Innovations for a Greener Tomorrow

Chad Kromrey, Fackender C., Hendricks C., Koll R., Little C., Loeks D., Mattson A., Massie B., Nasca L., Truskolaski D., Younger M.
Dr. Jason R. Blough
Michigan Technological University

ABSTRACT

The Michigan Technological University (MTU) Clean Snowmobile Team is entering the 2013 SAE International Clean Snowmobile Challenge with a redesigned 2013 Polaris Indy. The snowmobile has been redesigned to operate with reduced noise, reduced emissions, greater fuel efficiency, and ethanol based fuels while also maintaining competitive performance characteristics for the trail snowmobile market.

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 clean and quiet touring snowmobile to be ridden primarily on groomed snowmobile trails throughout the park. In 2003, the competition was moved to the Upper Peninsula of Michigan and was hosted by the Keweenaw Research Center (KRC) just north of Michigan Technological University's campus.

The Clean Snowmobile Challenge is sponsored by SAE International as part of the collegiate design series. The snowmobiles are evaluated in several static and dynamic events, including manufacturers suggested retail price (MSRP), technical presentations, emissions, noise, and fuel economy. For 2013 the competition remains at the KRC and runs from March 4th to the 9th. The competition has evolved to include both internal combustion snowmobiles and zero emissions electric snowmobiles.

In 2012 the MTU Clean Snowmobile Team placed fifth overall in the internal combustion category. Table 1 shows a breakdown of the team's performance from the 2012 competition.

Table 1: 2012 MTU Clean Snowmobile Competition results.

Event	Score	Place (out of 12)
Design Paper	82.3/100	3
Static Display	50.0/50	-
MSRP	35.3/50	4
Subjective Handling	35.38/50	8
Fuel Economy	100/200	4
Oral Presentation	64.7/100	5
Noise	88.3/300	4
Acceleration	37.0/50	6
Lab Emissions/BSFC	222.22/300	9
Fuel Economy/ In service Emissions	44.9/100	5
Cold Start	50/50	-
Objective Handling	68.5/75	2
Penalties/Bonuses	-10/100	-
Overall Score	869/1525	5

For 2013, the team focused on the underlying design goal of the competition; to design a touring snowmobile to be primarily ridden on groomed snowmobile trails. The team also focused on improving the overall fuel economy, emissions, and handling of the snowmobile. Table 2 displays the 2013 goals alongside the goals of the 2012 IC entry.

Table 2: Comparison of MTU team goals from 2012 to 2013

2012 Goals	2013 Goals
Improve on implementation of 750cc Weber engine in Polaris Pro-Ride chassis	Implement 875cc Polaris Pro-Star Four-Stroke engine in 2013 Polaris Indy Chassis
Pass 2012 EPA Emissions Regulations while operating on ethanol fuel blends ranging from E10 to E40	Pass 2013 EPA Emissions regulations while operating on ethanol fuel blends ranging from E40 to E85
Achieve a sound pressure level lower than 74 dBA per SAE J192 Specification	Achieve a sound pressure level lower than 73 dBA per SAE J192 specifications
Reduce overall vehicle weight by 10% while maintaining stock ergonomics and appearance	Implement a more capable closed-loop Engine Control Module to improve emissions and fuel economy

Michigan Tech's team is composed of 28 members from various educational disciplines including Mechanical Engineering, Mechanical Engineering Technology, and Civil Engineering. The team is divided into three sub-teams: engine, chassis, and business. The chassis and engine teams are focused primarily on the design, fabrication, and calibration of the snowmobile, while the business team is dedicated to public, sponsor, and inter-team relations.

INNOVATIONS FOR A GREENER TOMORROW

With pressure mounting from both state and federal government, there is a large effort to increase fuel economy and reduce emissions, which affects the power-sports industry. There are also federal noise limits as well as many local noise ordinances, which stress the importance of minimizing the overall noise of the snowmobile.

To design a comfortable, quiet, and fuel-efficient touring snowmobile, the team implemented a Polaris Pro-Star 875cc four-stroke engine in a 2013 Polaris Indy SP Chassis. The excellent handling of the Indy chassis in combination with the efficiency of the Pro-Star engine provides an ideal snowmobile for the trail-riding enthusiast.

The 2013 MTU entry closely resembles a modern, market available Polaris snowmobile with several enhanced components and design features to increase the desirability, while decreasing the overall environmental impact of the OEM model. The largest design changes include a four-stroke engine, implementation of a flex fuel sensor, enhancement of exhaust and intake systems, suspension modifications, and closed-loop fuel control.

Table 3 shows a list of components and equipment specifications used to meet the 2013 goals of the MTU Clean Snowmobile team. Key vehicle components include chassis, engine, fuel system, intake, exhaust, drivetrain, track, and suspension systems.

Table 3: Primary component breakdown of the 2013 MTU clean snowmobile

Component	Description
Chassis	2013 Polaris Indy SP
Engine	875 cc Polaris Pro-Star
Fuel System	Standalone P.E. engine management with stock Polaris RZR injectors and Indy fuel pump
Intake System	Polaris RZR throttle body with MTU designed and fabricated air box
Exhaust System	**Catalyst:** V-Converter 3-way catalyst
	Muffler: MTU designed and fabricated two-chamber system
Drive Train	**Primary Drive:** OEM P-85 Polaris
	Secondary Drive: Team Tied Rapid Reaction Roller
Suspension	**Front Suspension:** Stock Polaris A-Arms with Walker Evans Clicker Shocks
	Rear Suspension: Stock Indy Coupled Rear Suspension with front and rear Walker Evans Clicker Shocks
Track	121"x1.063"x15" Camoplast Ice Attak

ENGINE

For 2013, a Polaris Pro-Star 875cc Dual Overhead Cam (DOHC) four-stroke engine was chosen as a starting point for modification. The engine is offered in the Polaris Ranger product line. The Pro-Star Engine has been modified to operate with a dual-throttle body from the Polaris RZR engine instead of the original single-throttle body. The dual-throttle body was chosen in an effort to reduce restriction in the intake system, allowing for an increase in airflow to improve the overall efficiency of the engine. The dual throttle body is cable actuated rather than the single throttle body's electronic throttle control.

Through extensive dynamometer testing, the Pro-Star engine has proven to be reliable and tolerant with a wide range of ethanol fuel blends. With the implementation of a flex-fuel sensor, closed-loop fuel control, standalone engine management, and an emissions after treatment system, the overall environmental impact of the stock engine has been reduced while maintaining stock performance.

