100	5
Cold Start	50/50	
Weight	17/100	4
Design Paper	74.9/100	6
Oral Presentation	31.2/100	4
MSRP	30.7/50	5
Static Display	50/50	
Penalties / Bonus	100	
Overall	**1120/1525**	**2**

For 2010, the team focused on the underlying design goals of the competition; to design and produce a touring snowmobile to be primarily ridden on groomed snowmobile trails in Yellowstone National Park. Attention was also focused on the overall 2010 competition objective to improve fuel economy. With the focus of improving fuel economy, scoring changes resulted in a 50% reduction to the acceleration event while brake specific fuel consumption and in-service fuel economy events were added.

The top four goals for the MTU team in 2010 can be seen in Table 2.

Table 2: MTU Clean Snowmobile Team Goals

2009 Goals	2010 Goals
Increase horsepower from the 2008 design by 20%	Increase fuel economy by 30% over the 2009 design
Pass 2012 EPA emissions regulations while using flex fuel, as well as surpass all 2009 entries	Pass 2012 EPA emissions regulations while using flex fuel, as well as surpass all 2010 entries
Achieve a sound pressure level lower than 73 dBA per SAE J192 specification	Achieve a sound pressure level lower than 72 dBA per SAE J192 specification
Reduce overall vehicle weight by 7% while maintaining stock ergonomics and appearance	Reduce overall vehicle weight by 12% while maintaining stock ergonomics and appearance

The Michigan Tech team is composed of 27 members from various educational disciplines including Mechanical Engineering, Mechanical Engineering Technology, Civil Engineering, and Business. The team is divided into four sub-teams: engine, chassis, drive train, and business. The first three of these teams are focused primarily on the design and fabrication of the snowmobile. The business team, however, is dedicated to public and sponsor relations as well as team dynamics.

TOURING AT ITS BEST

With pressure coming from both state and federal government bodies, the effort to increase fuel economy for all fueled vehicles is a high priority. The power sports industry is no exception. There are federal noise limits in both Canada and the United States as well as many local noise ordinances which are more strict than the federal levels. For these reasons, the noise generated by a snowmobile is a very important quality of the snowmobile and must be minimized to preserve the available snowmobile trail system and riding privileges.

To design a comfortable and fuel-efficient snowmobile, the team reworked various suspension, chassis, and engine components to reduce weight and improve efficiency. The largest design change was in engine induction, eliminating the turbocharger and related components to make way for a naturally-aspirated system. Table 3 shows a list of components and equipment specifications used to meet the 2010 goals of the MTU Clean Snowmobile team. Key vehicle components include chassis, engine, fuel, intake, exhaust, drive train, track, and suspension systems.

Table 3: 2010 MTU Entry Components

Component	Description
Chassis	2008 Polaris FST Switchback
Engine	750cc Weber Parallel Twin Four-Stroke
Fuel System	AEM Engine Management System
	Mallory 4060FI Competition Fuel Pump
Intake System	**Airbox**: MTU Clean Snowmobile Designed and Fabricated Chambered ABS Plastic
	Intake Plenum: MTU Clean Snowmobile Designed and Fabricated 6061-T6 Aluminum
Exhaust System	**Exhaust Header:** MTU Clean Snowmobile Designed and Fabricated 1020 Mild Steel 2-1 System
	Catalyst: V-Converter 3-way Catalyst with Integrated Noise Dampening
	Muffler: MTU Clean Snowmobile Designed Expansion Chamber Muffler
Drive Train	**Primary Drive:** Polaris OEM P-85
	Secondary Drive: Team Tied Rapid Reaction Roller Secondary
Suspension	**Front Suspension:** MTU Designed and Fabricated 4130 Chromoly Lower A-Arms and 6061-T6 Aluminum Upper A-Arms
	Rear Suspension: MTU Clean Snowmobile Modified Ski-Doo SC-5
Track	120"x1.352"x15" Camoplast Cobra

ENGINE

For 2010, the stock Weber 750cc, four-stroke engine was used as a starting point for modifications. Using the original engine in the selected chassis allowed for more time to be spent on modifications to increase efficiency rather than engine mounting and positioning. Through countless hours of testing and tuning, the Weber engine has proven to be very tolerant and reliable, making it an ideal candidate for a low maintenance production snowmobile.

Head Rotation

The Weber 750cc multi-purpose engine has a symmetrical cylinder head design that allows the engine to operate properly when rotated 180° from the stock position. This effectively reverses the location of the intake and exhaust ports. The rotation is also made possible due to the design of the Weber engine utilizing a central timing chain located between the cylinders. In order to reverse the head, a specially-ground camshaft and modified coolant rail were required. In the stock Polaris configuration, the intake ports face the fuel tank while the exhaust is routed forward under the hood. The configuration used in the MTU entry is rotated 180° from this orientation. This allows for improved packaging, making way for a custom under-hood intake system as well as the entire length of the tunnel for an exhaust system.

Intake

With the implementation of the rotated cylinder head, a new intake system was designed and fabricated to fit under the hood. In previous years a side inlet style plenum was used for ease of connecting to the intake cooling system. For 2010 a symmetrical center inlet plenum was designed allowing for increased and balanced airflow between cylinders. As a baseline, a side inlet design was tested on a flowbench at various speeds to determine airflow rates between each cylinder as seen in Figure 1. This data was imported into a computational fluid dynamics (CFD) program and a base analysis was conducted.

Figure 1: Flowbench Test Setup

With baseline data established, four design concepts were evaluated in Fluent CFD, containing the same parameters as the side inlet baseline analysis. The concepts tested contained geometerys of a center inlet, center inlet with hemispherical ends, center inlet with bellmouth, and dual inlets. All concepts were evaluated at vaious engine speeds and vacuum pressures to mimic engine conditions. The results from each concept can be seen in Figures 2-5.

