Emissions, Fuel Economy, and Sound Reduction Improvements to the 2016 Polaris Pro-S featuring the Prostar 1000 Engine

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ABSTRACT

The University of Minnesota Duluth's Clean Snowmobile Team has a new entry for the 2018 SAE International Clean Snowmobile Challenge. A move to a new manufacturer has given the team the opportunity for a clean slate and new design cycle. The 2016 Polaris Pro-S trail performance chassis is paired with a Polaris ProStar 1000cc parallel twin 4-stroke engine sourced from a Polaris Ranger UTV. This package is well suited to meet the demands of both the competition and the consumer. To improve emissions and engine efficiency, a custom intake and electronic throttle system was implemented to not only make the airflow more efficient, but also provide better driveability. Using the Ricardo-WAVE model, a custom 2-way catalyst is implemented in a custom exhaust. A standalone MoTeC M130 engine control unit provides comprehensive calibration capabilities for the package. Building on the testing done in previous years, a simulated acoustic imaging system was built to better target sound emission areas. Through this testing advancement, chassis and drivetrain noise was drastically decreased. For engine noise emissions, a custom designed dual-chamber muffler was implemented. The finished product is a reliable 65-horsepower class snowmobile that is efficient, fun to ride, and competitively priced.

MARKET ANALYSIS

The goal of the competition is to modify a snowmobile to be more fuel efficient and achieve better emissions, however the ultimate goal is to develop new technologies that will eventually get to market. This goal of a marketable snowmobile is something that has always been a priority for the UMD Team. As a club made up of snowmobile enthusiasts, an enjoyable, marketable snowmobile is just as important as emissions and economy. The 65-horsepower class is a small, but growing market of snowmobiles. It caters to riders who prefer a quiet, efficient, smooth snowmobile over higher performance. This demand is currently being met by two machines: the Ski-doo 600 ACE and the Arctic Cat ZR 3000. The lightweight Polaris Pro-S chassis, coupled with the 1000cc 4-stroke engine will provide a cost effective package that is competitive on fuel economy and emissions, while being quieter and more enjoyable to ride than the competition.

ENGINE IMPROVEMENTS

Fuel economy and emissions are two pillars of this competition. After multiple successful seasons with the Arctic Cat 3000 Turbo, the transition was made to a new engine package. A completely new engine package meant the start of a new design cycle as well. The goals for the first year of the design cycle were to calibrate the engine with a standalone ECU, catalytic converter, flex-fuel capability, and an electronic throttle. While not pushing the boundaries of the competition, this first year engine package design will provide a strong foundation for the coming years.

Engine Package Design

When observing the trends of the last decade of the snowmobile industry, it is clear to see the emergence of 4-stroke engines. What began as only a handful of models in the trail/utility category has grown to a sizeable portion of the market, with 4-stroke models available from three of the four manufacturers. Everything from high performance mountain snowmobiles to value-oriented trail models have seen the arrival of the 4-stroke engine, and with great success. The reasons are clear: the outgoing 2-stroke models are typically louder, with worse emissions and fuel economy. With a reputation for better reliability and drive quality as well, the 4-stroke segment grows every year. The 1000cc twin engine provides an ideal foundation, with a 2-way catalytic converter and custom intake and exhaust improving engine efficiency. The advanced control logic of the MoTeC ECU, coupled with the drive-by-wire throttle, provides enhanced driveability and run quality. Most importantly, this engine package provides a great foundation to build on in the years to come.

Table 1. ProStar 1000 Specifications

Engine	ProStar 1000
Displacement (cc)	999
Configuration	Inline Twin
Valve Layout	Dual Overhead Camshaft
Fueling	Full Sequential Port Fuel Injection
Compression Ratio	10.6:1
Bore x Stroke (mm)	93x73.5
Ignition Type	Coil on Plug
Block Material	Aluminum

Utilizing a Land & Sea Dynomite dynamometer, a full baseline test was done on the new engine in stock form. The engine is rated as 60 kW of power. In-house dyno testing resulted in 56 kW and 73 newton-meters (N·m) of torque.

