Advancements in Fuel Economy, Emissions, and Acoustics for the 2016 Polaris Switchback Adventure

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Innovations

At the 2018 SAE Clean Snowmobile Challenge, the University of Minnesota - Twin Cities Clean Snowmobile Team (UMN-CST) placed 8th overall. This was our best finish in school history, which included many performance and reliability highlights; however, our inability to develop an effective emissions strategy cost us valuable points. Following the Spring 2018 graduation, only half of the team remained. This provided ample opportunities for newer members to take charge and build off of our best competition to date.

For the 2019 competition, our team decided to use the same 2016 Polaris Switchback Adventure chassis. We realized that the stock 600cc 2-stroke engine would not suffice in meeting our team goal of 5th place or better overall. Therefore, a 2015 Polaris ACE 570 SP was purchased for the use of its engine in our snowmobile. For the first time in team history, the UMN-CST is running a 4-stroke engine. Taking on an engine swap required an increase in project management, time management, and commitment to our goals.

A ProStar 570 from a Polaris ACE 570 SP was selected for the swap to reduce both emissions and noise. As the stock engine, a Polaris Liberty 600 Cleanfire 2-stroke, has different dimensions than the 570, multiple sled modifications have been implemented. In order to securely attach the new engine to the bulk-head, the team designed engine mounts and a torque stop. To allow for the skis to have full range of motion, the steering column was modified to avoid interference with the taller 570 engine. In order to obtain clearance for the oil pan of the new engine, a chassis modification was also completed; a horizontal cross bar was redesigned while avoiding major modification of the pyramidal over-structure.

Another challenge of completing a full engine swap is the packaging of intake and exhaust components. This year, emphasis on mounting the engine with minimal changes to the stock chassis resulted in minimal space for a retrofit intake system. To account for this, a custom intake system routing was developed and manufactured using 3D printed materials to accommodate the necessary complex shapes. Similar problems arose with the exhaust system. Due to its shape and size, the team decided to reuse the stock muffler from the Polaris Liberty 600 2-stroke, while redesigning the exhaust header to incorporate a catalytic converter.

To accompany the new engine, a different engine management system was implemented. In past years, a piggy back ECU (engine control unit) were installed to give the vehicle the ability to run fuel with varying ethanol contents. The team realized that these past strategies were not successful for the team and studied the engine management strategies of other teams. It was discovered that many teams, mostly those that passed the lab emissions portion of the event, used custom aftermarket ECUs with custom flex fuel tunes. The team decided to take this approach to engine management as it would allow for precise engine tuning for various situations and ethanol contents.

To reduce noise, the team undertook the task of researching and testing sound absorbing and blocking materials for multiple locations on the snowmobile. Using the previously designed and built impedance tube, sound properties were tested of fifteen different material samples from various manufacturers. Sound absorbing products, consisting of soft foam-like materials, are optimal for areas with significant open space such as the bulkhead of the sled; sound blocking materials, made of more dense polymers, are effective at vibration damping on sheet metal. Additional research led to the use of materials for different applications instead of an overall coating to reduce noise.

With the engine swap, it was necessary to develop a new system to use the dynamometer set up that the team had access to. The build ultimately consisted of customized engine mounts for the new ProStar 570 motor and a pulley system to couple the crankshaft to the dynamometer. The pulsation of the single cylinder engine resulted in dynamic loading that was too significant for a straight coupling between the motor and dynamometer. A pulley between the two shafts allows for damping of the pulses, allowing the coupling to have a longer lifespan. This setup requires running a shaft from the dynamometer to the pulley, which was supported by bearings to prevent excessive horizontal loading on the dynamometer bearings. To safely vent the exhaust, plumbing was created with flexible tubing that connects the engine exhaust to a tank which then connected to the lab exhaust system. The tank is used to dampen pulsations created by the motor to achieve more accurate measurements. This, along with a cooling system was mounted to a T-slot table with the rest of the components. This allowed for mobility of the entire setup, making it easier to mount the motor and transport it.

Team Organization and Time Management

The UMN-CST was formed in the summer of 2014, and first attended the SAE Clean Snowmobile Challenge in 2015. As a newer team to the competition, the team's organization and structure continue to evolve each year. For this school year, our team was led by four main officer positions; president, vice president, senior project manager, and junior project manager.

Each of these leadership positions have different responsibilities. The Sr. Project Manager is responsible for managing the various student led design teams. He/she is responsible for ensuring that projects are on schedule and that team members can effectively communicate their problems and solutions to the team leaders. The Jr. Project Manager has very similar responsibilities, but is designated as a younger member of the team. This ensures that management and leadership experience will be continually passed down within the team. The President and Vice President also have very similar team responsibilities. While participating in the engineering design teams, the presidents also plan and lead all team meetings, visit and host team sponsors and donors, act as team treasurers, and manage grants and other funding sources.

Table 1. Officer organizational chart for the team.

Officer Position	Member Name
President	Nick McCormick
Vice President	Austin Iverson
Sr. Project Manager	Ryan Fix
Jr. Project Manager	Travis Walbon

More so than any previous year, effective project management was vital for on time completion of tasks. The engine change and associated projects required teamwork and dedication. A project tracking spreadsheet was used to track the status, priority, due date, task lead, assignees, and deliverable for the tasks under each project. Additionally, the team began constructing formal agendas for team meetings and workdays, which included administrative and project focuses. With a substantial number of changes throughout the snowmobile, SolidWorks was heavily utilized for design prior to manufacturing. To track parts and assemblies in an organized fashion, our team created subassemblies with associated part numbers. These numbers were tracked in spreadsheets with additional information and links to dimensioned drawings for manufacturing.

From the start, our team understood that replacing the Polaris Liberty 600cc 2-stroke with a 4-stroke would be financially demanding. Therefore, a detailed sponsorship package was constructed to provide information about the UMN-CST, our goals, and the SAE Clean Snowmobile Challenge to prospective sponsors. Within the package, several levels of sponsorship were outlined to highlight the advantages of supporting our group. Through the use of the sponsorship package, the UMN-CST strengthened existing and developed new sponsor relationships. The first venue used to talk with current and potential sponsors was Haydays. This powersports showcase event allowed the new officers to rapidly visit companies and gauge sponsorship interest.

Multiple sponsors invited us to visit the company or attend a company event as part of the fundraising. For example, members of our team attended the ANSYS Innovation Conference in October and displayed the snowmobile from last year's competition. This helped ANSYS showcase the capabilities of their software through a SAE Collegiate Design Series. Our team president and vice president also attended a regional meeting for MnUSA. They discussed the goals of the SAE Clean Snowmobile Challenge and how it aims to benefit the sport of snowmobiling. These events, along with many others, were meaningful sponsor engagement experiences.

As previously mentioned, the UMN-CST was left with a low number of members following graduation in Spring 2018. Successful recruitment in the fall was essential to accomplishing team goals and constructing a team for future years. Through on campus events, such as Paint the Bridge and Student Organization Fairs, our team has tripled in size since the beginning of the school year. The majority of these active new members are freshmen, which sets the mark for success in future years. As you can see, the management and organization of the team have changed immensely.

Build Items of the Snowmobile

Table 2. Specifications for the UMN-CST snowmobile.