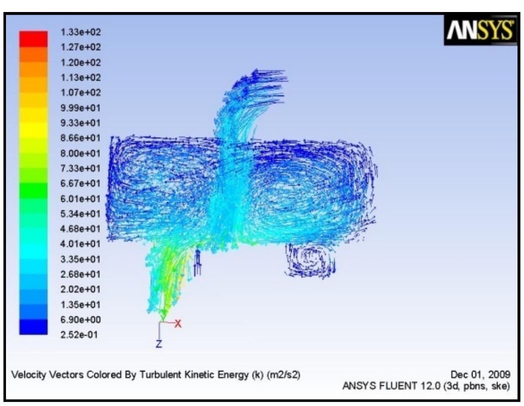

Figure 2: Center Inlet Fluent Flow

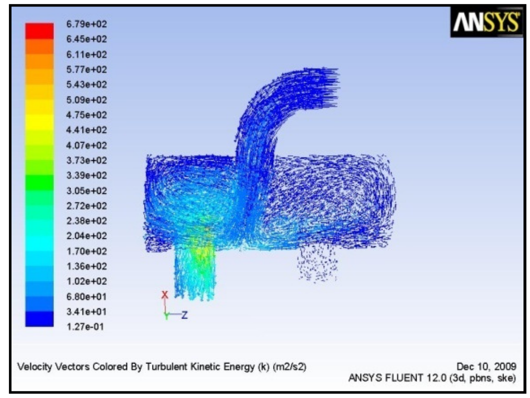

Figure 3: Center Inlet with Bellmouth Fluent Flow

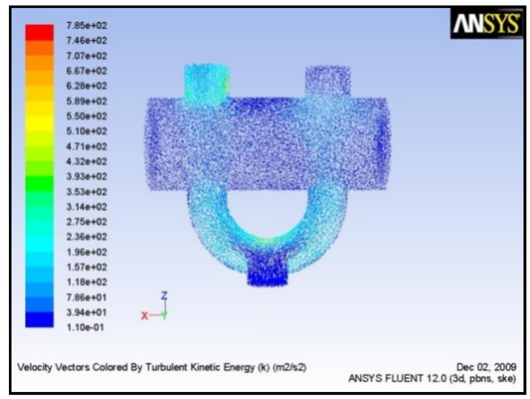

Figure 4: Dual Inlet Fluent Flow

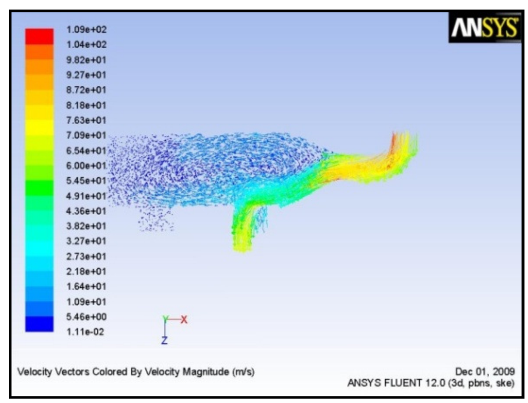

Figure 5: Side Inlet Fluent Flow

The volumetric flowrate for each cylinder was determined and compared against each other as seen in Appendix A: Fluent Flow Test Results. It was found that all center inlet designs had a greater balance of airflow between cylinders than the side inlet design. However, all center inlet designs had a slightly lower flowrate than the side inlet. The Dual Runner design had both a higher volumetric flow rate and the smallest imbalance between cylinders. The dual runner design was choosen for use on the 2010 snowmobile allowing for optimized and precise tuning.

Turbocharger Removal

The stock Polaris FST was a turbocharged engine. For the 2010 entry, the turbocharger has been removed to enhance the development of a high fuel mileage touring snowmobile.

Turbocharged engines generally require more fuel to reduce the occurrence of detonation due to the increased temperature and pressure of the intake air. These effects cause a turbocharged engine to consume more fuel per horsepower per hour than a normally aspirated engine.

With the turbocharger removal, the engine's brake specific fuel consumption (BSFC) will decrease. Using the general concept that BSFC should be between 0.45 and 0.50 Lb/HP*Hr for naturally-aspirated engines, 0.55 and 0.60 for supercharged engines, and 0.60 and 0.65 for turbocharged engines, the recommended fuel flow rate for our engine was determined from Equation 1.

$$\text{Fuel Flow (Lb/Hr)} = \frac{\text{Power} * \text{BSFC}}{\#\text{ of Injectors} * \text{Duty Cycle}} \qquad (1)$$

Power = Max Engine Power
BSFC = Ideal BSFC

Using Equation 1, an ideal BSFC of 0.45 Lb/HP*Hr, estimated engine power of 60 HP, and 2 fuel injectors at a maximum duty cycle of 80%, it was determined that a fuel flow rate of 16.97 Lb/Hr was needed. This correlates to 178cc/min, a 76.3% decrease from the 750cc/min rate used in the turbocharged configuration.

Exhaust

With the removal of the turbocharger, the exhaust system had to be evaluated and redesigned to work with the rotated head and new rear packaging options. The new exhaust system design was produced as a 3-D model and imported into the SolidWorks software for FEA to be conducted. An analytical modal analysis study was then performed on the system. Boundary conditions were applied that imitate the system's rubber isolation mounts on the muffler and solid mount of the header to the engine block. The natural frequencies and mode shapes gathered from an experimental modal analysis were then used to validate and update the FEA model to more accurately represent the frequencies and mode shapes of the actual exhaust system.

After estimating the first five natural frequencies and mode shapes in FEA, mode four was re-examined to understand the mode shape as this shape was excited very near to the snowmobiles trail cruising rpm. From this analysis, an area of concern was found. This area shows a section where the stresses are high and may cause failure. From the analysis it was determined that a flexible joint at this location was needed. A ball joint was used for this purpose due to its ability to seal while allowing movement in all directions, and can be seen in Figure 6.

Figure 6: Exhaust Joint

Initially, the exhaust system was fabricated with stainless steel because of its high temperature strength and corrosion resistance. Through trail testing, it was found that stainless steel has properties which cause it to expand and contract frequently due to changes in temperature. With a snowmobile's exhaust system vulnerable to expansion and contraction due to hot exhaust gas flowing through the pipe, a high thermal gradient across the material was present. Snow and ice are thrown into the snowmobile's tunnel hitting where it hits the exhaust pipe and creates a rapid decrease in temperature. It was apparent that this thermal shock was repeatedly occurring and causing failures of the exhaust system. To fix this problem, 1020 carbon steel was used in the final exhaust system design due to the lower thermal conductivity as well as the lower thermal conductivity coefficient. These two important material properties led to a robust exhaust system with no failures in testing.

Increased Compression Ratio

For 2010 the compression ratio of the Weber engine was increased from 9.5:1 to 11:1. This was accomplished through the use of different pistons. In the turbocharged engine, dished pistons are used. For the naturally-aspirated engine, flat-top pistons from the similar Weber watercraft engine were selected for use. By eliminating the dish in the piston, the clearance volume within the combustion chamber was decreased, in turn increasing the compression ratio. This relationship can be seen in Equation 2.

$$CR = \frac{V_d + V_c}{V_c} \qquad (2)$$

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

Based on information from the book *Internal Combustion Engine Fundamentals* by John B. Heywood, efficiency and exhaust temperature are positively influenced by increasing the compression ratio. [6] The relative efficiency of the engine was expected to improve between 3% and 6% overall. Exhaust temperatures are also known to decrease as compression ratio and efficiency increase. Another benefit to increased compression ratios are reduced energy losses, in the form of heat transfer, to the combustion chamber walls. Although an 11:1 compression ratio is higher than the stock 9.5:1 ratio, more than 250 hours of dynamometer run time and 500 trail miles have verified this to be an acceptable option.