In an effort to expedite the engine package design before it was even constructed, a full Ricardo WAVE simulation was created. This simulation allowed for many different exhaust and intake designs to be tested before fabrication. This was crucial to the success of the build. Knowing that the custom intake, throttle body, and exhaust specifics were chosen correctly and would work well with the engine is invaluable, as it was both a cost and time-saving provision.

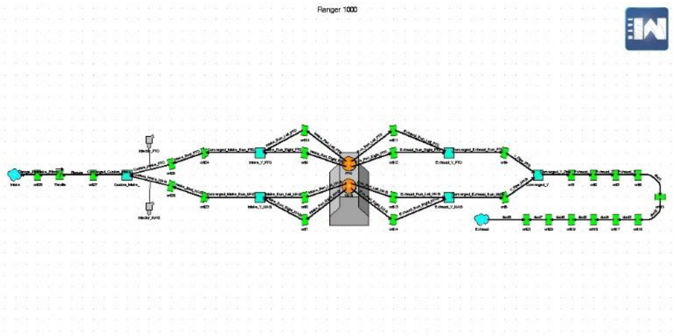

Figure 1. Full engine package modeled in Ricardo WAVE

Engine Calibration and Testing

The engine package was constructed and calibrated separate from the bulkhead this year. Although this was a slower process, it allowed for an engine to be properly mated to the foreign chassis all while engine improvements were conducted on a separate engine. After the engine modifications were complete, the engine was placed in the dyno cell for calibration. This year the Engine Control Unit (ECU) is a MoTeC M130. This ECU provides a more customizable calibration approach then the Haltech Elite 2500 that was run in previous years. The MoTeC offers increased tuning capabilities for the engine, as well as the additional components in the sled controlled by the ECU. The electronic drive-by-wire throttle system from Ski-Doo was utilized on the snowmobile again this year. In conjunction with the MoTeC, the drive-by-wire allows for customized throttle characteristics. These two systems work in harmony to increase both transient and steady state fuel economy, as well as driveability.

The goal this year was to produce a snowmobile that provides lower engine and sound emissions, while remaining competitive in the 65 hp class. Moreover, this year is the first year in a multi-year design cycle. Special care was taken to thoroughly understand the engine package, it's characteristics, and the new engine control software.

The engine calibration strategy utilized a closed loop tuning system with a wideband O2 control. Closed loop tuning offers more finite control over the fueling and timing, and the MoTeC M130 ECU handled it well. A stoichiometric (stoich) fuel mixture was used throughout the engine calibration map. This means that the lambda (air-to-fuel ratio) is 1.00. A stoich fuel mixture means that the fueling is never 'lean' or 'rich'. Maintaining a 1.00 lambda allows for ideal combustion characteristics, and effectively decreases the harmful emissions constituents, namely hydrocarbons (HC) and carbon monoxide (CO). Using Maximum Brake Torque (MBT) timing, the ignition map is well calibrated to prevent detonation (knock) and keep exhaust gas temperatures (EGT's) below 900° C. Overall, this calibration strategy produced a safe, reliable engine package that provided adequate power, while efficiently managing fuel consumption.

Last year, the UMD team received the five-gas emissions analyzer from HORIBA. The new, state-of-the-art emissions tester was a welcome addition, pairing well with the auto-load servo control on the dynamometer. Together, they provide an accurate and robust testing system, resulting in easy to use data.