Snowmobile Chassis	2016 Polaris Switchback Adventure
Engine	2015 Polaris ProStar 570
Fuel	Gasoline/Ethanol
Displaced Volume	567 cc (Single Cylinder)
Compression Ratio	10:1
Peak Power @ RPM	45 hp @ 7350 RPM (Estimated)
Engine Control Unit	Motec M800
Wiring Harness	Custom
Track	Camso Storm 150 137"
Muffler	Snowmobile Stock
Header	Student Designed
Oxidation Catalyst	Heraeus 33 g/ft^3 Pt:Rh/1:1 400 cpsi
Intake	Custom
Skis	Snowmobile Stock
Sound Absorption	3M Thinsulate (Various Thicknesses)
Vibration Damping	Noico ESN10 Deadening Mat

Design Content of Snowmobile

Engine Mounts

The optimal engine position in the bulkhead was determined using SolidWorks models of both the Switchback bulkhead and ProStar 570 engine. Because the decision was made to continue using the stock clutches and clutch belt, keeping the stock clutch center distance was the most important consideration in positioning the 570cc 4-stroke engine in the bulkhead. After finding an engine position that minimizes the interference between the engine and the bulkhead, the decision was made to tilt the engine back 15 degrees off vertical (towards the rear of the snowmobile) to eliminate interference with the pyramidal over-structure. By avoiding modification of the pyramidal over-structure, a considerable amount of design and manufacturing time was saved. This created more time to focus on the many other projects that come along with an engine swap.

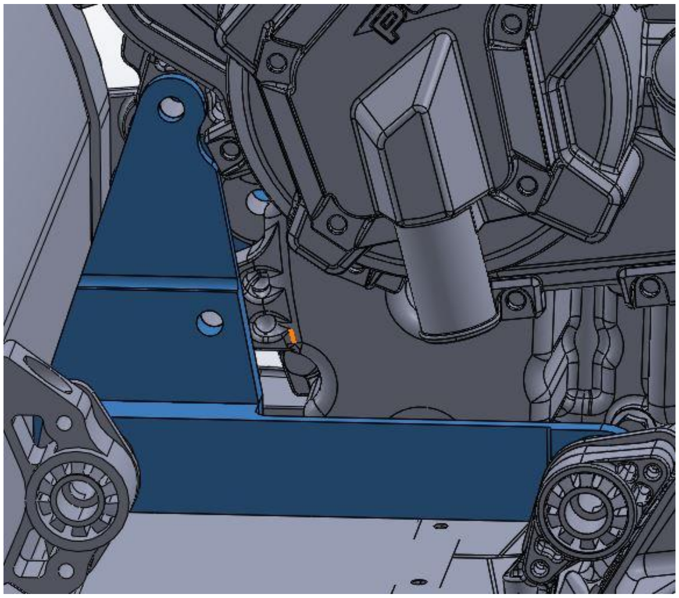


Figure 1. SolidWorks model of the ProStar 570 right side engine mount.

Once the optimal engine position was determined, the engine mounts were designed using SolidWorks. The stock aluminum engine mounts in the bulkhead were chosen as the best mounting locations for the new engine, because they utilize rubber dampers to reduce the intensity of the vibrations that are transferred to the chassis. This is an important feature to have for a single cylinder engine since they are unbalanced. Therefore, an engine mounting solution was designed to go from the stock bulkhead mounts to the rear engine mounts on the ProStar 570. In the ACE, the front mounts on the engine were bolted to the chassis, and the rear mounts supported the transmission. Since only one set of mounts was used to support the engine in the ACE, it was concluded that it would be acceptable to use one set of mounts to support the engine in the snowmobile. Any minor oversites as a result of using the rear engine mounts instead of the front engine mounts were accounted for by overestimating the loading condition the newly designed engine mounts would experience.

The loading condition for the engine mount design used a drop height of 5 feet. The calculation was completed assuming 6 inches of suspension travel and an engine weight of 200 lbs. The Polaris Switchback's front suspension possesses 9.3 inches of travel, so 6 inches of compression is realistic for a fall from 5 feet onto rigid ground. The ProStar 570 engine actually weighs less than 100 lbs, therefore the use of 200 lbf provides a proper safety factor to the analysis. Following a hand calculation, a vertical reaction load of 2000 lbf was applied to the engine mounts at the bulkhead connections, and the engine connections were held fixed. Figure 2 displays the equivalent stresses on the engine mounts. The material chosen was 1018 steel, which has a yield stress of 53.7 ksi. ANSYS revealed a maximum equivalent stress of 40.8 ksi, which is well below yield. The initial engine mounting solution for 1018 steel did not show stresses remotely near yield. As a result, all low stress areas underwent reductions in thickness. The large area shown in the lower right of Figure 2 that connects the outside and inside planes was originally solid steel. Due to the minimal stresses in this location, square structural steel tube was used to reduce the mass.

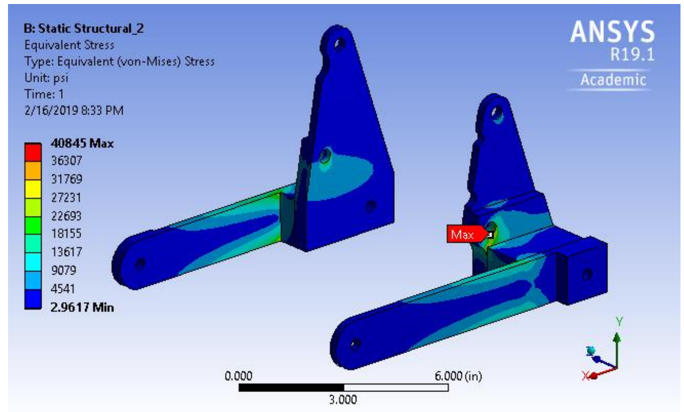


Figure 2. Static structural analysis of the ProStar 570 engine mounts.

Another crucial element associated with the engine mounting solution was the torque stop. The sole purpose of this part is to prevent the engine from rotating due to the reaction torque imparted on it by the snowmobile's drive system. As the OEM (original equipment manufacturer) torque stop did not line up with any available attachment points on the 570cc engine, the team was required to create a new torque stop. In order to keep the design as simple as possible, the bolt pattern around the crank shaft that originally secured the clutch cover on the ACE was used to fasten the torque stop to the engine. The other end of the part was bolted to the same location on the snowmobile as the OEM torque stop. Solidworks was used to design the new torque stop, and ANSYS was used for stress evaluation.

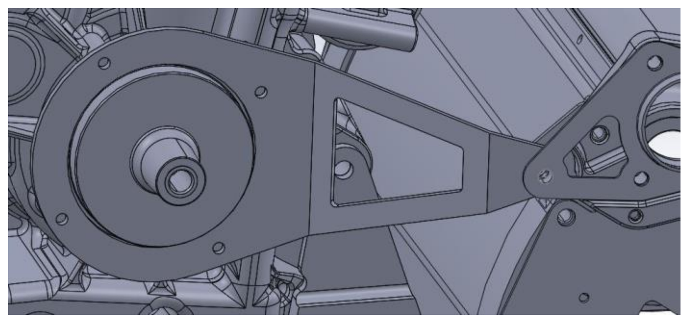


Figure 3. SolidWorks model of the ProStar 570 torque stop.

The ProStar 570 exerts an estimated peak torque of 35 ft-lbs, however, 50 ft-lbs was used for the structural analysis. The torque stop was fixed at the holes surrounding the crankshaft. A force of 80 lbf at the chassis bolting location was found by converting the engine torque to a tangential force at the radius from the crankshaft. The torque stop consists of A1011 steel at a thickness of 7 gauge (0.179 inches). Through the ANSYS analysis shown in Figure 4, the maximum stress of 27.4 ksi sits below the 36.3 ksi yield strength of A1011. The trapezoidal hole was not originally included, but due to negligible stresses in that area, the material was removed.