Oil Cooler

Through extensive dynamometer testing, it was determined that the Weber engine runs more efficiently with hotter oil temperatures than attainable with the stock configuration. Analysis showed that increasing the oil temperature to 200°F, 20°F more than the normal 180°F, was ideal. This was achieved by removing the stock water-to-oil cooler and replacing it with an air-to-oil cooler. This cooler was strategically placed inside the belly pan to allow minimal airflow. Installation of the air-to-oil cooler also reduced vehicle weight by 1.02 pounds, not including the weight of additional coolant and oil from connecting hoses.

Flex Fuel Implementation (E20-29)

For the 2010 Clean Snowmobile Competition, teams competing in the IC engine division are required to run flex-fuel. Today's flex-fuel vehicles operate on a blend of gasoline and ethanol ranging from E10 (10% ethanol; 90% gasoline) to E85 (85% ethanol; 15% gasoline). The focus fuel range for the 2010 Clean Snowmobile Competition will be between E20 (20% ethanol; 80% gasoline) and E29 (29% ethanol; 71% gasoline).

On the MTU snowmobile, a Siemens fuel composition sensor was chosen to detect the fuel's ethanol content. This sensor outputs a square-wave frequency between 50 Hz and 150 Hz. A 50 Hz output corresponds to 0% ethanol, while a 150 Hz output corresponds to 100% ethanol. The frequency was then sent to a custom-made frequency-to-voltage converter. This converter produces a programmable 0-5V output depending on fuel content, allowing information to be transferred into the EMS. The AEM EMS used on the 2010 snowmobile does not have a provision for flex-fuel. Therefore, the voltage is sent to a generic AEM input. This configuration allows the EMS to add/subtract fuel from the current fuel map based on the 0-5V input. Using various controls within the EMS, the ignition advance map will switch between a high timing advance (fuels from E25-E29) and a mild timing advance (fuels from E20-E24).

A baseline fuel map was created using E85. A modified version of this map was used as the reference point for flex-fuel compensation. From this base map, the fuel trim system compensates based on the 0-5V input. Table 4 shows the control algorithm used for the system. If the fuel's ethanol content falls outside or between values listed in the table, the processor in the AEM EMS will automatically interpolate and extrapolate based on a system of averages. This control algorithm is based upon stoichiometric air/fuel ratios for the various ethanol blends. This ratio is important because it provides proper, detonation-free combustion.

Table 4: AEM EMS Fuel Trim Table used for Flex Fuel Implementation

Input (V)	Ethanol Content (%)	Adjustment (%)
0	12.50	-25.7
0.3125	14.05	-25.33
0.625	15.65	-24.96
0.9375	17.20	-24.59
1.25	18.75	-24.22
1.5625	20.30	-23.73
1.875	21.85	-23.25
2.1875	23.45	-22.76
2.5	25.00	-22.27
2.8125	26.50	-22.215
3.125	28.10	-21.71
3.4375	29.65	-21.21
3.75	31.25	-20.7
4.0625	32.80	-20.21
4.375	34.35	-19.73
4.6875	36.00	-19.24
5	37.50	-18.75

Emissions

For 2010, a reduction in engine emissions from both the 2009 MTU entry as well as a baseline test snowmobile was a main focal point. To achieve lower engine emissions, two options were utilized. The first involved extensive catalyst testing to determine which catalyst makeup would give the best benefit. After selecting the correct catalyst, precise engine management system tuning allowed for fuel and ignition to be altered allowing the lowest possible engine out emissions. To select the correct catalyst, emissions data was collected while the engine was run on a dynamometer at various rpm. The data was collected using an EMS model 5001 gas analyzer and compared to the final engine out emissions from the 2009 MTU competition entry.

Recognizing that a three-way catalyst would give the results sought, two new catalysts were chosen to test and the results can be seen in Table 5.

Table 5: Engine Out Emissions Data

Engine Emissions - 2009 Catalyst			
RPM	**HC (ppm)**	**CO (%)**	**NOx (ppm)**
Idle	259	3.09	1
3000	235	3.62	1
4000	114	3.44	2
5000	103	5.13	5
6000	93	5.14	7
7000	73	4.84	8
Engine Emissions - Catalyst 1			
RPM	**HC (ppm)**	**CO (%)**	**NOx (ppm)**
Idle	472	3.97	12
3000	152	4	20
4000	167	4.2	47
5000	149	5.49	33
6000	129	5.29	52
7000	134	5.59	50
Engine Emissions - Catalyst 2			
RPM	**HC (ppm)**	**CO (%)**	**NOx (ppm)**
Idle	37	3.66	4
3000	44	2.37	3
4000	41	2.82	8
5000	24	3.39	19
6000	9	3.15	31
7000	27	4.03	37

From Table 5, it can be seen that Catalyst 2 provided the lowest emissions results. From this data, a final catalyst makeup was determined and produced to further reduce the engine emissions. Table 6 shows the final engine out emissions levels for the 2010 MTU snowmobile.

Table 6: Final Engine Out Emissions Data

RPM	HC (ppm)	CO (%)	NOx (ppm)
Idle	21	2.15	2
3000	32	2.56	4
4000	34	2.68	8
5000	31	3.57	12
6000	22	3.87	15
7000	30	4.63	21

Figure 7 shows the emissions trends at various RPM's for the respective snowmobile. When comparing Figures 7 and 8, a noticeable emissions decrease can be seen between the stock Polaris FST and the 2010 MTU entry.

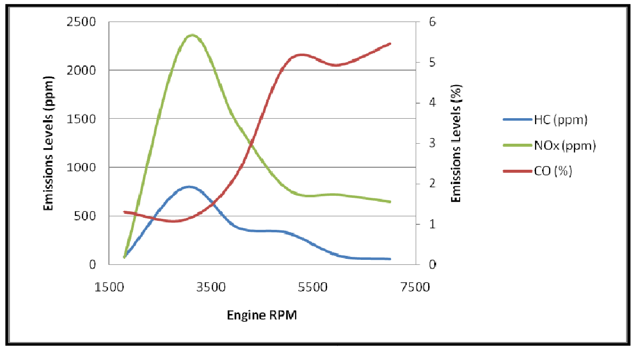

Figure 7: Stock Engine Emissions

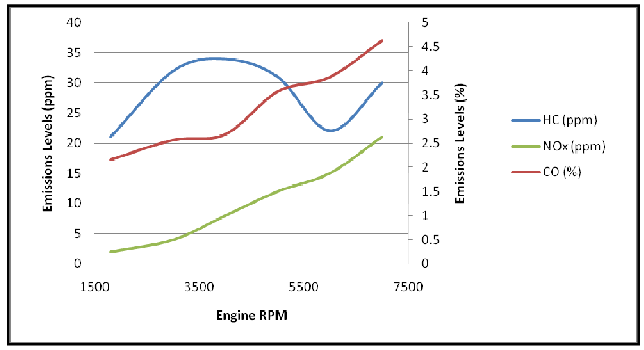

Figure 8: MTU Engine Emissions

CHASSIS

The chassis chosen for the 2010 entry was a 2008 Polaris FST Switchback. This chassis provided the team with the most advanced chassis incorporating the four-stroke engine, while also having a long tunnel to allow for exhaust packaging. To give the snowmobile an updated look, 2010 plastics off of an RMK were installed.