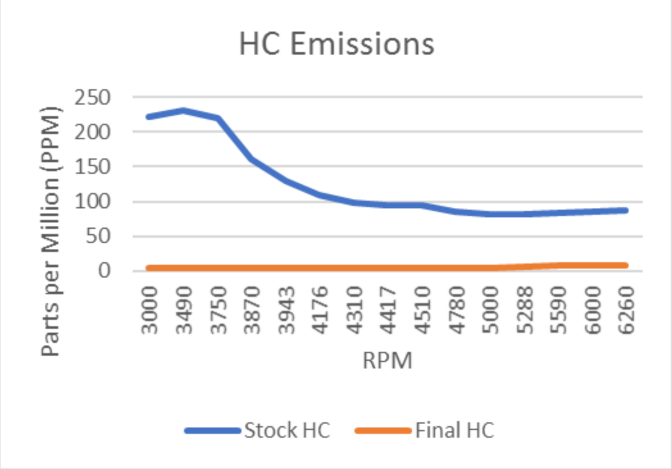

Figure 2. Hydrocarbons emissions in stock form compared with the final engine package.

The implementation of a 2-way catalytic converter saw a great reduction in emissions across the board. As the catalyst is the only exhaust aftertreatment in the system, it was the greatest source of emissions reduction. Working with Heraeus, a specially designed 2-way catalyst was used. Featuring Platinum and Rhodium, the catalyst is especially effective in reducing oxides of nitrogen (NOx). As a stoich engine calibration strategy leads to a reduction in HC and CO, eliminating NOx was the primary goal of the catalyst.

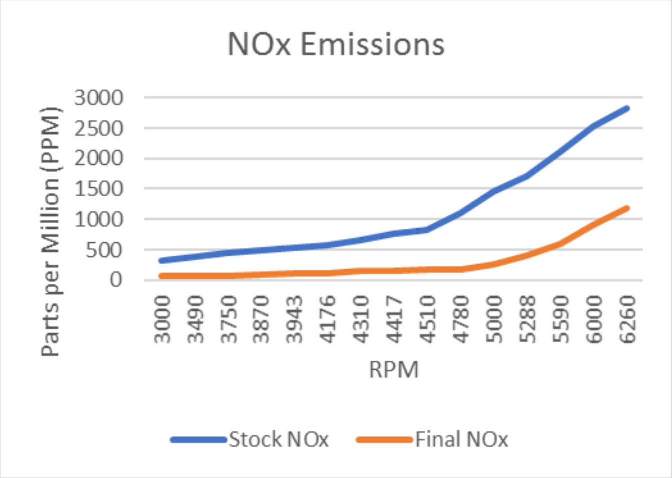

Figure 3. Oxides of Nitrogen emissions in stock form compared with the final engine package.

The resulting engine package produced a strong, reliable engine that produced 45 kW of power and 68 N-m of torque. This result keeps it firmly in the 65-hp trail class of snowmobiles, and is a reliable, well calibrated package. The package produced a 97% reduction in CO emissions, 92% reduction in HC, and a 73% reduction in NOx.

Cooling

As the ProStar 1000 is typically found in a UTV, it features an automotive style radiator mounted in the front of the vehicle. The snowmobile features a heat exchanger in the tunnel to cool the factory 2-stroke engine. A front mounted radiator was implemented. This would provide extra cooling capacity, especially at lower speeds and idle.

Figure 4. The aluminum radiator mounted in the nosecone of the snowmobile.

A 6” by 6” aluminum radiator was attached to the front bumper using a custom 3D-printed mount. This provided mounting for the radiator itself, as well as the electric fan. Engaging the electric fan helps to draw air through the radiator at idle and low speed.