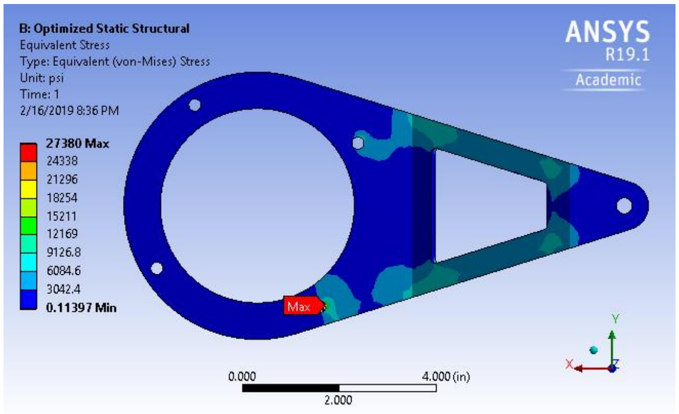
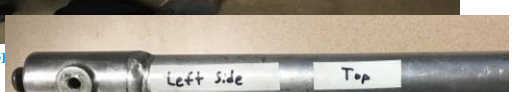


Figure 4. Static structural analysis of the ProStar 570 torque stop.

Chassis Modification

As a result of the optimal engine position, the OEM horizontal crossbar spanning the bulkhead interfered with the oil pan of the ProStar 570 engine. Therefore, a 1020 cold rolled steel bar was designed with bends to replace the stock aluminum 6061-T6 bar such that no interference occurred. ANSYS was used to confirm this design by applying equal loads to one face of the OEM and proposed bars while holding the opposite end fixed. Two compressive load cases were used in the analysis. One that would provide insight for failure magnitudes, and one below yield for more realistic expectation based on the OEM design. A 2500 lbf load placed in compression was used for the lower load case. Figures 6 and 7 display ANSYS analysis images for the OEM and modified crossbars, respectively.

Figure 5: Side by side co



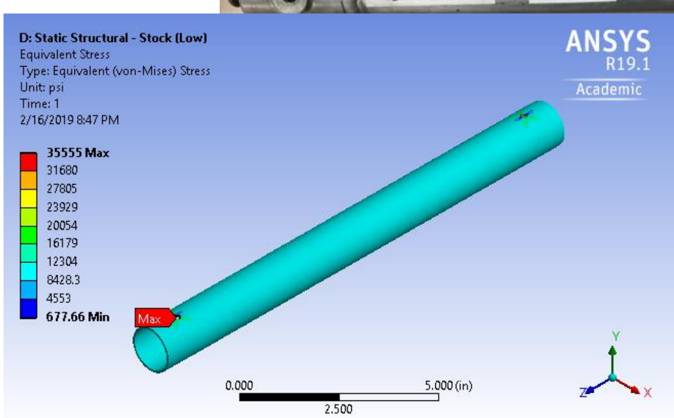


Figure 6: Static structural analysis of the OEM horizontal crossbar under 2500 lbf of compressive load.

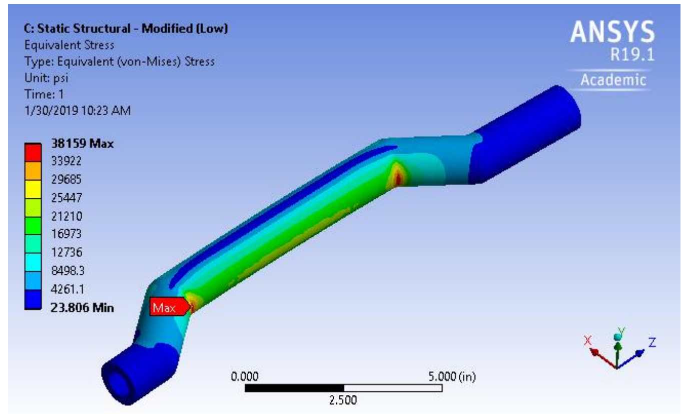


Figure 7: Static structural analysis of the modified horizontal crossbar under 2500 lbf of compressive load.

The highest stress in the OEM bar was at the drilled holes with a magnitude of 35.6 ksi. This stress is about 89% of the yield strength for aluminum 6061-T6. The modified bar model shows a maximum stress at the inside bends of 38.2 ksi, which is approximately 75% of A1011 steel's yield strength. Therefore, the results showed that the proposed 1020 steel crossbar exceeds the strength of the OEM aluminum 6061-T6 crossbar by almost 20%. Please see the Chassis Modification Report submitted by our team for additional information.

Clutching Adaptation

This year's engine change brought forth several potential clutching approaches for the ProStar 570 engine. The most realistic possibilities were the use of the 600cc 2-stroke clutches, the 570cc 4-stroke clutches, or a combination of the 570 primary clutch with the 600 secondary clutch. Both ACE 570 clutches could not be utilized without modification of the jackshaft to allow for proper fitment of the smaller secondary clutch. The ACE 570 primary clutch could not be used in tandem with the Switchback 600 secondary, because the belt widths were too dissimilar. Therefore the Switchback 600 clutching would need to be adjusted to allow for proper engagement and peak RPM.

The stock weights in the ACE 570 primary clutch were 25-52 grams, but the stock weights in the Switchback 600 primary clutch were 10-64 grams. The desirable solution for primary clutch weights would be 52 gram weights with the profile of the Switchback 600 weights. To accomplish this, 52 gram "Belly Buster" primary clutch weights fit for the Switchback 600 were purchased from EPI Performance. The other element involved with adapting the primary clutch to the ProStar 570 engine was the primary clutch spring. The stock Switchback 600 and ACE 570 primary springs had rates of 140/330 lbs and 35/240 lbs, respectively. The solution to this issue was to select a primary spring with reasonable agreement between initial spring rate of the Switchback 600 spring and the final spring rate of the ACE 570 spring. The spring selected for the primary clutch was an EPI Performance Polaris orange with spring rates of 125/260 lbs. The Switchback 600 secondary clutch and belt remained stock. The ProStar 570 will not achieve full shift of the secondary clutch due to a large reduction in torque and horsepower. This will not hinder the ability to operate the snowmobile and will be the subject of investigation next year.

Impedance Tube

Several improvements were made to the impedance tube used for the 2018 Clean Snowmobile competition. These include using a two-electret condenser microphone setup, and adding an additional operational amplifier (op-amp), to increase the signal from the microphones. For material testing, a sinusoidal excitation across the speaker was used instead of the square wave that had been used previously. Materials to be tested were cut into roughly 5”squares to be able to fit between the flanges of the impedance tube, which allowed for simplicity in changing out samples. The improvement in both test speed and fidelity allowed the team to diagnose problems and test more samples at a faster rate than the previous design allowed.

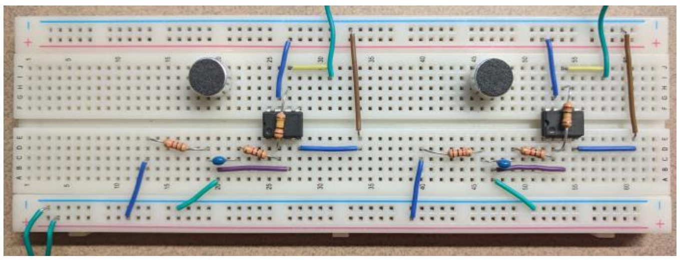


Figure 8: Circuit setup including two op-amps which connect to the DAQ (data acquisition).

The two-microphone design has one microphone before the sample and the other microphone after the sample, see Figure 9. The microphones are mounted flush with the wall of the impedance tube in order to reduce their effect on the plane wave in the tube [4]. This also allows for different anechoic termination at the end of the tube to reduce the amount of sound reflected by the end of the impedance tube. Several pieces of foam were used as the anechoic termination in the following material tests.

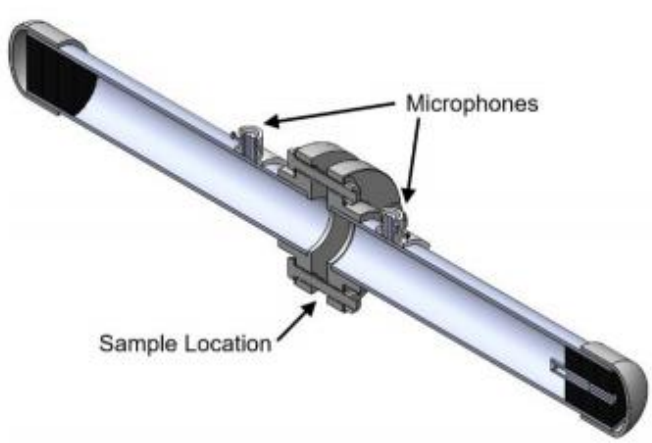


Figure 9. Impedance tube design including two microphones.