<u>Tunnel</u>

The 2008 FST Switchback tunnel is constructed of five structural members. Due to the desired layout of the exhaust system, the center piece of the tunnel was removed. This can be seen in Figure 9.

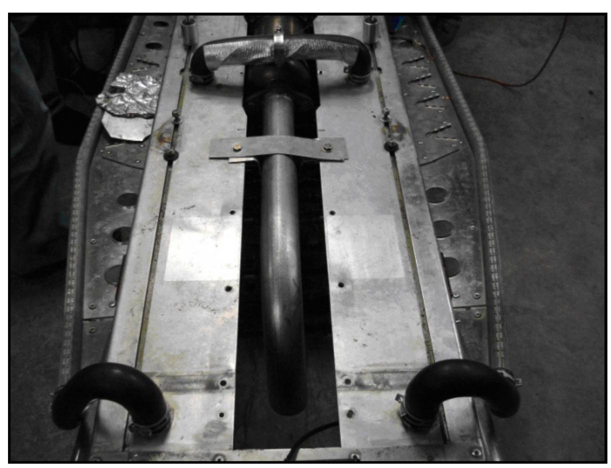

Figure 9: Switchback Tunnel with Removed Section

In order to make this change, the structural integrity of the tunnel had to be verified and proven through FEA. Since the exact loads experienced by the tunnel were not known, a comparative analysis was performed against the stock tunnel. It was deemed that modifications made would be acceptable if the maximum stresses and displacements present were similar to the stock tunnel. The first step in this process involved constructing a 3-D model of the tunnel in the stock configuration. The model can be seen in Figure 10 along with loading constraints and the assigned boundary conditions. The tunnel was fixed in all six degrees of freedom at the edge where it mounts to the bulkhead. At the rear suspension mounting points, a 500-pound torsion load was applied. Other methods of loading were also tested, but torsion was determined to be the most severe loading case.

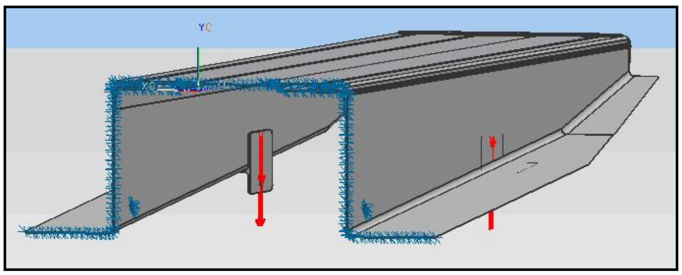

Figure 10: Stock Tunnel Model with Loading Constraints

Upon completion of modeling, the FEA was run. This yielded a baseline for our comparative analysis. The results of the stock tunnel FEA can be seen in Figure 11 which shows a maximum displacement along the edge of the running board of 0.1020". The maximum stress found was 12.67 ksi.

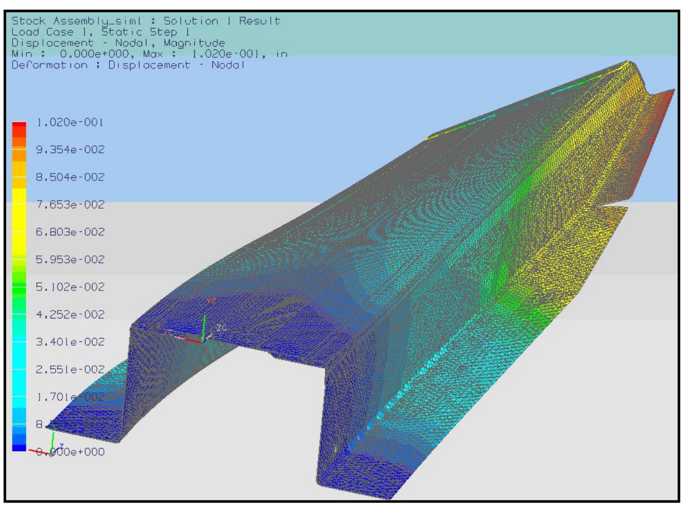

Figure 11: Stock Tunnel Displacement Results

After the analysis of the stock configuration was completed, a model representing the desired modifications was constructed. Modifications made included adding a tubular tank lift system at the front of the tunnel as well as a tunnel bubble down the entire length of the tunnel. The tunnel bubble provided a heat barrier between the exhaust system and the gas tank as well as added structural support. The same loading constraints and boundary conditions were then applied to this model. These can be seen in Figure 12.

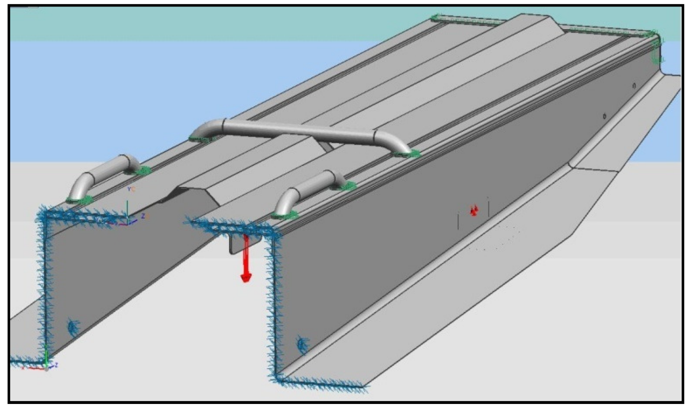

Figure 12: Modified Tunnel with Loading Constraints

FEA was then run on the modified tunnel model, and results can be seen in Figure 13. Upon inspection of the results, it was verified that the desired modifications would maintain the structural integrity of the tunnel. The displacement of the modified tunnel was found to be 0.1019" which was virtually identical to that of the stock tunnel, thus, the differences in displacement can be considered to be negligible. The maximum stress that resulted was 12.06 ksi, again, similar to the stock tunnel loading scenario.