Performance Electronics ECU

The 2013 competition snowmobile utilizes a PE3-8400A Engine Control Unit (ECU) from Performance Electronics Ltd. The compact size and lightweight of the stand-alone control unit allowed for easy mounting into the Indy chassis. The control unit handles fuel and ignition needs of the engine over 500 load breakpoints based on manifold air pressure and engine speed. Using the controller, modifications can be made to the fuel flow and ignition timing of the engine as well as numerous other engine parameters to optimize performance and efficiency. In addition, the control unit allows for real-time calibration of the engine with on-board data logging of engine parameters and external inputs. Performance Electronics also supports wireless calibration, which allowed the MTU Clean Snowmobile Team to operate the snowmobile at a wide range of in-service testing modes while adjusting the timing and injection parameters remotely. Utilizing the tuning capabilities of the ECU, the team was able to optimize the capabilities of the Pro-Star 875cc engine.

Flex-Fuel Implementation

Teams competing in the 2013 Clean Snowmobile Competition internal combustion engine category are required to run on flex-fuel. Flex-fuel vehicles are able to operate on a blend of gasoline and ethanol ranging from E10 (10% ethanol; 90% gasoline) to E85 (85% ethanol; 15% gasoline). The fuel range for the 2013 Clean Snowmobile Competition will be between E40 (40% ethanol; 60 % gasoline) and E85 (85% ethanol; 15% gasoline).

The 2013 MTU entry uses a Siemens fuel composition sensor. This sensor outputs a square-wave frequency between 50 Hz and 150 Hz. A 50 Hz output frequency corresponds to 0% ethanol, while a 150 Hz output corresponds to 100% ethanol. This output frequency is then input into a Zietronix ethanol content analyzer. The analyzer displays a real-time ethanol content reading, as well as a 0V to 5V signal. The signal is transferred to the Performance Electronics (PE) ECU. The PE EMS used on the 2013 MTU entry does not have a provision for flex-fuel, so the voltage is input into a generic PE input. An MTU generated ethanol content trim table allows the PE EMS to add or subtract fuel from the fuel map based on the 0V to 5V ethanol content analyzer input.

In order to generate the ethanol content trim table, an MTU calibrated fuel map was created for the Pro-Star engine with E60 as the base fuel. To determine the amount of fuel added or subtracted for varying ethanol contents, equation 1 was used. The brake power output using E60 was determine to be 60 brake horsepower through dynamometer testing with a corresponding heating value of fuel (Q_{HV}) of 36.7 MJ/kg [1]. With the mass flow-rate ($\dot{m}_f$) of fuel determined from the calculated values of volume flow-rate of the injectors with a supply pressure of 3 bar and a known density of E60, a fuel conversion efficiency (n_f) of 32% was determined using equation (1).

$$n_f = \frac{P}{\dot{m}_f \cdot Q_{HV}} \tag{1}$$

To ensure the fuel conversion efficiency and power output of the engine is constant for varying ethanol contents, mass flow rates for the varying heating values of ethanol contents ranging from E40 to E85 was determined. The values were than compared to the calibrated E60 fuel map to determine the percent change of injector open time needed for stoichiometric combustion, shown in Table 4. A trim table using the values shown was then created from inputted signal from the ethanol content analyzer.

Table 4: Calculated percent change of injector open time with varying ethanol contents.

Fuel	Density of fuel (kg/m^3)	Required Flowrate (g/s)	Percent Change (%)
E40	761	3.53	-0.10
E45	758	3.61	-0.08
E50	754	3.69	-0.05
E55	751	3.78	-0.03
E60	747	3.87	0.00
E65	744	3.96	0.03
E70	740	4.06	0.06
E75	737	4.17	0.09
E80	733	4.28	0.13
E85	730	4.40	0.16

The volumetric efficiency (n_v) was calculated to determine the effectiveness of the engines induction system using equation 2. With a target lambda value equal to one, a corresponding air-fuel ratio of 10.4 was targeted during the calibration process using E60 fuel. From this, the mass flow-rate of air ($\dot{m}_a$) was determined by multiplying the target air fuel ratio by the mass flow-rate of fuel. With the density of air assumed to be atmospheric for a naturally aspirated engine and the volumetric displacement and engine speed known, a volumetric efficiency of 83.6% was determined with equation (2).

$$n_v = \frac{2 \cdot \dot{m}_a}{\rho_{air} \cdot V_d \cdot N} \tag{2}$$

The Pro-Star engine has proven to be tolerant through a wide range of ignition timing without detonation. Based on this observation, the ignition map is tuned to be most efficient on E60 and tolerate fuel blends from E40 to E85. A knock sensor is utilized to detect detonation and retard ignition timing if detonation is detected.

CHASSIS

The 2013 MTU entry is based on the 2013 Polaris Indy. The chassis offers several important advantages over other available chassis in the industry including weight reduction and improved rider ergonomics. The Indy also uses a similar platform to the Switchback and Rush models, which allowed for previous knowledge to be utilized with this model. While the snowmobile uses the same Pro-Ride chassis as the higher-end snowmobiles, it also offers a consumer friendly MSRP of $8,999.00.

For fitment, the team implemented a Ski-doo xp gas tank and seat. This caused the stock a-frame to be in the way and it was redesigned. The xp gas tank formed a gap from the front of the tank to the back of the stock Polaris plastics. This was addressed by building side panels out of thermo plastics.

ENGINE MOUNTING

The 2013 MTU entry combines the efficiency of the Polaris Pro-Star 875cc engine and the lightweight, rider ergonomic 2013 Polaris Indy Snowmobile Chassis. The Pro-Star engine was not designed to be implemented in the Indy chassis; therefore, the development of an engine mounting system was necessary. The MTU designed mounting system securely cradles the engine with a combination of two rear mounts, a front mount and a torque stop. Both engine mounts and the torque stop were machined from 6061-T6-billet aluminum. Each rear mount is isolated from the chassis by two vibration damping rubber isolators, while the front mount uses one vibration damping rubber isolator between the upper portion and lower portion of the mount. Figure 1 and figure 2 show the configuration of the rear mounting system installed on the engine.