The microphones were connected to analog inputs 0 and 1 on a National Instruments USB-6009 DAQ. The sensitivity of the microphones used this year was -44 dB which corresponds to a change of 1 V/Pa, which is relatively weak. The analog input on the DAQ has a resolution of 0.002 V. Low voltages like the output from the microphone are susceptible to electrical noise introduced by the environment. An op-amp increases the voltage from the microphone by a factor called the gain. The op-amps for the microphones were designed to have a gain of 100. The analog input reads the amplified signal which better utilizes the sensitivity of the microphone. The gain is then removed from the signal numerically after the analog input reads the signal. The sound testing data was collected using a LabVIEW program that would output the frequency and amplitude for both microphones. The program utilized band-pass filters to allow for the data being collected to be within a specified frequency range. The data would then be exported to Excel were it would be compiled and analyzed further

Material Testing

This year, materials advertised to reduce sound were ordered as samples from multiple companies including 3M, Noico, Super Soundproofing, and BQuiet. This gave us a wide variety of materials to test to see which of them would perform the best, and also be the most applicable for reducing sound in the snowmobile. Samples were cut to the correct size for testing and then labeled. Next, the sample would be placed between the two sides of the impedance tube, and would be tested on a range of frequencies from 100 Hz up to 4000 Hz, after which the data would be recorded.

Sound Absorbing Materials

The goal of sound absorbing materials is to reduce noise and vibration throughout the snowmobile by converting the sound energy into heat or transmitting it away. Acoustic insulators are generally porous and soft which allows for better absorption and less reflection of the sound. Snowmobile engines tend to output sound at lower frequencies; therefore, 0 to 1000 Hz is chosen as the critical frequency range for testing these materials. Sound frequencies higher than this chosen range occur in the sled but are less prominent. More negative dB values indicates better reduction in noise as seen in Figure 10 below.

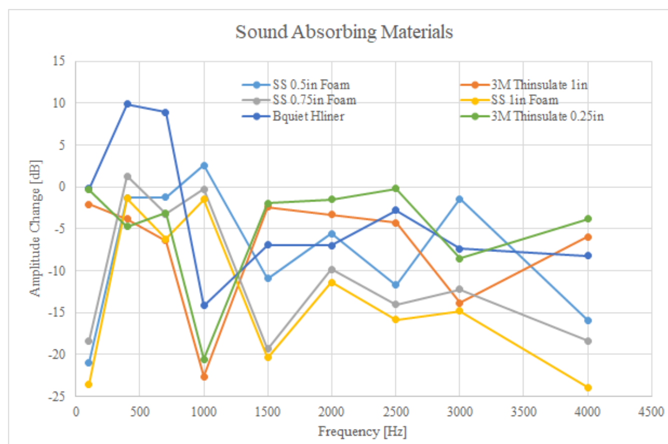


Figure 10. Sound absorbing material samples tested to see which performed the best.

As shown by Figure 10, Bquiet Hliner is the least effective in the critical frequency range, and even had a positive amplitude change under frequencies of 100, 400, and 700 Hz. As for the Super Soundproofing Foams (SS), all three thicknesses peaked as the frequency increased within the critical range, performing especially poorly at frequencies of 400 and 1000 Hz. The 3M Thinsulate 0.25 inch was relatively effective at higher frequencies within this critical range, reducing amplitude to approximately -5, -3, and -22 dB for frequencies of 400, 700, and 100 Hz, respectively. As expected, the 3M Thinsulate 1in sample outperformed its 0.25in counterpart in all but one of the critical frequency tests, and also performed the best overall between 500 and 1000 Hz with approximate amplitude reductions of -6 and -23 dB, respectively.

Weight also plays an important factor in material selection. The 3M Thinsulate had a density of 0.16 lb/sqft, while the Bquiet Hliner and the Super Soundproofing foam were slightly heavier being 0.24 lb/sqft and 0.25 lb/sqft, respectively. For the above reasons and also considering MSRP, 3M Thinsulate 1in was chosen to replace all stock foam and was also added to previously un-insulated portions around the engine compartment to further increase noise reduction.

Sound Blocking/Damping Materials

The goal of sound blocking materials is to minimize the transmission of direct sound waves by blocking its path of travel. They are also useful for sound damping which reduces the resonance of the mechanical structures in the snowmobile, including the tunnel, clutch cover, bulkhead, and footrests, along with acoustic resonances generated. In general, a higher mass of material will block more sound, but for our application there will be a tradeoff between weight and sound blocking. As before, the more negative dB indicates better reduction in noise as seen in Figure 11 below.

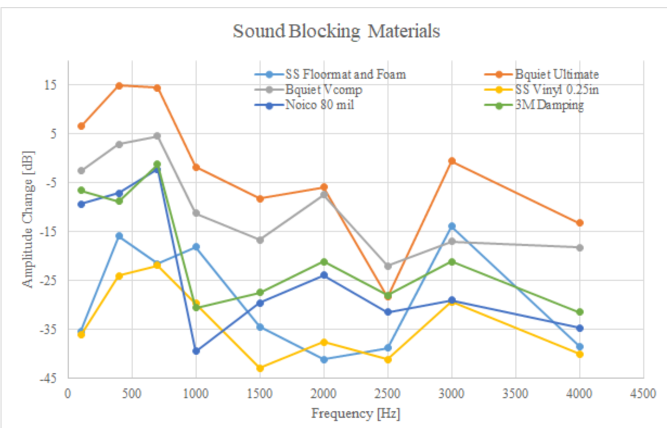


Figure 11. Sound blocking material samples tested to see which performed the best.

As shown in Figure 11, the two Bquiet material options were the least effective at sound blocking at nearly all tested frequencies, making them unsuitable sound blocking choices. The SS materials were the two most effective samples across the test frequency range. However, the two SS samples are also the two most dense samples with densities of 1.2 and 1.8 lb/sqft respectively, making them ideal for sound blocking but not for minimizing sled weight. The SS vinyl material is much thicker than other materials tested, which has the potential to interfere with moving components, and is also much stiffer which would make it hard to apply to the irregular shapes found on the sled. The Noico 80 mil and 3M damping samples performed similarly under low test frequencies, but the Noico sample had slightly better performance at the higher frequencies. The Noico sample's density is 0.78 lb/sqft, and the 3M damping material has a 0.29 lb/sqft density. Due to the nature of the materials in the 3M damping, we were advised that it would not perform well in cold environments. Since Noico is relatively low density and was one of the most effective materials at sound blocking, it was selected for application in the snowmobile.

The sound materials that were chosen to be used in the sled were then tested compared to the stock materials that are originally used by Polaris, which is shown in Figure 12, and Figure 13 below.

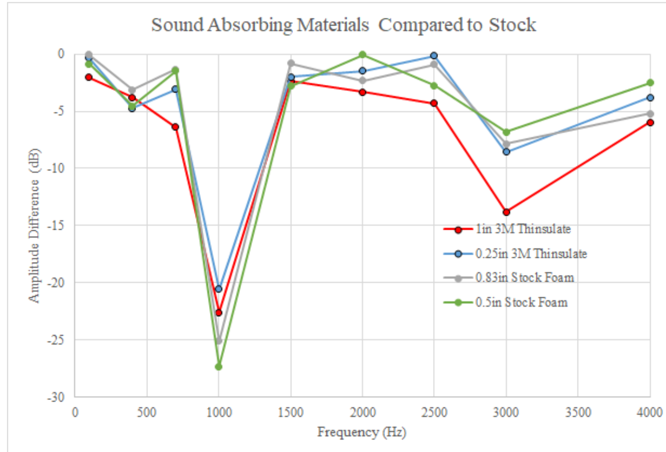


Figure 12. Stock sound absorbing foams compared to the two types of 3M Thinsulate that were selected.