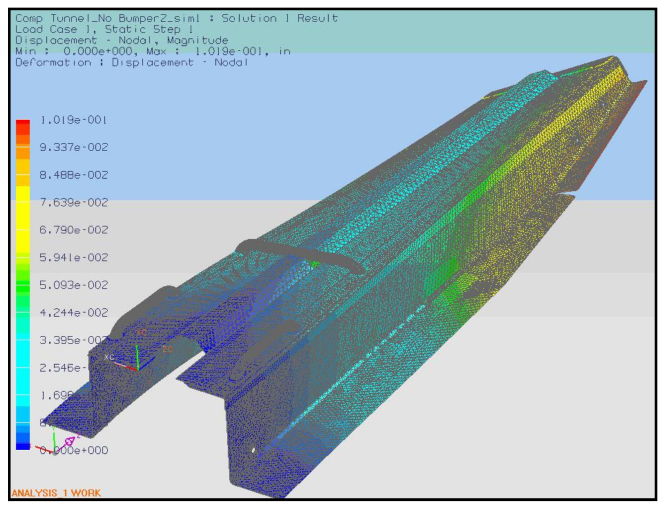

Figure 13: Modified Tunnel Displacement Results

<u>Rear Suspension</u>

A survey of industry publications showed that the stock Polaris M5 suspension is not considered the best suspension on the market. To increase the ride quality of the 2010 entry, a 2009 Ski-Doo SC-5 suspension was installed.

To determine the effects of the suspension changes, accelerometers were placed on the handlebars, running boards and seat of the MTU entry and a stock Polaris FST. Data was collected while the snowmobiles were driven over a constructed course at 15mph and again at 25 mph. From the data, it was determined that the SC-5 did provide a reduction in acceleration at the seat in the vertical direction, which can be seen in Figure 14. Test setup and data collection can be seen in Figure 15.

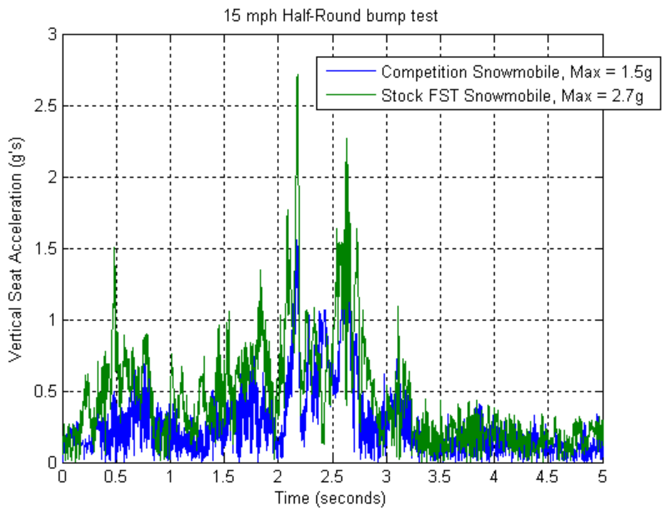

Figure 14: 15 mph Seat Acceleration

Figure 15: Suspension Data Testing

Using four riders, a subjective ride quality test was performed on the stock FST and the 2010 entry. From this experiment, it was determined that the Ski-doo SC-5 suspension provides a 42% increase in rider comfort to the stock Polaris M5. The subjective scores can be seen in Table 7, where each category was rated on a 1 to 10 scale.

Table 7: Subjective Suspension Test Results

Rider 1		
Snowmobile	**FST**	**MTU**
Handling	4	7
Shock Absorption	3	9
Ride Quality	4	7
Rider 2		
Snowmobile	**FST**	**MTU**
Handling	5	6
Shock Absorption	3	6
Ride Quality	5	6
Rider 3		
Snowmobile	**FST**	**MTU**
Handling	3	5
Shock Absorption	2	8
Ride Quality	4	7
Rider 4		
Snowmobile	**FST**	**MTU**
Handling	6	6
Shock Absorption	4	8
Ride Quality	5	8
Total	48	83

Different methods were tested to reduce friction caused between the rear suspension and the snowmobiles track. Of these methods tested, installing hyperfax slides provided the efficiency gains sought. By implementing hyperfax slides, a reduction of 6.2 lbs of force was required to rotate the track over the standard plastic slides.

Front A-Arms

The stock Polaris front suspension consists of two unequal length, non-parallel A-arms with a coil-over shock mounted to the lower control arm on each side. A 3-D model of this suspension can be seen in Figure 16. In an effort to reduce the overall weight of the 2010 competition snowmobile, the front suspension A-arms were redesigned using various lightweight materials.

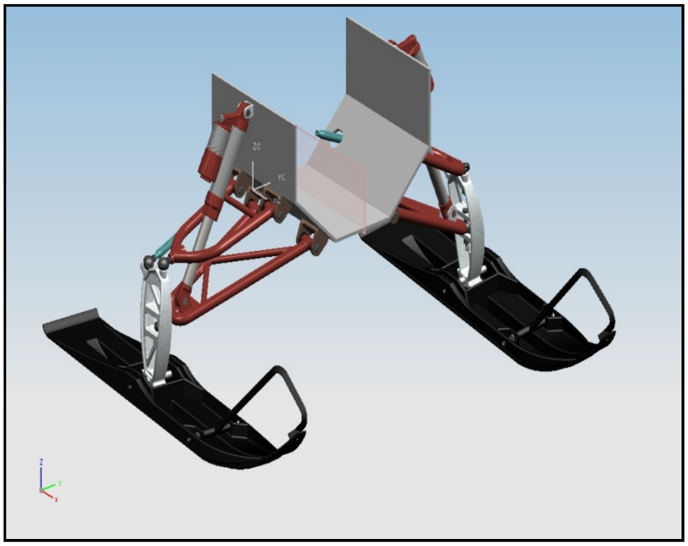

Figure 16: Stock Polaris Front Suspension

Using 6061-T6 Aluminum, replacement upper A-arms were designed and proven through FEA and can be seen in Figure 17.

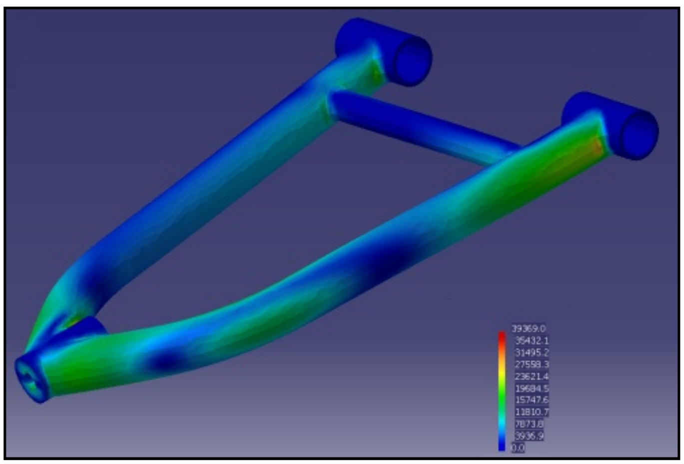

Figure 17: Upper A-arm Stress Concentrations

To further reduce weight and prevent failure, a new design was sought for the lower A-arms. A conceptual design was achieved and two materials were selected for analysis. To verify the design and material selection, a front impact load was applied to the model and FEA was performed. Figure 18 shows the stress concentrations during the impact loading on the 4130 Chromoly model.