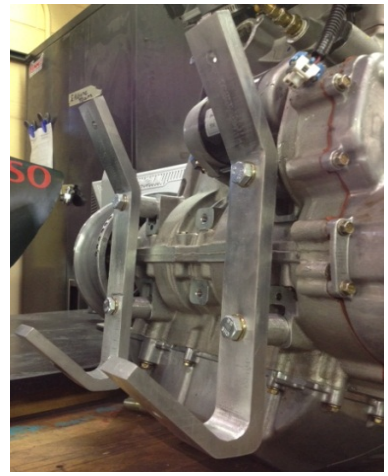


Figure 1: Rear engine mounts on engine

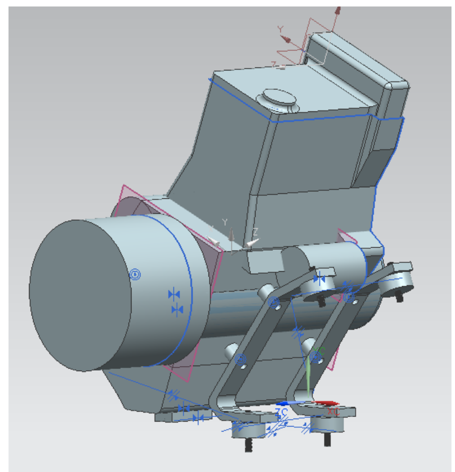


Figure 2: CAD model of rear engine mounting system

The front mount is bolted to the bottom of the bulkhead and braced to the front of the bulkhead as shown in figure 3.

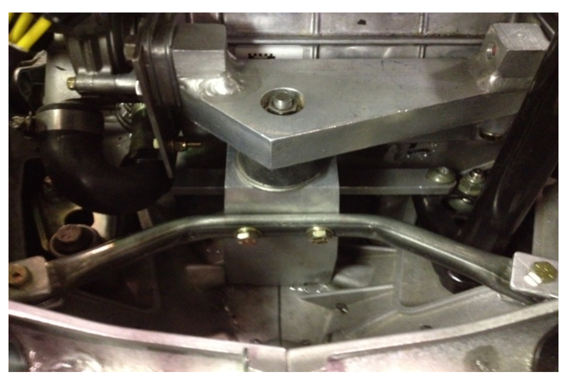


Figure 3: Front engine mount with bracing

The torque stop shown in figure 4 is from a stock Polaris Pro RMK and contains a vibration damping rubber bushing in combination with a CNC machined aluminum plate that straddles the crank shaft and is attached by three mounting locations found on the PTO side of engine.

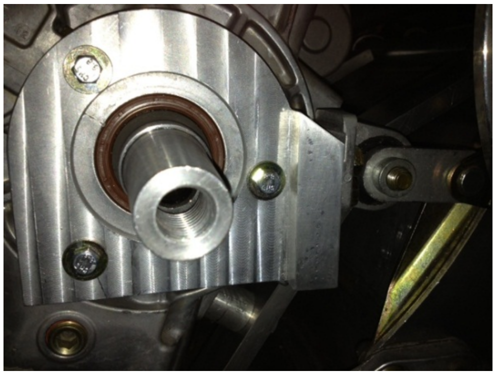


Figure 4: Torque stop after machining.

ENGINE MOUNTING ANALYSIS

To ensure the engine mounts can withstand the forces emitted by the engine, Finite Element Analysis has been performed. The purpose of the analysis is to verify that the engine mounting system can handle the static load of the engine, an impact load caused by the dynamic trail inputs, and the belt tension when the drive clutch is engaged.

The snowmobile chassis is assumed to be rigid, which represents a worst-case scenario. An impact load may be placed on the mounts due to a dynamic input load on the chassis from varying trail conditions. The impact from hitting a bump on the trail is assumed to occur as a suddenly applied load. The impact-loading factor was determined for a suddenly applied load by reducing the velocity (v) to zero in equation (3) [2]. The impact-loading factor determined from this calculation was equal to 2.

$$\text{Impact Loading Factor} = 1 + \sqrt{1 + \frac{v^2}{g} * \delta_{st}} \qquad (3)$$

Using equation (4) with an engine weight of approximately 110 pounds, the equivalent static load was determined to be 220 pounds.

$$\text{Static Load}_{eq} = \text{Static Load} * \text{Impact Loading Factor} \qquad (4)$$

The Polaris Pro-Star engine utilized in the 2013 entry is used in the Polaris Ranger 900 and produces a power output of 60 HP. The engine used in the Polaris RZR is similar in design but produces a maximum power output of 88 HP at 8250 RPM. For the purpose of calculating the maximum belt tension produced, the horsepower and torque information of the Polaris RZR engine was used. A maximum torque for the stock engine of 65 ft-lbs was assumed. This value was used to model the worst-case scenario, allowing for future performance improvement of the engine.

The free body diagrams of the forces placed on the crankshaft by the belt and clutch system are shown in figure 5.

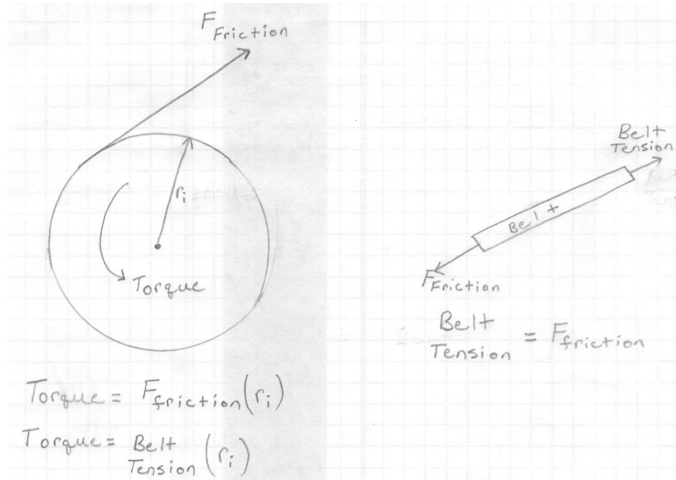


Figure 5: Free body diagram to determine belt force.

The moments on the primary clutch are due to the torque of the engine and the friction due to the belt. The forces on the belt are due to friction from the clutch and the belt tension. Therefore, the belt tension acting on the clutch can be determined from the torque of the engine and the inner radius of the clutch. The inner radius of the clutch is 0.048 ft. Using the minimum possible radius (0.048 ft) and the maximum engine torque (65 ft-lbs), the maximum force placed on the clutch by the belt was calculated using the free body diagram shown in figure 5. This results in a high approximation of the force because the belt is riding on the inner radius of the clutch only at clutch engagement with a corresponding torque far less than maximum torque. The belt force is 1354 lbs. as shown in equation 5.

$$F_{friction} = Belt_{tension} = \frac{Torque}{r_i} = \frac{65}{0.048} = 1354\ lbs \qquad (5)$$

The equivalent static load of the engine is applied at the center of mass of the engine shown in figure 6. The force due to the belt tension is not actually applied at the center of mass and for modeling purposes the force was moved to be centered on the center of mass. Moving this force caused moments about the x, y, and z-axes at the center of mass.