As shown in figure 12, all four materials performed very well at a frequency of 1000 Hz, with an amplitude difference between -20 and -27 dB. The stock foams performed the best at this frequency, however, through the rest of the frequencies the stock foams were consistently worse at absorbing sound, when compared to the 3M Thinsulate samples. The 1in 3M Thinsulate particularly stands out at a frequency of 700Hz where it has a 6 dB better amplitude difference than both stock foams. This is a frequency that is within the critical range meaning it will have a large impact on the overall loudness of the snowmobile. This sample also shows significant superiority throughout the frequencies above 1500 Hz. When comparing the two 3M samples, the 1in sample overall had a better reduction in both the low and high frequency ranges, making it the overall best choice in terms of sound absorption.

When comparing the densities of these four samples, the stock foam had a density of 0.23lb/sqft while the 3M thinsulate had a density of 0.16 lb/sqft. Having lower density combined with the overall improved sound absorption, the 3M samples make a better material for lining the snowmobile. The 1in 3M sample was better at almost every frequency than the 0.25in sample, making it the best choice for the sound absorbing material.

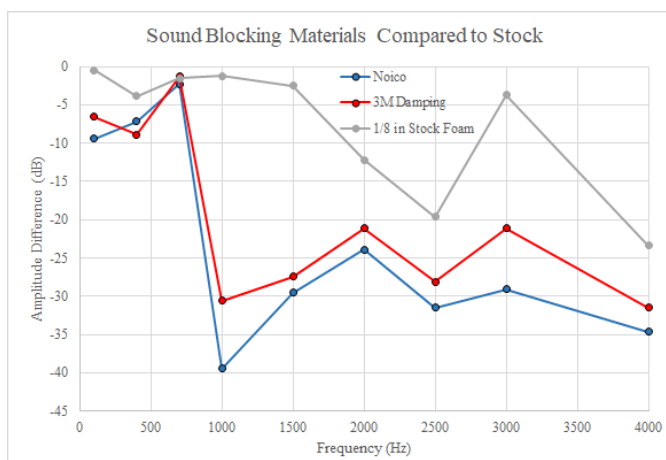


Figure 13. The thin dense stock foam from the sled was also tested and compared to the sound blocking materials that were selected.

As mentioned previously, the 3M damping material and the Noico sample perform similarly for frequencies under 1000 Hz; however, Noico is significantly more effective at greater than 1000 Hz, and doesn't have the added concern of poor performance at low temperatures. As seen in Figure 13 above, both non-stock materials performed better than the stock foam, at all test frequencies, and approximately as well as the stock foam at 700 Hz. These results justify adding an aftermarket solution of Noico 80 mil for sound blocking application.

Intake and Exhaust

Intake

One of the major problems caused by an engine swap is the packaging issues created by the larger engine. The OEM intake routing used on the ACE 570 had to be redesigned to allow for sufficient room between the throttle body and the gas tank. A short, 35° bend was added in between the OEM adapter and the throttle body. The bend was 3D printed using ULTEM 1010 Resin from Stratasys. This material was chosen because it is a strong alternative to normal 3D printed plastics and provides a better thermal resistance. After the throttle body, the rest of the intake routing had to be repositioned to accommodate the gas tank and various coolant lines. To provide enough room to reroute the intake, a box was designed to divert the flow of fresh air 180°. Flexible tubing was then routed to the outside of the sled to provide cold, fresh air to the intake.

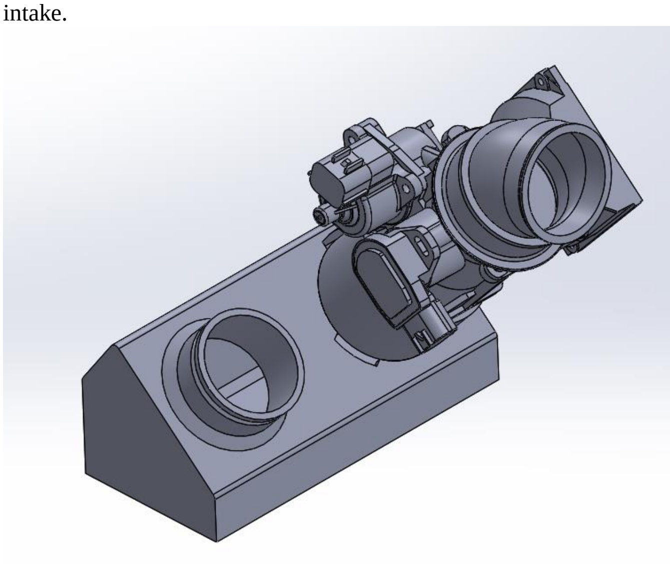


Figure 14. Intake routing from inlet adapter to intake box. Flexible pipe and filter not shown.

Exhaust

The team has struggled in previous years to effectively incorporate a catalytic converter into the snowmobile's exhaust system. Last year, issues with placement and shielding forced the team to switch back to the stock muffler just days before the 2018 competition, which affected the exhaust noise reduction of the snowmobile. The strategy for this exhaust system was to retain as much of the OEM system as possible. The stock exhaust system consisted of the OEM muffler and the Liberty 600 expansion pipe. As the new motor is a 4-stroke, the expansion pipe was no longer needed, and a custom header was designed to take its place. The goal of this custom header was to route the exhaust gases to the stock muffler with minimal back pressure and house the catalytic converter. Figure 15 shows the custom header with the catalyst incorporation, alongside the stock muffler.

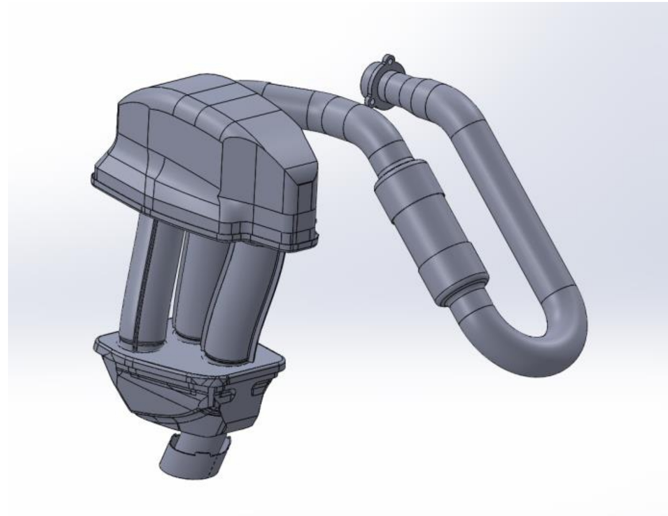


Figure 15. SolidWorks model of the competition exhaust system.

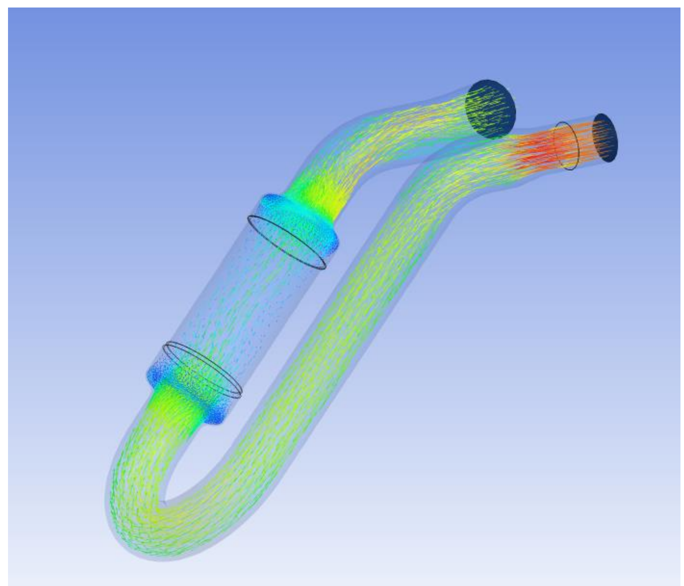


Figure 16. ANSYS Fluent simulation of the custom exhaust header. Exhaust gases enter on the far right and flow through the header to the stock muffler. Vectors are shown and indicate local stream velocity, with red corresponding to a higher velocity.