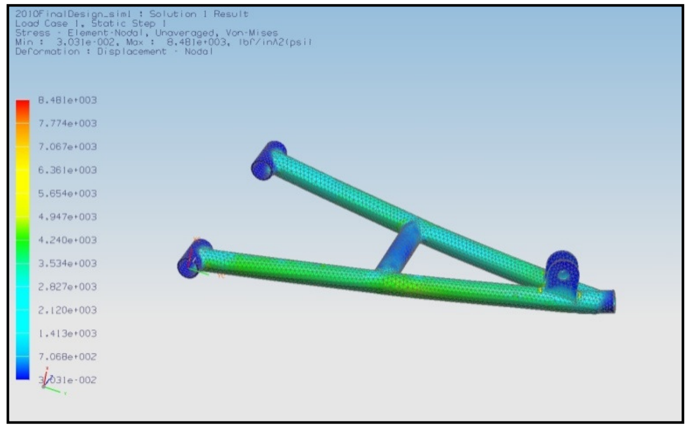

Figure 18: Lower A-arm Stress Concentrations

With the current design, 4130 chromoly saw a maximum deflection of 0.0069”, while 6061-T6 aluminum saw deflections of 0.023”.

In addition to lightening the A-arms, the front suspension setup has been modified to increase simplicity by removing the front sway bar. In order to maintain ride quality, gas-charged, coil over shocks were installed. To help reduce body roll, the shock valving was modified to lower the initial bleed off rates, resulting in a stiffer initial compression.

Steering

For 2010, the “Rider Select” system, which allows varying handlebar positions, was removed and a solid mount steering system was implemented in an effort to reduce the force required to turn the snowmobile. To do this, a lightweight steering hoop from a Polaris RMK was installed. This system eliminated all the aluminum brackets used in the stock FST steering hoop, allowing a 5.81 pound weight reduction.

Weight Reduction

To reduce the vehicle weight by the 12% goal, many areas of the snowmobile were evaluated including the steering system, rear suspension, front suspension, turbocharger, drive train, and lighting. Smaller areas that impacted the weight of the sled included a reduction in the amount and length of cooling and oil hoses. While reducing weight was important in all of these areas, the team refused to jeopardize the strength or integrity of the snowmobile. Careful planning ensured that new parts were just as strong, if not stronger than removed parts. A summary of recorded weight reductions can be seen in Table 8.

Table 8: Major Weights Reduced

Item	Initial (lbs)	Final (lbs)	Savings (lbs)
Lower A-arms	7.43	6.80	0.63
Upper A-arms	5.25	3.67	1.58
Steering Hoop	15.4	9.56	5.84
Airbox	5.13	4.25	0.88
Rear Suspension	55.0	45.0	10.0
Jackshaft	6.03	5.52	0.51
Brake Rotor	3.69	2.47	1.15
Oil Cooler	1.81	0.79	1.02
Battery	15.2	9.40	5.80
Skis	7.20	6.13	1.07
Spindles	2.25	1.98	0.27
Headlight	3.44	1.04	2.40
Taillight	0.42	0.15	0.27
Rider Select	1.12	0.75	0.37
Battery Box	2.15	1.65	0.50
Turbocharger	17.3	0.00	17.3
Intercooler	11.4	0.00	11.4
Clutch Cover	3.84	3.55	0.29
Plenum	2.03	1.30	0.73
Catalytic Converter	6.16	3.89	2.27
Total			**64.28**

Due to design and strength concerns, it was important to add components, causing slight weight gains. Taking into consideration both weight reductions and gains, the 2010 entry has a wet weight of 622 pounds, a 43 pound reduction from 2009 and a 61 pound reduction from a stock FST.

NOISE EMISSIONS

For 2010, a goal of 72 dB in the competition J192 Noise Test was set while reducing the overall packaging size of the noise control devices. Through various manufacturer testing, the three main noise sources on a snowmobile are the engine exhaust, engine intake, and the track and rear suspension [1]. 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. Soundown acoustical absorption and barrier material was strategically placed under the hood to help reduce the radiant noise produced from the engine. Sound barrier material was also used to cover the entire engine valve cover to help reduce the highest source of engine noise on the Weber engine, the valve train.

Airbox

An airbox was constructed to fit in the front-most part of the snowmobile engine compartment and contain the largest volume possible. A series of baffles and sound absorption material were placed in the airbox.

Exhaust Noise Reduction

With the snowmobile having a layout allowing for a rear exit exhaust system, the muffler was located behind the seat of the snowmobile. Since packaging size and weight is a major concern, the team chose to use an expansion chamber style muffler consisting of dual baffles. The style designed consisted of three varying size chambers to target the low frequencies produced by the engine.

Before constructing the muffler, Catia V5 was used to construct a 3-D model of the muffler so that boundary element analysis could be conducted using LMS Virtual Lab. This ensured that the design would be effective in eliminating target frequencies. A list of target frequencies was generated based on testing of the Weber engine. Figure 19 shows the 3-D model that was used in the initial analysis, to determine the effects of an extended inlet or outlet.

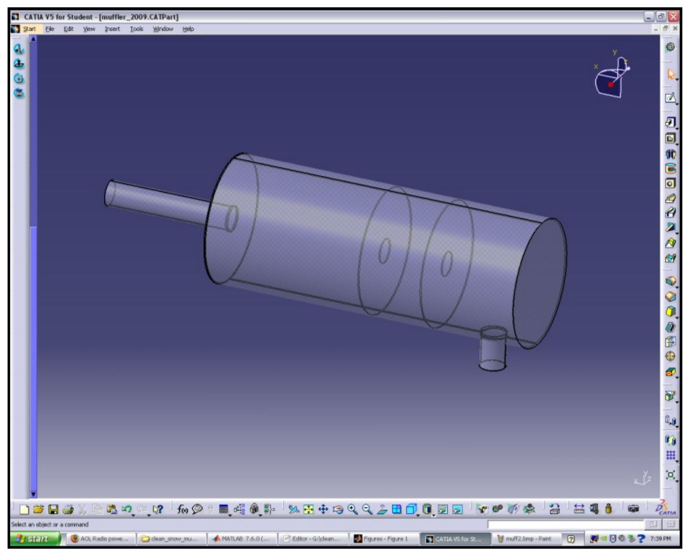

Figure 19: Initial 3-D Muffler Model

Using Matlab simulations based on acoustic impedance modeling, a transmission loss curve was generated for the model. This curve can be seen in Figure 20. The dips in the curve became targeted frequencies for improvement with the extended inlet and outlet design.