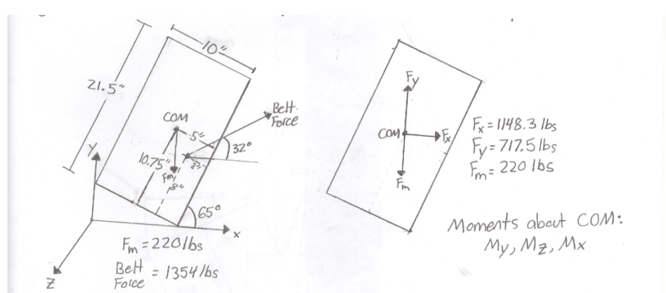


Figure 6: Forces on center of mass due to belt tension.

The moments were calculated as shown in figure 7.

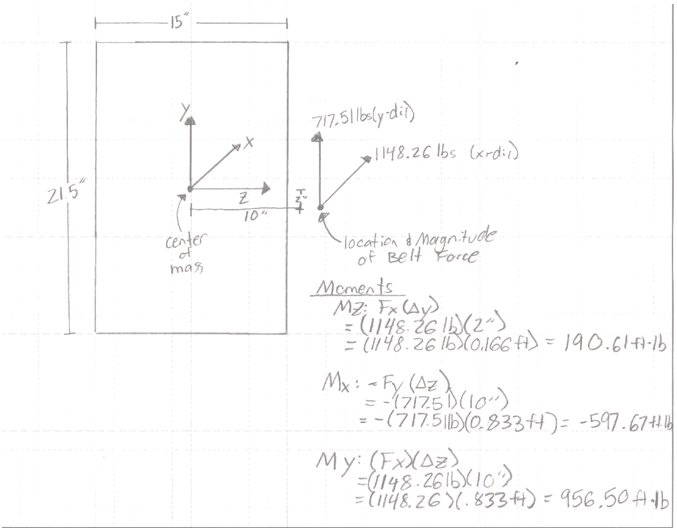


Figure 7: Front View of Engine and Moments on Center of Mass Due to Belt Tension.

The coordinate axis of figure 7, with the view looking at the power take off (PTO) side of the engine was used for the entire analysis. The belt tension is the only force acting in the x-direction, while both the belt tension and equivalent static weight of the motor are acting in the y-direction as shown on the right side of figure 7. By summing the forces and moments acting on the center of mass there is a force in the U1 direction of 1148.3 lbs, a force in the U2 direction of 497.51 lbs, a moment about the R1 axis of -597.67 ft-lbs (-7172.04 in-lbs), moment about the R2 axis of 956.50 ft-lbs (11,478 in-lbs) and a moment about the R3 axis of 190.61 ft-lbs (2287.32 in-lbs).

For the analysis, the rear isolators were assumed to be rigid and the front isolator was modeled as a stiff rubber as these conditions would simulate the worst case loading conditions on the aluminum components of the mounts. The stiff rubber isolator allows for maximum force transfer between the front mounting components. The loads were applied to the location of the center of mass of the engine. The Von Mises contour plot of the entire system shown in figure 8, shows that the maximum stress of 23,290 psi and is located on the torque stop plate.

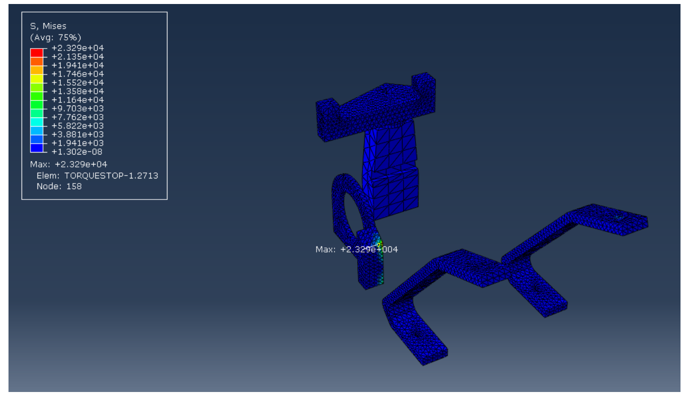


Figure 8: Von Mises contour plot of entire system.

The yield strength of Aluminum 6061-T6 is 40,000 psi [4], therefore the aluminum mounts will not fail due to the maximum load. The average stress on the system is 17,467.5 psi, giving a safety factor of 2.29. Figure 9 contains a contour plot of the torque stop plate, where the area of maximum stress is highlighted.

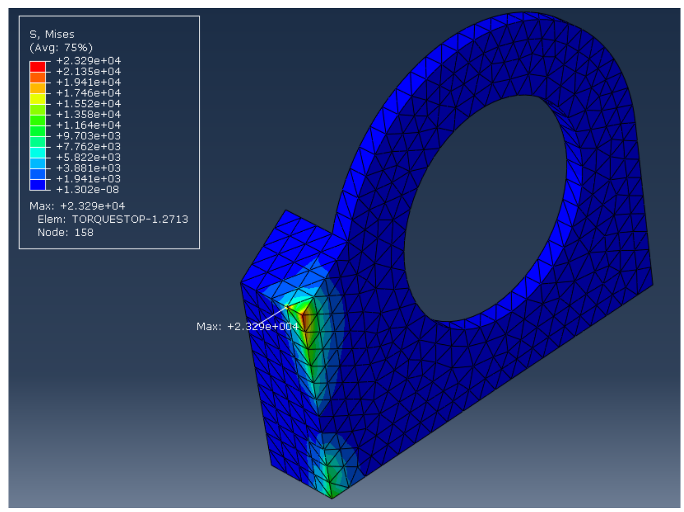


Figure 9: Von Mises Contour Plot of Torque Stop Plate.

Figure 10 contains a contour plot of the system displacements. The maximum displacement in the system will be .002 inches, which is very minimal and will be sufficient to ensure performance of the snowmobile.