The catalytic converter chosen is a Heraeus 1:1 Platinum/Rhodium coating, double 400 CPI matrix design. This catalyst has an operating range of 450°-800° Celsius. Exhaust temperature tests were conducted with the ProStar 570 engine running with its OEM exhaust system to get an idea of the exhaust gas temperature at various lengths down the header pipe. Temperatures maxed out at around 850° Celsius four inches downstream and 806° at 11 inches downstream. The catalyst was then placed 25 inches downstream to prevent it from overheating. Precautions were taken to shield the catalyst too, as extra vents were cut into the stock hood to allow hot air to escape the engine bay around the catalyst. The stock muffler was reused due to its size and fitment in the snowmobile.

Electrical

Engine Management

To be able to run the ProStar 570 on fuels with various ethanol contents a custom engine control unit was used. A MoTeC M800 ECU was loaned to the team by the University of Minnesota Thomas E. Murphy Engine Lab for this purpose. As the Lab and In-Service Emission events are weighted so heavily in the SAE Clean Snowmobile Challenge, the team wanted to focus on engine emissions while attempting to retain as much of the stock power from the ProStar 570 as possible. Focusing on emissions led the team to decide to run the engine as close to stoichiometric as possible. A wideband O2 sensor (Bosch LSU 4.2) was added to the exhaust header to allow the team to determine what air-fuel ratio the engine is running and tune for lambda=1, or stoichiometric. To read the various ethanol contents and convey that information to the ECU, a Continental ethanol sensor was added to the fuel line. As ethanol content increases more fuel needs to be added to the cylinder to maintain a stoichiometric ratio, and unique fuel and ignition tables were developed to ensure that the engine is properly operating no matter the ethanol content of the fuel. More information on the ethanol sensor, wiring harness, and ignition control is given below. A system level wiring schematic is located in Appendix A and B.

MoTeC M800 ECU Harness

A custom wiring harness [Appendix A] was constructed to incorporate all sensors and actuators from the Polaris Switchback chassis and the ProStar 570 4-stroke engine with a MoTeC M800 ECU. There are four types of interfaces used to transmit I/O data that were physically routed and configured in MoTeC tuning software:
Differential Signal: Crank position sensor and Idle air control motor utilize differential signals for communication in a noisy environment.
Control Ground: Includes injector driver and ignition coil. Used for high energy applications, non-linear current sinks to ECU output.
Analog: Variable voltage received from potentiometers acting as the throttle position and exhaust lambda sensor. Thermocouple sensors report analog voltages for engine and air temperature.
PWM/Frequency Modulation: This signal is unique to the ethanol sensor that was added to the engine. Duty cycle and pulse period are variable on the output line, which is also a control ground since it must be connected to power via a weak pull-up.
No documentation was available for the idle air control motor, and operation had to be experimentally verified by creating a custom test circuit, see Figure 17. Three flip flops were used to 4x divide a clock signal and supply two differential outputs with a 90◦ phase shift. Plunger extension/retraction speed was able to be controlled and measured by frequency and leading phase.

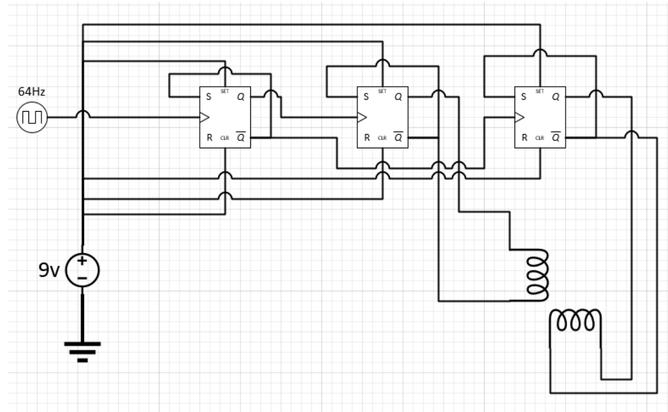


Figure 17. Idle Air Control Motor Circuit

Ignition Control

The ignition control wiring [Appendix B] was designed to have three main user controls and three active components to distribute power amongst various systems in the snowmobile. User inputs include a 3-position key switch and two emergency shutoff devices, one single pole normally open kill switch and a normally open tether to be attached to the rider. Three usable states exist for the key switch which include:
OFF – No connection made, and all power remains isolated from engine/chassis.
RUN – Without either emergency shutoff activated, power will be available for all engine/chassis supply nodes.
START – Connection is made between battery and starter solenoid to activate the starter motor, continuity also exists between RUN contacts.
Active components are comprised of two double throw relays and an NPN MOSFET. The ignition relay is controlled by the key switch and supplies power to the ECU, EFI relay, and all engine peripheral sensors and actuators. The EFI relay controls fuel pump operation and acts as a switched supply for other running accessory devices. Both relays have fused output connections to protect against overcurrent and polarity reversal events. The NPN transistor was implemented in the design to remove emergency shutoff control from the ECU in case of a malfunction. Drain and source contacts are placed between the battery and control input of the ignition relay to disrupt all power transmission to the snowmobile’s electrical components. The gate is controlled by a weak pull-up to battery voltage and both emergency shutoff switches. When the switches are open the MOSFET will remain on but will turn off as soon as one is activated and drags the gate down to reference voltage.

Flex Fuel Ethanol Sensor

A flex fuel sensor was integrated into the snowmobile design to provide AFR correction data based on varying ethanol content mixtures. The sensor is mounted in-line near the fuel rail and provides a PWM/Frequency modulated signal to the ECU. Duty cycle signal component provides fuel temperature, and the pulse period indicates ethanol content of the fuel via dielectric permittivity calculation. Baseline data was taken at a full range of ethanol levels to realize a linear output trend that spans from 50Hz-150Hz increasing per degree of ethanol in mixture, see Figure 18.

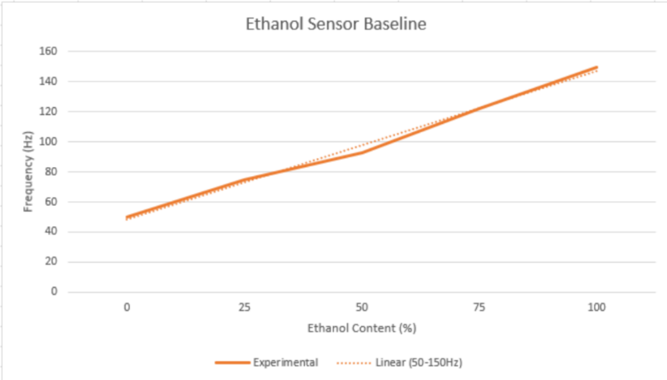


Figure 18. Flex Fuel Sensor Baseline Data

Dynamometer

The UMN Clean Snowmobile Team partnered with the Murphy Engine lab in order to update one of their dynamometer rigs. The team integrated the Polaris ProStar 570 engine into the dynamometer rig. The dyno had previously been used with a ProStar 30. Several problems with the ProStar 30 dyno setup were addressed in the update. The ProStar 30 wore out the flexible element in the coupling connecting it to the dyno much faster than expected. The Murphy lab concluded that the flexible element was being prematurely worn out by the pulsations in applied load.