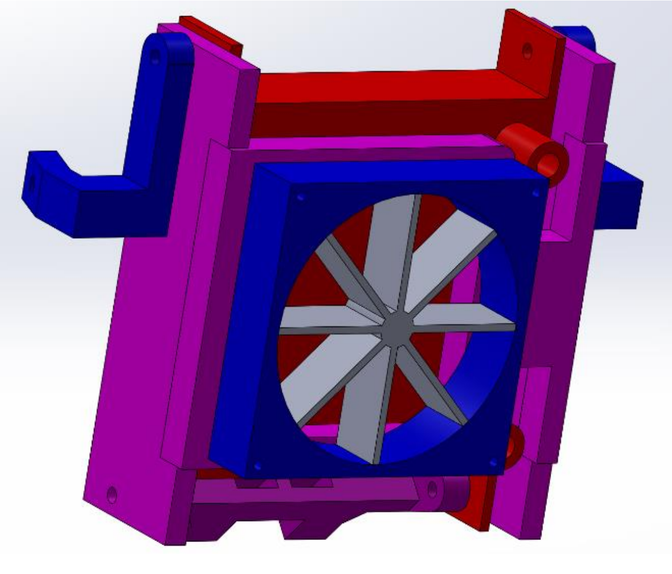

Figure 5. A SolidWorks model of the radiator and cooling fan mount.

The radiator and cooling fan mount was printed out of polylactic acid. This material was chosen due to its ease of manufacturability, as well as high yield strength and resistance to heat. Through on-snow testing, the combination of the factory tunnel coolers and radiator worked well, keeping the machine at operating temperature.

Intake

Fitting with the theme of this project, the intake also had to be completely redesigned to accommodate the new engine. The intake is on the rearward side of the engine, so packaging became top priority. As the overstructure and gas tank are very close to the intake, it had to be a compact design that fit the space available.

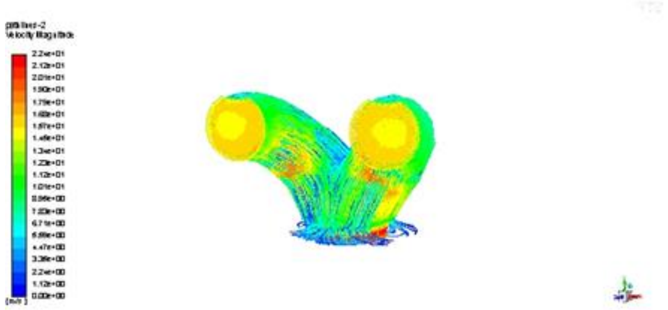

Figure 6. ANSYS flow simulation of intake runner.

The intake runners were modeled in SolidWorks, and further developed in conjunction with the Ricardo-WAVE simulation. The intake runners were designed to work with the factory injectors and fuel rail placement. Although they make a sharp turn up to the ports, the simulations confirmed that ample flow would be available. This sharp turn allowed for the airbox to be mounted below the intake runners, resting on the tunnel.

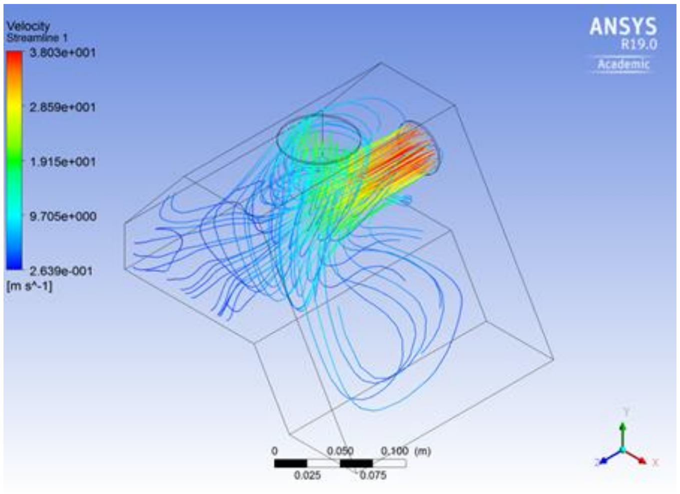

Figure 7. An ANSYS flow simulation of the airbox.

The airbox is shaped to fit the space restrictions of the snowmobile while still matching the volume of the factory airbox. The Ricardo-WAVE model confirmed that the airbox and intake runner design would work harmoniously to deliver unrestricted airflow.

Figure 8. The intake runners, airbox, and throttle body.