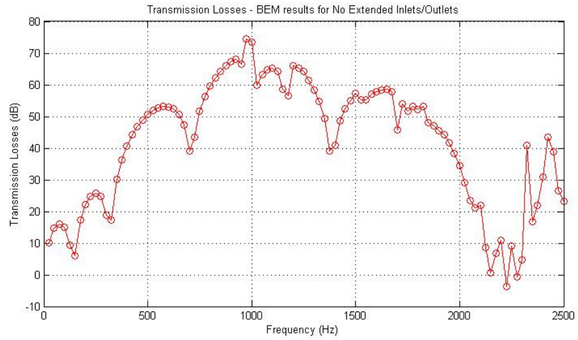

Figure 20: Initial Transmission Loss Curve

Using the initial analysis results in a Matlab program, the proper lengths for the extended inlet and outlet tubes were calculated to achieve optimum noise cancellation. The inlet tube was found to be 4.4" in length, with an outlet tube to be 2" in length. Using perforated tubing with solid end caps for the extended inlet and outlet tubes, the sound wave dispersion was increased. This is shown in Figure 21.

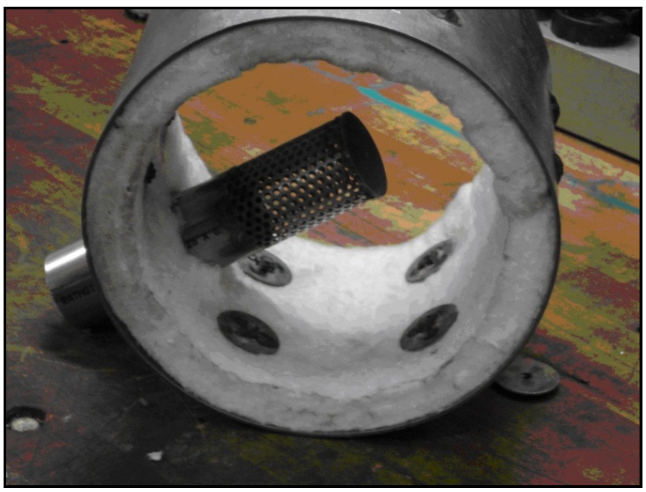

Figure 21: Extended Outlet

A final 3-D model was then generated in Catia V5 to accurately reflect the inlet and outlet findings and can be seen in Figure 22.

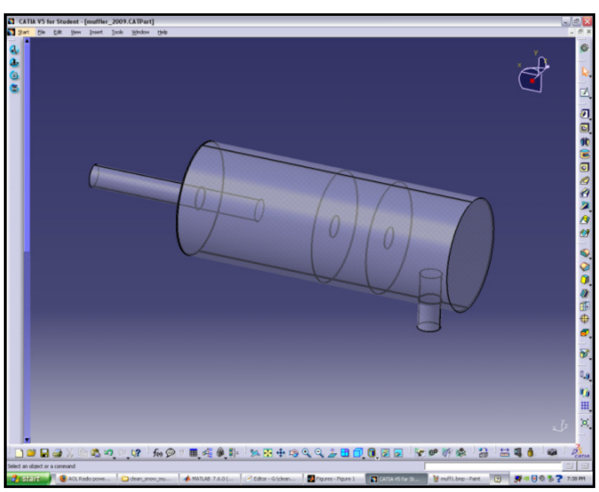

Figure 22: Final Muffler Model

Upon finalizing the 2nd generation design, the muffler was constructed. This muffler was bench tested to estimate its transmission loss characteristics. These results are shown in Figure 23. It can clearly be seen that the addition of the extended inlet and outlet improved the performance at the targeted frequencies from the initial design. To eliminate the higher frequency dips, Silco soft packing was used in the muffler construction.

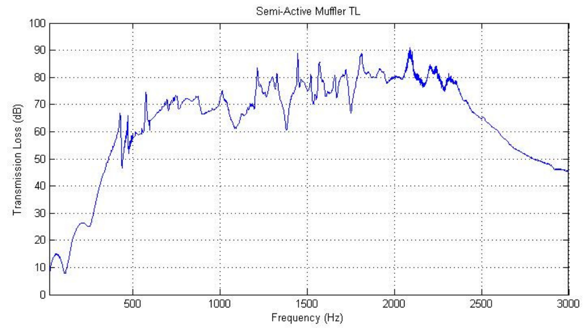

Figure 23: Final Muffler Transmission Loss Curve

DRIVE TRAIN

Many of the drive train components in the 2008 baseline snowmobile were replaced in an effort to reduce weight and increase efficiency. For 2010, the driveshaft, jackshaft, chain case, and brake rotor were the main points of focus. The chain case was replaced with a 2008 Polaris Dragon IQ chain case. This eliminated the reverse mechanism and complicated cover, which allows the rider to easily perform yearly maintenance.

The team investigated many options for reducing the rotational inertia within the drive train. The stock brake rotor was modified in an effort to reduce weight as well as improve cooling. The rotor was slotted, reducing the surface area by 14.9%. Taking into consideration rule 4.4.3 which states that the surface area of a brake rotor can be reduced by a maximum of 15%, the team needed to come up with an additional strategy for reducing the weight of the brake rotor. [7] Upon research, it was found that in 2009 Polaris used a lightweight brake rotor on the Polaris Dragon IQ. This rotor was 9.92 ounces lighter than the already modified rotor. The Dragon IQ rotor incorporated a WAVE geometry, which is known to be an industry leading lightweight rotor. Taking weight and performance into consideration, the team decided to use this particular rotor as shown in Figure 24.

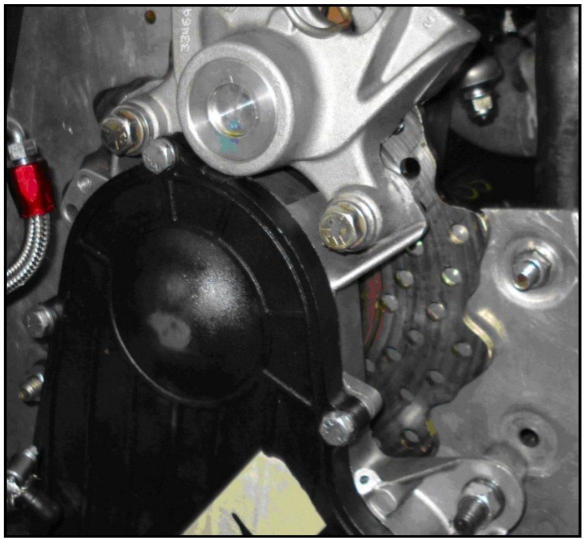

Figure 24: Polaris Dragon Brake Rotor and Chain Case

A 120" Camoplast Cobra track was chosen for its single-ply technology developed by Bombardier and Camoplast which reduces the amount of rotating mass thus increasing efficiency. Since the Cobra track has a pitch of 2.86", new drivers needed to be installed on the driveshaft. New drivers were installed on the stock extruded driveshaft, however the restrictions on the splined section of the extruded driveshaft only allowed the drivers to contact two rows of track drive cogs, instead of the intended four rows. Through field testing, this setup was determined to be insufficient as the track would skip on the drivers while under load. A hex-style driveshaft from a 2009 Polaris Shift IQ was implemented. This driveshaft allowed drivers to be mounted at any position, not simply where the extruded splines were. With this driveshaft, the team was able to install 2.86" drivers that pulled on all four rows of cogs. This solved the driver ratcheting problem. The newly installed drivers are molded plastic and elliptical in shape due to the molding process. This caused unwanted track tension changes while rotating. To further increase drive train efficiency, each track driver was trued back to a circle on a lathe.