In the redesigned dyno rig, a toothed belt was included to damp pulsations in the load seen by the coupling. A 1:1 gear ratio was used on the pulleys to allow direct measurements of engine rpm and torque. A bearing lifetime of 10,000 hours and shaft stress drove selection of the bearings and pulleys. Mild steel was selected as the runner shaft due to machinability. However, this severely limited the maximum allowable stress. The endurance limit of mild steel was determined to be 19.9 ksi, and a safety factor of 2 was sought in shaft design. The larger the diameter of pulley, the smaller the radial force on the shaft, which reduces the maximum stress. So, a very large pulley is desirable; however, a very large pulley increased the inertia of the powertrain. As the inertia of the system increases, the response time decreases. This is fine for steady state tuning. However, the ability of the dynamometer rig to measure transitients, like acceleration, would be reduced. A pulley with a pitch diameter of 4 inches was found to fulfill the requirements stated above.

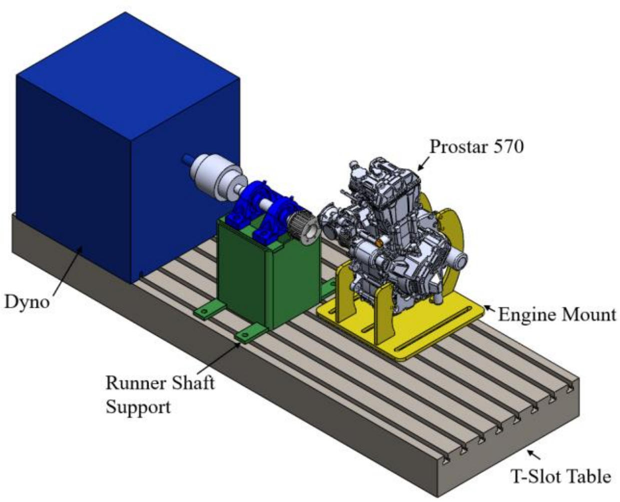


Figure 19. The powertrain components of the dyno setup were secured to a T-Slot style table. The accessory frame is not illustrated.

Fasteners loosening due to vibrations was another problem that the original dyno rig encountered. An accessory frame that held the ECU, fuel pump, throttle control, and other necessary systems was prone to having bolts come loose. In order to solve this problem, a welded accessory frame was constructed to minimize the number of bolts that could come loose. On the bolts that could not be eliminated, thread locker was utilized. In addition to minimizing fastener count, the vibrations in the accessory frame were reduced by bolting the frame directly to the dyno table instead of directly to the engine mounts.

In summary, the primary concern for the construction of the new dyno setup were designing sufficiently durable components and obtaining sufficiently correct alignment of the components. Durability was addressed through finite element analysis of critical components and generous safety factors which kept material stresses below their fatigue limit. Alignment was achieved through careful construction of components coupled with analysis of expected deformation, along with a close attention to detail during assembly.

Crankshaft Extension

While the center of crankshaft on the ProStar 570 is held at the correct spacing by the engine mounts, the axial location of the crankshaft will not work with the stock clutching. An extension was designed to axially locate the end of the crankshaft at the correct position, see Figure 20. The crankshaft on the ProStar 570 uses a different size thread than the Indy 600. The extension is subjected to two major forces, the force of the belt on the primary clutch which causes a torque and the preload of the primary bolt.

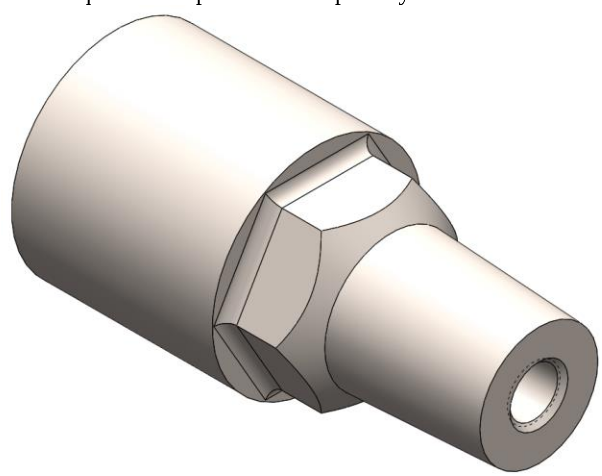


Figure 20. The crankshaft extension was designed to change the size of taper as well as position the primary clutch in the correct location relative the secondary clutch.

Bolt Preload Considerations

The bolt preload was determined to be the largest factor contributing to stress in the taper adapter. The clutch off the Switchback 600 uses a M14x1.5 bolt. At the torque specified in the Polaris manual, the bolt will experience a preload of 8,300 lbs. During stress analysis, this preload produced excessive stress in the taper cavity. The recommended bolt torque in the Dynomite dynamometer manual is about half of what Polaris uses for the primary clutch bolt. The taper cavity on the Dynomite dyno has less material surrounding it than the taper on the primary clutch.

The diameter of the crankshaft bolt had to be changed since the ProStar 570 engine uses a 7/16-20 thread which is smaller than the crankshaft bolt used with the Indy 600. The smaller bolt size necessitates a reduction in preload to prevent yielding. The minimum preload needed to prevent the taper from slipping was found analytically. The taper was modeled as a cone clutch with the maximum amount of torque transmitted before slipping given by equation 1.

$$T = \frac{2F\mu_s(r_o^3 - r_i^3)}{3\,sin(\alpha)(r_o^2 - r_i^2)} \quad (1)$$

Where T is torque, F is axial force, α is half the included angle, μ_s is the coefficient of friction, r_o is the large radius of the taper, and r_i is the smaller radius of the taper [1]. Equation 1 was rearranged to find the axial force. The axial force required to transmit a torque of 100 ft-lb was calculated to be 715 lbs when a dynamic coefficient of friction of 0.15 was used. Using the dynamic coefficient provides confidence that even if the taper started to slip for some reason, there would be sufficient friction to stop it from spinning. When the static coefficient of friction, 0.5, was used, a preload of 214 lbs was found to be necessary. Using a torque of 100 ft-lbs and the dynamic coefficient of friction, a safety factor in excess of 4 with respect to slipping was built into the required axial force. The required torque to produce 715 lbs of preload on the Indy 600 crankshaft bolt is 6.9 ft-lbs which is much less than the 80 ft-lbs specified in the service manual.

Stress

Analytical and numerical methods were used to find the stress in the crankshaft extension. The analytical model was used to confirm the results of the numerical model. The two models had a percent difference of 7%.

An analytical model was used to find the stress at the wide end of the taper cavity. Stress will be the greatest at the wide end of the cavity since there is the least amount of wall thickness to support the force. The tangential and radial components of an element were found by approximating a thin, cross-sectional slice at the end of the taper as a thick walled pipe using equation 2 and 3.

$$\sigma_{tangential} = p_x \frac{a^2 + b^2}{a^2 - b^2} \quad (2)$$

$$\sigma_{radial} = -p_x \quad (3)$$

Where "p_x" is the pressure normal to the taper centerline, "a" is the outer radius, and "b" is the inner radius [2]. The pressure distribution along the taper was assumed uniform allowing equation 4 to be used to relate axial force to pressure.

$$p_x = p * cos(\alpha) = \frac{F}{\pi(r_o^2 - r_i^2)} * cos(\alpha) \quad (4)$$

Equation 4 is derived by manipulating equation 1. The axial component of stress is given by the bolt preload over the cross-sectional area of the end of the taper cavity. This produces an overestimation of the axial stress since the reaction force to the bolt preload will be distributed over the length of taper.