The electronic throttle body mounts directly to the airbox, with the same system orientation as the factory ProStar 1000 engine. A silicon intake tube extends from the throttle body to an intake location in the hood.

Chassis and Structural Improvements

Polaris does not currently offer a production 4-stroke snowmobile, therefore significant changes and accommodations had to be made to mate the larger 4-stroke engine into the bulkhead. While this isn't necessarily engineering improvements over a production 4-stroke snowmobile, it simply had to be done to fit the engine. Time was taken on these designs, and they have all been well validated. While this took time and resources away from other projects, it provided a solid foundation to build on in future years.

Engine Mounts

As the bulkhead is four castings of aluminum bolted together, the engine mounts for the incoming 4-stroke engine had to utilize mounting locations already available. Three different mounting locations were used for the incoming 4-stroke: front and rear engine mounts, and a torque stop for the PTO side. The chassis uses a pyramid style overstructure system, which also needed to be modified to fit the larger engine.

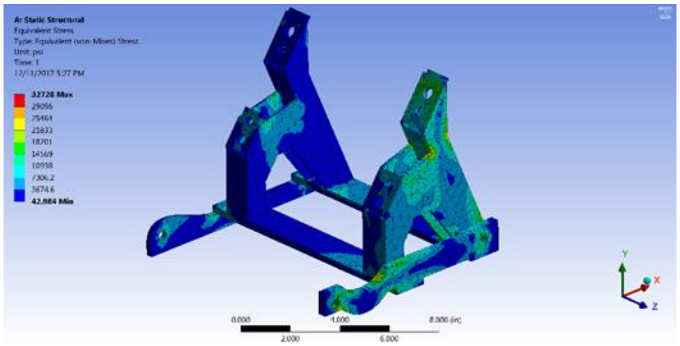

Figure 9. Von-Mises stress analysis of the rear engine mounts.

The rear engine mounts support most of the engine's mass. They utilize the stock engine mounts for the original 800 2-stroke engine. Due to its strength, cost effectiveness, and ease of fabrication, 1020 steel was chosen. The components were designed in SolidWorks, then run through Ansys for a strength analysis.

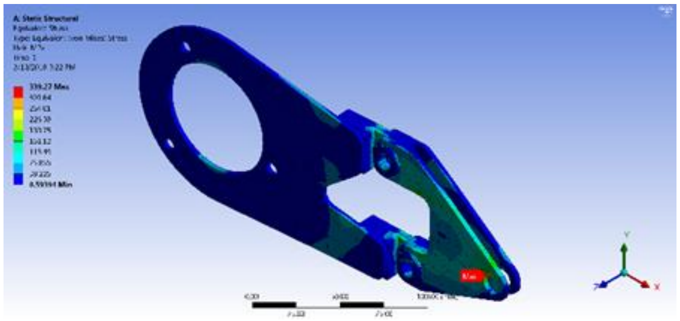

Figure 10. Von-Mises stress analysis of the torque link.

The factory 800cc 2-stroke engine had a torque link on the clutch side of the engine. This design concept was replicated for the new 4-stroke engine. ANSYS simulation was again used to ensure proper strength under the loads of the engine.

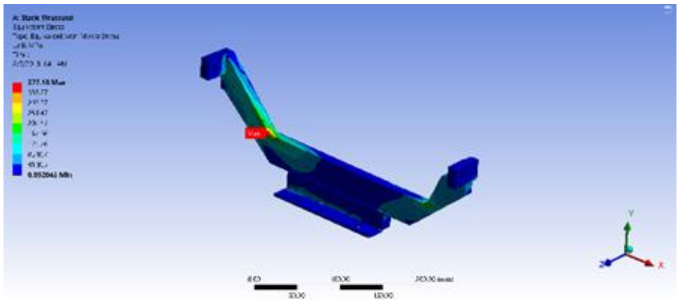

Figure 11. Von-Mises stress analysis of the crossbar.