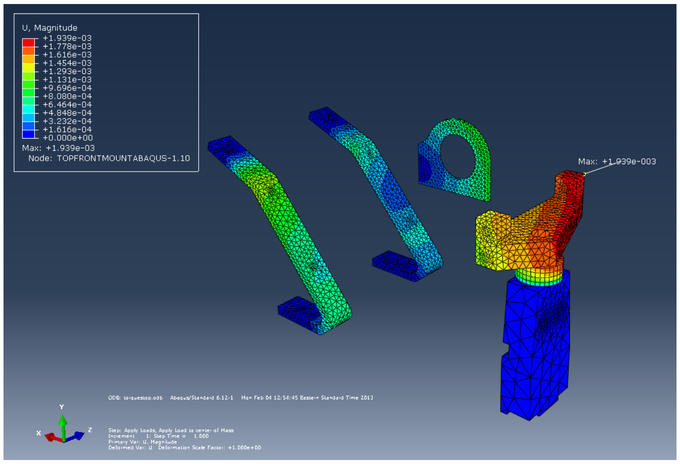


Figure 10: Displacement Contour Plot of Mounting System.

STEERING AND OVER STRUCTURE MODIFICATIONS

The over structure and steering linkage on the stock 2013 Polaris Indy required modification to accommodate the implementation of the Polaris Pro-Star 900 engine. When installed in the bulkhead, the engine is too tall for the stock over structure and steering system that is shown in figure 11.

Figure 11: Stock over structure and steering system

A new over structure was designed using the stock front a-frame and new rear supports that incorporate a Ski-doo XP gas tank. A model of the new structure is shown in figure 12.

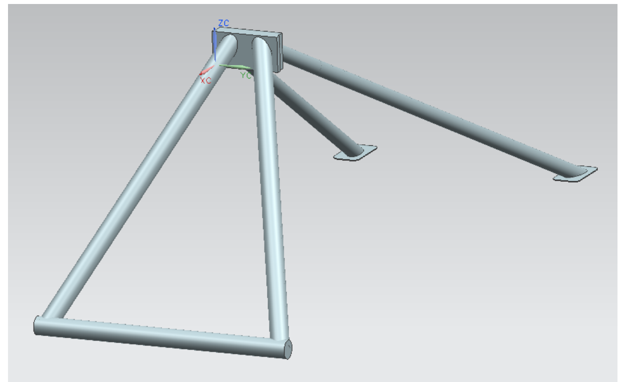


Figure 12: CAD Drawing of new A-frame design.

Both members of the front a-frame are welded to solid aluminum 6061-t6 machined bungs that slide inside the original tubing. The bungs are welded to an aluminum plate, which is bolted to a plate that ties the rear support system together. The rear support system is made of two pieces of aluminum tubing tied together by a similar bung and plate system as used for the front a-frame. The rear supports are attached to the tunnel using the Polaris t-slot mounting system.

Finite Element Analysis was completed on the new a-frame design to ensure the structural rigidity of the chassis was not compromised. A 300-pound rider was used when developing loads for the design. The front and rear sections of the new design are bolted together using two plates. Loads of 300-pounds were applied in the downward, side, and forward directions at this connection point, simulating the maximum load that a 300-pound rider could put on the a-frame structure through the steering post. Encastre boundary (fully fixed boundary condition) conditions were applied where the over structure connects to the chassis, simulating a rigid chassis. This would provide the worst case loading conditions on the design.

Figure 13 contains a Von Mises contour plot of the new over structure design. The maximum stress in the system is 6,275 psi. The yield strength of aluminum 6061-T6 is 40,000 psi, ensuring the material will not yield and the design will maintain the structural rigidity of the chassis.

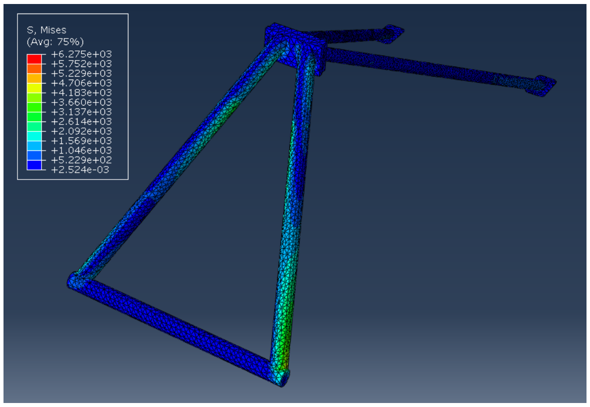


Figure 13: Von Mises Stresses in New Over Structure Design.

Figure 14 shows the displacements that will occur due to the loading and boundary conditions discussed above. The maximum displacement in the system will be 0.019 inches, which is minimal and will not affect the snowmobiles performance.

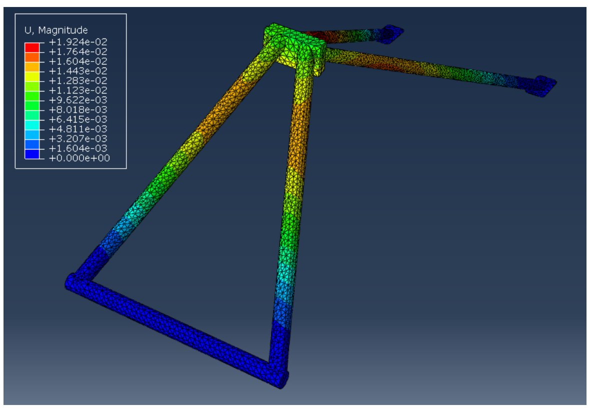


Figure 14: Displacements in New A-frame Design.

The new over structure design also required modifications to be made to the steering system. The Polaris Pro-Ride chassis utilizes two steering posts (front and rear) that are connected by a fixed length bea. The mounting of the front steering post on the MTU entry was modified to be compatible with the new over structure. The flat bar connecting the two steering posts was replaced by an adjustable length tie rod that was designed to keep from interfering with the engine.

HAYES ANTI-LOCK BRAKING SYSTEM

The 2013 MTU CSC Team has implemented the Hayes TrailTrac braking system. The TrailTrac system is an anti-lock braking system that consists of both a hydraulic control unit (HCU) and a Hayes electronic control unit (HECU). This system, in combination with the Camoplast Ice Attak Track, will allow the machine to slow with greater control by pulsing the brake pressure to prevent long term locking of the track.