<u>Team Tied Driven Clutch</u>

For the 2010 entry, a Team Tied driven clutch was installed. This is an improvement over the stock Team TSS-04 driven clutch due to its moveable sheave opening axially to the stationary sheave rather than rotationally. This motion produces less heat and friction in the belt which increases the belt life. The new clutch design also allows torque to be transmitted through the helix producing a near instant backshift allowing for increasing efficiency and more accurate tuning. Lower spring rates are also a result of the helix-torque transmission which reduces side pressure on the belt, which, again, increases efficiency.

Fuel Economy

With the 2010 entry to be a touring snowmobile, fuel economy plays a major part of marketing. To increase the entry's fuel economy, alterations using the onboard EMS were utilized along with the reduced fuel flow calculated from Equation 1.

Other means of increasing fuel economy included extensive clutch testing. Based off rule 9.8.3 which states, the snowmobile and driver's ability must be capable of safely driving at steady speeds up to 45 mph dependent on trail conditions in order to keep pace with the group, testing was done to determine the optimum engine cruising RPM at 45 mph [7]. To increase fuel economy, the basics of BSFC were applied. Using basic four-stroke comparisons, Figure 25 shows that BSFC is at its least at 100% load near peak torque [5].

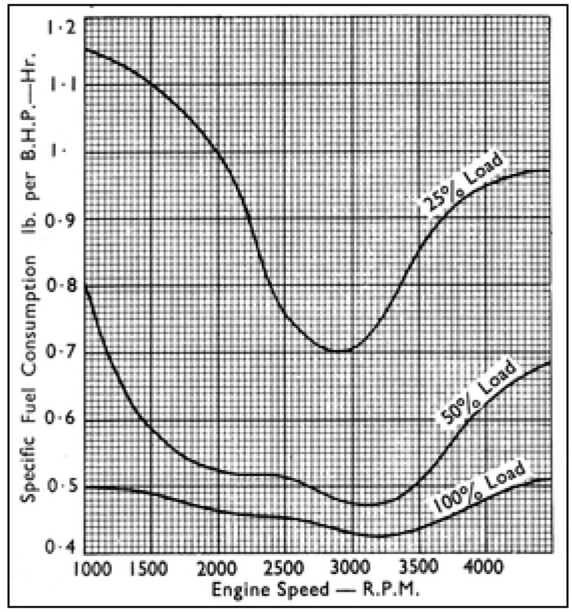

Figure 25: BSFC Trends at Varied Engine Loads

The reduction in BSFC on the 2010 entry was achieved through clutching the engine. The best condition requires the engine to be at full load and peak torque level while cruising at the required speeds of 45 mph. Dynamometer testing showed the peak torque levels to fluctuate between 5800 and 5900 rpm. The final clutch setup allows for cruising speeds of 45 mph to be achieved at 5875 rpm.

To accurately monitor improvements in fuel economy, a Lowrance LMF-200 fuel monitoring system was implemented during testing. Coupling paddlewheel style fuel flow meters with an onboard global positioning system (GPS), vehicle speed, miles traveled, instant fuel usage (gal/hr), and total gallons used could be monitored. The systems display can be seen in Figure 26.

Figure 26: Fuel Monitoring System Display

With the product in the development stages, the return fuel system presented problems in accurately displaying the fuel flow results, but efforts are being made to further develop the system. The onboard GPS allowed for accurate speed monitoring during clutch tuning. Using the vehicle speed displayed on the GPS and that displayed on the vehicle's speedometer, the efficiency of the drive system was maximized by reducing the difference in speed which is a result of track slip.

Table 9 shows the advancements to our final fuel economy through various stages of testing and development.

Table 9: Fuel Mileage Data

Sled	Fuel	Miles	Fuel added (gal)	MPG
Stock FST	E10	62	4.93	12.58
Base 2010 entry	E22	11.2	1.05	10.66
2010 entry (Tied clutch)	E22	62	4.56	13.59
2010 entry (Final Clutch setup)	E25	38	2.69	14.12

CONCLUSION

The 2010 Michigan Tech Clean Snowmobile team applied both state of art modeling tools and experimental analysis to increase the snowmobile's performance and lower its exhaust and noise emissions. To improve the snowmobile's fuel economy, the turbocharger was removed, weight was reduced, and efficiency was increased in all possible aspects. With the turbocharger removal, the snowmobiles BSFC and engine fuel flow requirements were reduced. A reduction in engine noise was obtained by implementing a catalyst with integrated noise dampening and an expansion chamber muffler. To package the exhaust system, chassis modifications were made. The 2010 entry incorporates improved ride quality due to a Ski-doo SC-5 rear suspension.

The 2010 Michigan Tech Clean Snowmobile entry is a step away from tradition, leading towards the future. It incorporates new technology that will lead the future of snowmobile manufacturing.

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- 3M
- A.E.D. Motorsports Products
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- Cummins
- DENSO
- Ford Motor Company Fund
- Keweenaw Motorsports
- National Instruments
- Oshkosh Corporation
- Polaris Industries
- Soundown
- Team Industries
- USG
- V-converter

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CONTACT

Dr. Jason R. Blough is an Associate 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

Appendix A: Fluent Flow Test Results.

RPM	Plenum Design	PTO Volumetric Flow Rate (m^3/s)	MAG Volumetric Flow Rate (m^3/s)	% Imbalance
3000	Current Plenum	0.060505	0.048314	25.23356149
	Failed Center Inlet	0.04455364	0.05074366	13.89341028
	Concept Center inlet	0.044661	0.044643	0.041350314
	Concept Hemispherical	0.04493491	0.04488573	0.109567116
	Concept Center inlet Bell mouth	0.04987132	0.05282577	0.059241464
	Concept Dual Runner	0.06864028	0.06873937	0.144361
5500	Current Plenum	0.097572	0.077715	25.55111325
	Failed Center Inlet	0.06805924	0.08110918	19.17438396
	Concept Center inlet	0.071608	0.070614	1.406969535
	Concept Hemispherical	0.07185575	0.07193275	0.107159135
	Concept Center inlet Bell mouth	0.078621	0.083552	0.062711003
	Concept Dual Runner	0.1097348	0.1099178	0.166766
8000	Current Plenum	0.106979	0.085313	25.39580618
	Failed Center Inlet	0.07412387	0.08885504	19.87371949
	Concept Center inlet	0.078659	0.077512	1.479477016
	Concept Hemispherical	0.0786845	0.07884923	0.209355083
	Concept Center inlet Bell mouth	0.085939	0.091351	0.062977345
	Concept Dual Runner	0.1202266	0.1204306	0.16968