The equivalent stress surrounding the taper was then found from the three principal stresses. A balance between stress in the taper cavity and sufficient bolt preload was achieved. Sufficient bolt preload is necessary to prevent bolt loosening and increase the fatigue resistance of the bolt [3]. When 45 ft-lbs of torque are applied to the crankshaft bolt, a preload of 6,200 lbs results. This equates to a stress of 89 ksi in the taper cavity region of the extension.

A finite element model of the crankshaft extension was created to verify the analytical model. A multiple body simulation was used to increase the accuracy of the model at the connection between the crankshaft and extension. As seen in Figure 21, the contact region between the crankshaft and extension had some nodes that had very high stress that were not consistent with their neighbors. However, when taken in aggregate, the stress in the taper region is 95 ksi. The analytical and numerical models have a percent difference of 7%.

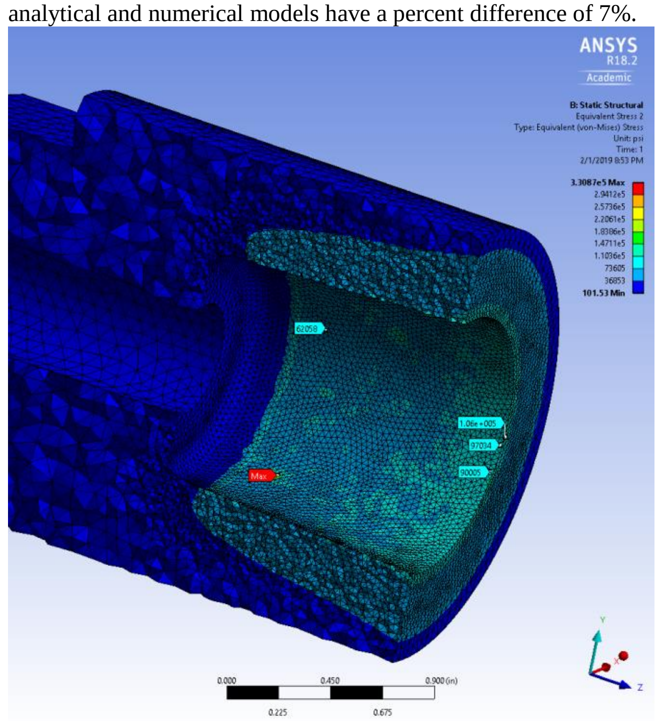


Figure 21. The finite element model developed in ANSYS agrees well with the analytical model.

Summary/Conclusions

Through effective project management and collaboration, the team achieved an engine swap. The team designed custom engine mounts and a torque stop to allow mounting of the ProStar 570 engine into the Switchback engine bay. Without the expansion pipe associated with the stock 2-stroke engine, the team placed a catalytic converter in the exhaust system without having to modify the stock muffler. This enabled the team to run the larger absorptive muffler that came stock with the sled instead of being limited to a smaller muffler due to manufacturing capabilities. Employing 3D printing for intake construction allowed the team to make a geometrically complex intake that was still manufacturable. The complex geometry was driven by the lack of space between the engine and fuel tank. Empirical validation of the damping properties of prospective sound deadening materials allowed the team to select the optimum material for use on the sled. The team changed the weights and spring in the Switchback 600 clutch in order to tailor the performance of the clutch to the new engine. Since the ProStar 570 engine sits further in the engine bay than the Indy 600, the team designed an extension to correctly locate the Switchback 600 clutch. To improve the team's engine calibration capabilities, the team designed a dynamometer rig to measure engine power. These projects enable the UMN-CST to compete at a higher level than ever before.

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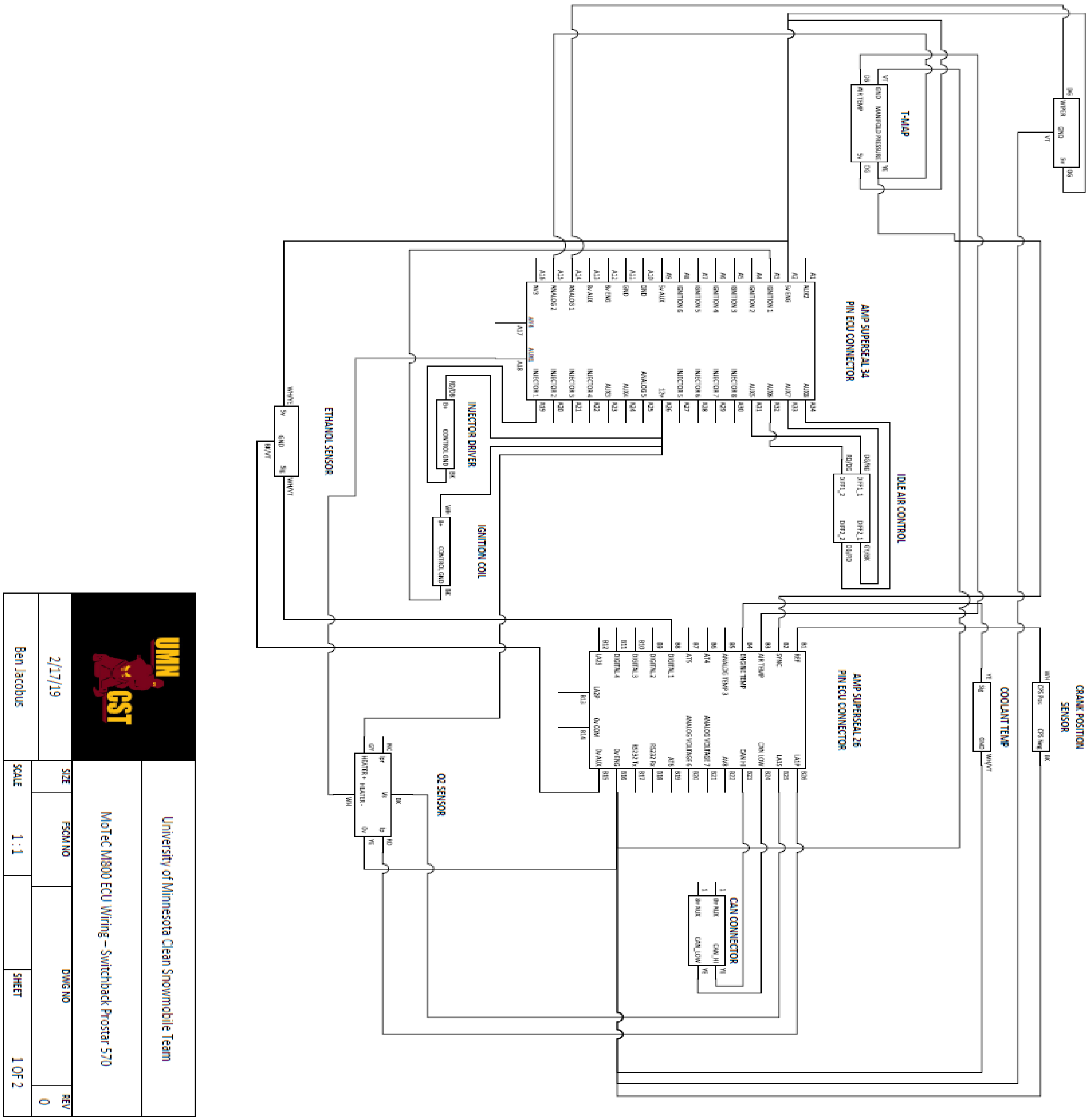
Definitions/Abbreviations

AFR	Air-to-Fuel Ratio
CVT	Continuously Variable Transmission
ECU	Engine Control Unit
EFI	Electronic Fuel Injection
I/O	Input/Output
MOSFET	Field Effect Transistor
OEM	Original Equipment Manufacturer
PWM	Pulse Width Modulated
RPM	Revolutions per Minute
UMN-CST	University of Minnesota - Twin Cities Clean Snowmobile Team

Appendix A: ECU Wiring Harness Schematic



Appendix B:Ignition/EFI Control Wiring Schematic