Brake lines are run from the master cylinder on the handlebars to the HCU, and from the HCU to the caliper on the snowmobile. The HECU is mounted on the air box to keep it away from heat that is produced by the engine and exhaust. The HCU is located near the HECU and mounted to the top of the clutch guard, also keeping it removed from heat that is being produced. The orientation of the HCU is known to cause issues when bleeding the system, therefore, the MTU Clean Snowmobile Team mounted the unit horizontal to the direction of motion and with the fittings upright to ease bleeding the system as shown in figure 15.

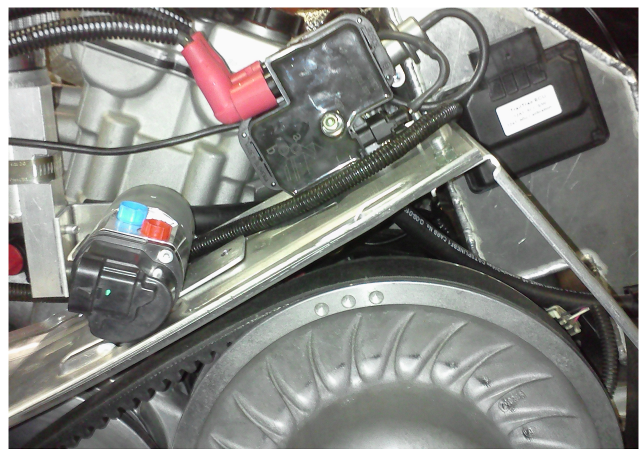


Figure 15: Hayes HCU and HECU mounting locations.

The HCU was also bled by splicing the wire harness to cycle the electric motor, as brake fluid was present, in order to fill the piston with fluid and force out excess air.

EXHAUST

Michigan Technological University designed an exhaust to fit the demands of the Polaris Pro-Star engine. The exhaust was made to address noise and harmful emissions. A design was made, tested, and then fabricated for use on the 2013 competition snowmobile.

CONSTRUCTION

A list of the constraints involved when creating the exhaust system is shown in Table 5.

Table 5: List of critical exhaust design constraints

Exhaust Design Constraints	
1	Package exhaust components under/inside of stock hood and side panels
2	Exhaust must consist of a MTU designed muffler and catalyst
3	Exhaust must maintain a minimum of .25" from all other parts
4	Design must account for heat management and heat expulsion
5	Must not weigh more than 2012 MTU exhaust

The exhaust system designed for the 2013 competition snowmobile is based off of the 2012 exhaust system but incorporates many new design features. The 2013 exhaust system consists of equal length headers from the exhaust ports to MTU designed collection chamber, shown as element 1 in figure 16 below. The exhaust headers were designed as close to equal length as possible in order to keep backpressure characteristics the same between each cylinder. The exhaust enters the collection chamber as two pipes and exits as a single pipe that flows into the catalytic converter (CAT) shown in figure 16 as element 2. Exiting the CAT the exhaust next enters the MTU designed 2-chamber muffler, element 3, and exits out of the bottom of the right side panel.

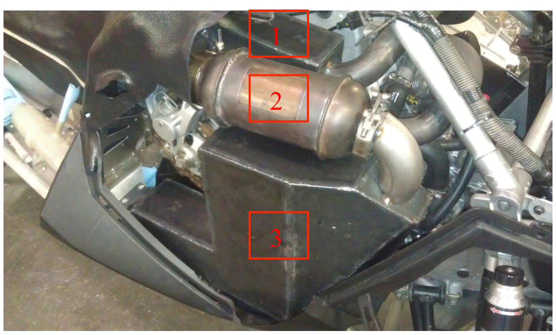


Figure 16: 2013 Exhaust Configuration

The collection chamber serves multiple functions, the first is to act as a "y-pipe" to reduce the two header pipes to a single outlet pipe, and the second is to act as an additional muffler chamber for noise cancelation. This collection chamber was the most robust solution to the space constraints that the Indy chassis provided while still efficiently merging the header pipes and reducing overall system noise.

The muffler was designed to provide the least amount of backpressure while significantly lowering overall exhaust noise. The first step taken to design the muffler was to calculate the available space under the hood while keeping the snowmobile's stock appearance. The 2012 competition muffler layout was used as a starting point and volume was added in order to increase the overall volume of the muffler. Generally, the larger the volume of a muffler the more noise cancelation occurs. The muffler was extended vertically and a section was added below the brake rotor to significantly increase overall volume in comparison to the 2012 muffler. After the overall size constraints were determined, the outer shell of the muffler was modeled and final dimensions of each piece were found as shown in figure 17.

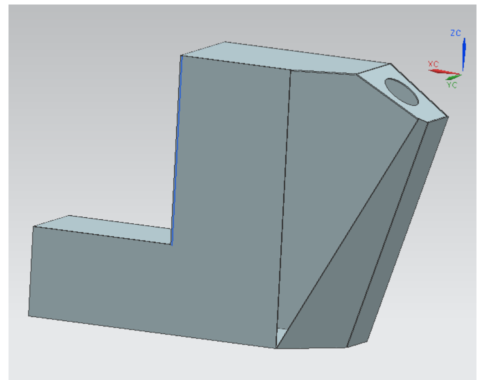


Figure 17: 2013 Muffler Design

Using a Matlab muffler simulation developed by a former MTU Clean Snowmobile student and a grad student researching acoustical performance, the muffler chamber was designed to eliminate as many noise frequencies as possible. The Matlab simulation uses a very basic cylindrical muffler design as shown in figure 18.

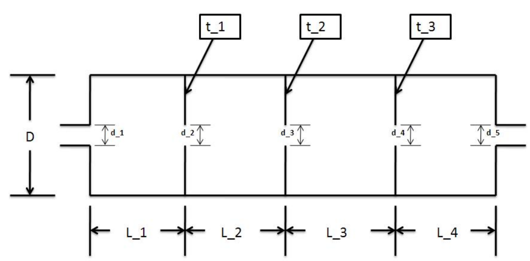


Figure 18: Acoustical Simulation Model.

Since the MTU designed muffler is not cylindrical, the volumes of the different sections tested had to be made equivalent to the cylindrical dimensions of the test muffler shown below. Entering the converted values for different exhaust layouts, results were produced and analyzed in order to decide the most appropriate muffler design.

First, a single chamber muffler was tested in the simulation, the results of which are shown in figure 19.

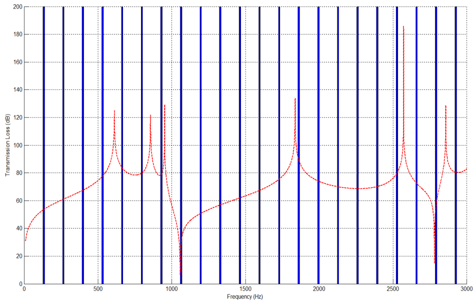


Figure 19: Matlab results for single chamber muffler.

The Matlab simulation produces a plot of Transmission Loss (dB) vs. Frequency (Hz) shown in figure 19 by the red dotted line. Each spike in the plot is where this particular muffler design will resonate. The blue vertical lines are the frequency ranges where the engine is expected to hit based on the firing frequency of the engine. These were found using equation (6) below and then arrayed along the simulation plot. The maximum engine speed is 8000 RPM and the estimated engine speed of the snowmobile at 45 mph is approximately 7000 RPM. Since the engine uses is a two-cylinder four-stroke engine, a 2 was inputted for the number of cylinders and a 2 was used in the denominator of the second half of equation (6) to represent the number of crankshaft revolutions per cycle for a four-stroke. This firing frequency was then multiplied by integers and plotted on top of the simulation results. Multiplying the firing frequency by each integer is a proven method of determining which frequencies the engine will most likely produce in the exhaust stream. If a resonance spike (red) hits any of the same frequencies propagated by the engine (blue), the muffler will not cancel out that particular frequency causing the snowmobile to produce unwanted noise. Also, since lower frequencies contain more energy, if hit during a run, they will produce a higher decibel level. Because of this, spikes hitting at the lower frequency ranges are of greater concern then hitting higher resonance frequencies. Analyzing the single chamber results in figure 19, one low frequency resonance spike hits a predicted engine frequency and one higher frequency does the same. There are also four resonance spikes in the lower frequency ranges, which is more than other simulations that were run. Because of this, the single chamber muffler design was eliminated from consideration.

$$\text{firing frequency} = \frac{(\text{engine RPM})}{60} * \frac{(\#\text{ of cylinders})}{2} \qquad (6)$$

In later tests three different temperatures were inputted and the results were overlaid. The competition engine is expected to run at 950 degrees Celsius, however, in order to compensate for any variations in exhaust temperature, a range of 900-1000 ℃ was tested. Six different two chamber designs were tested using the Matlab simulation. The distance between the chamber dividing wall and top of the muffler was used for the naming convention of the different muffler layouts. Simulations were run for 5, 6, 7, 8, 9, and 9.5 inch chamber lengths. In order to compare the results the total number of spikes and the total number of hits at each temperature range were counted. For example, the simulation at 8 inches is shown below in figure 20.

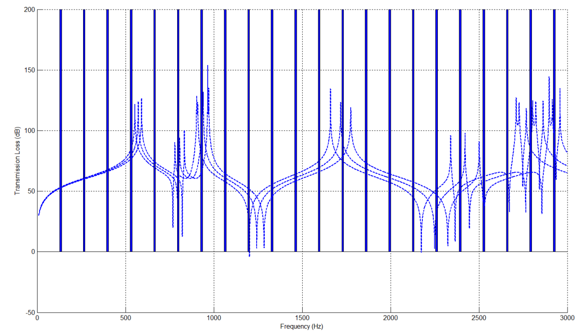
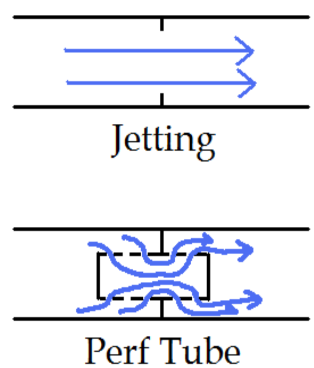


Figure 20: Matlab results for dual chamber design.

There are 11 spikes at each temperature range, four occurring in the lower frequencies. Because of this, the 8-inch muffler layout was eliminated. After analysis a dual muffler design with the dividing plate 7 inches from the top wall of the muffler was found to be the best layout.

Another aspect taken into account was the flow characteristics of the exhaust traveling between chambers. If exhaust is allowed to flow freely through a circular hole, a phenomenon called jetting will occur which will produce noise similar to that of a jet engine. In order to avoid this issue, capped perforated tubing is placed at all inlets and outlets of the collection chamber and muffler. As shown in figure 21 the perforated tubing forces the air to change directions, which eliminates jetting and promotes more complete utilization of the chamber volume.

Figure 21: Air flow diagram of open exhaust port versus air



through perforated tubing.

The lengths of the perforated tubes were calculated using equation (7) below. The radius of the perforated tubing was 1 inch and the tubing was rated to have an open area of 63%. The length of each piece of perforated tube was found to be 1.19 inches in length and a circular cap was welded on so the exhaust is forced to flow through the perforated tubing.

$$1.5 * \pi * r^2 = 2 * \pi * r * L * (\%\ open) \qquad (7)$$

Other components of the exhaust included muffler packaging and two different types of heat protection. The muffler packing shown in figure 22 was applied to the inside of all of the muffler chambers and acts as a damper for the noise vibrations. This means that even if a resonance frequency from the chamber design matches up with an engine frequency, the overall magnitude of that resonance will be much lower than if the packing was not used.

Figure 22: Inside view of exhaust with packing and perforated tube.

For all plumbing, a basic heat wrap was used and secured with wire ties. A heat shield was fit around the collection chamber, catalyst, and muffler. The heat shield material used claims that it will reduce radiant heat by up to 60%, which will prevent heat from affecting other components of the snowmobile and improve engine performance.

EMMISIONS

For 2013, the same catalyst wash coat formula as last year's snowmobile was used again this year. The catalyst was purchased from V-Converter in order to lower the release of hydrocarbons, nitrogen oxides, and carbon monoxide. This wash coat formula has an acceptable range of effective operation temperatures and is adequately sized for the exhaust flow rates outputted by the 875cc engine. The MTU clean snowmobile team has used this catalyst for the past two competitions with positive results.

The Polaris Ranger version of the 875cc Pro-Star engine is one of the most fuel efficient and clean burning engines in the off road market. It features mild cam profiles ideal for providing strong performance while minimizing emissions and fuel consumption. It's slightly spherical shaped cylinder head promotes lean burn and a fast initial burn which is ideal when emissions and fuel economy are more important than maximum horsepower. Table 6 shows the basic cam profile of the Polaris Ranger Engine in comparison to its higher output counterpart used in the Polaris RZR. The less aggressive valve lift, duration, and overlap help the Polaris Ranger Engine achieve the best emissions and fuel economy possible while still providing enough power and torque to entertain off road enthusiasts.

Table 6: Cam profiles of RZR and Ranger engines.

	Lift (mm)	Duration (CAD)	Overlap (mm Deg)
RZR Engine	9.13	221	53.340
Ranger Engine	8.75	218	26.489

Hydrocarbons are produced from inadequate combustion where there is not enough oxygen to fully combust the fuel. Hydrocarbons can be significantly reduced by operating at or leaner than stoichiometric conditions. Figure 23 is a plot of hydrocarbon levels at different rpms. As shown by the data, hydrocarbon emissions are higher at lower operation temperatures. Figure 24 shows a plot of carbon monoxide levels at different operation RPMs. Carbon Monoxide is the result of incomplete fuel burn from insufficient oxygen. The team has calibrated the engine to operate near stoichiometric conditions, which allows for low hydrocarbons and carbon monoxide from the engine that are further eliminated by the three-way catalyst.

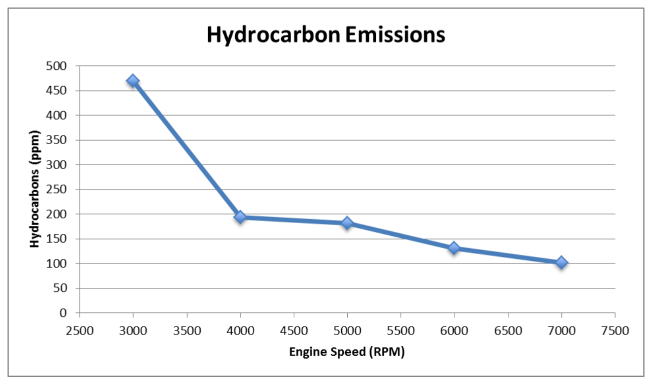


Figure 23: Hydrocarbon levels at varying rpms

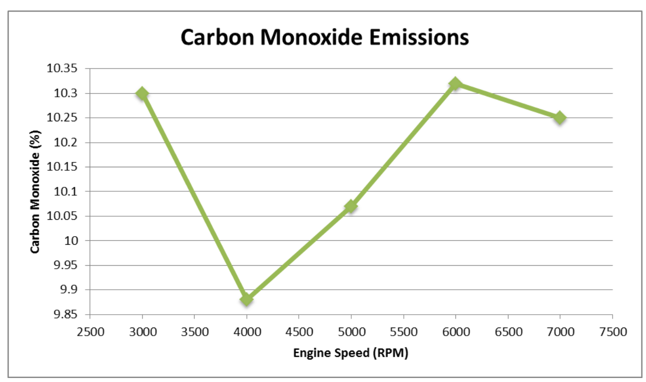


Figure 24: Carbon monoxide levels at different RPM levels.

Nitrogen Oxide (NOx) is directly related to exhaust temperature meaning as temperature increases, NOx levels increase as well. NOx is influenced also by compression ratio and oxygen levels in the fuel. By operating near the stoichiometric ratio, combustion temperatures are low therefore NOx levels are reduced. The closed-loop calibration developed regulates stoichiometric conditions, thus lowering NOx as shown in figure 25, while also keeping hydrocarbon and carbon monoxide levels to a minimum.

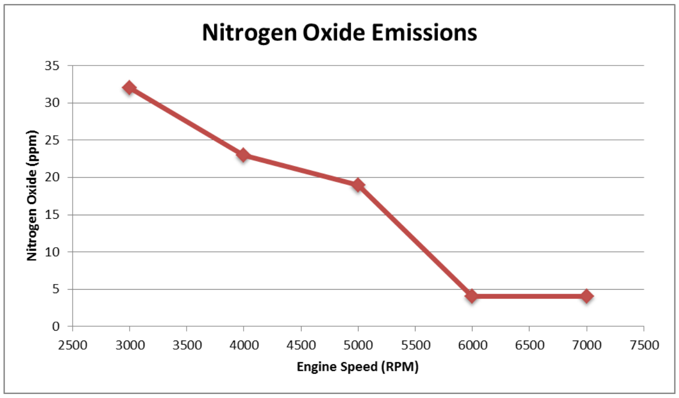


Figure 25: NOx levels at varying RPMs.

COST

In an effort to keep manufacturing costs as low as possible, every component added to the 2013 MTU IC entry was carefully analyzed. The original MSRP of a stock 2013 Polaris Indy is $8999.00 and the 2013 MTU IC entry is $12,038.17.

Since the 2013 MTU IC entry includes advancements in chassis, flex-fuel technology, fuel management, and produces significantly less emissions, the MTU Clean Snowmobile Team feels the additional $3039.17 is well justified.

SUMMARY/CONCLUSIONS

The 2013 MTU IC entry utilizes state of the art chassis and suspension technology to reduce weight, increase drive efficiency, and improve rider ergonomics. Comprehensive data collection and analysis for emissions after treatment and noise reduction were analyzed in order to design and fabricate an optimized exhaust system. Through implementation of a standalone engine management system, stock performance has been preserved, while reducing noise and emissions. The 2013 MTU IC entry represents a first-of-its-kind engine and chassis combination which melds proven four-stroke emissions and noise characteristics with modern lightweight chassis technology.

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CONTACT INFORMATION

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 the Michigan Technological University.

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

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- CUMMINS
- DENSO NORTH AMERICA FOUNDATION
- FORD MOTOR COMPANY FUND
- GM CORPORATE HEADQUARTERS
- PI INNOVO
- JOHN DEERE FOUNDATION
- MITSUBISHI ELECTRIC AUTO AMERICA
- OSHKOSH CORPORATION
- HMK
- VCONVERTERS
- M&M SHOP & STAFF
- HAYES
- TEAMTECH
- SPD

DEFINITIONS/ ABREVIATIONS

ABS Anti-lock Braking System
BSFC Brake Specific Fuel Consumption
CAT Catalytic Converter
CNC Computer Numerical Control
CO Carbon Monoxide
ECU Electronic Control Unit
EMS Engine Management System
EPA Environmental Protection Agency
FEA Finite Element Analysis
HC Hydrocarbon
HCU Hydraulic Control Unit
HECU Hayes Electronic Control Unit
IC Internal Combustion
KRC Keweenaw Research Center
MSRP Manufacturer Suggested Retail Price
MTU Michigan Technological University
NOx Nitrogen Oxide
OEM Original Equipment Manufacturer
PE Performance Electronics
PTO Power Take Off