In stock form, there is a brace across the middle of the bulkhead that provides the strength and mounting points for the front engine mounts. As the new 4-stroke engine is much larger, this brace had to be removed, with a newly designed crossbar in its place. The crossbar was stress tested in ANSYS like the other mounts, and provides plenty of rigidity for the bulkhead.

Over-Structure

The Polaris Pro-S features a pyramid style structure, connecting the bulkhead to the top casting, which houses the upper steering post mount. The stock over-structure would not clear with the new 4-

stroke engine, so the two rear spars were redesigned. Outward curves provide clearance for the fuel system and intake.

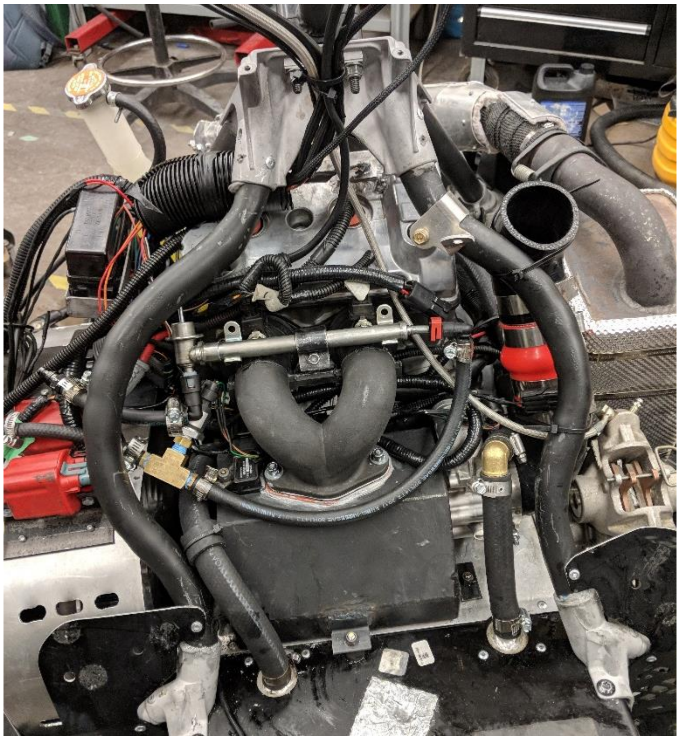

Figure 12. The rear spars redesigned to clear the intake system.

As the over-structure is a major source of strength for the chassis, it was important not to compromise that. The front spars were carbon fiber, and the rear spars were aluminum. All four spars were replaced with 1020 steel tubing with 1/8th inch wall, which has a higher yield strength than both materials.

Clutch Cover

As the primary clutch placement of the new 4-stroke engine is in a different place than the 2-stroke, the stock clutch cover could not be used. For the safety of the rider and protection of other components in the event of belt failure, a new 6061 aluminum cover was made. The 0.090” thick aluminum had 1” slots cut in it to provide ample airflow to the clutches and belt.

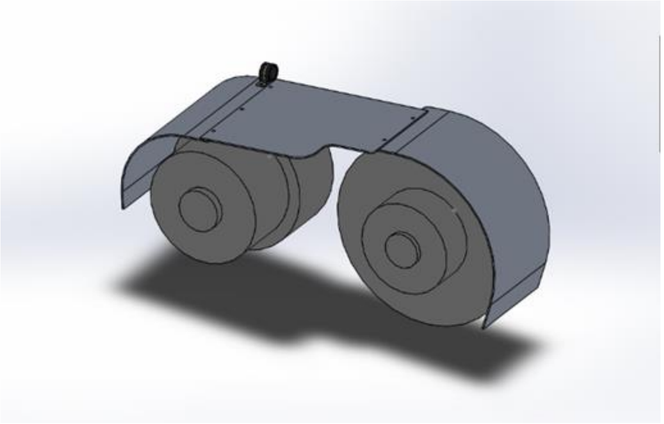

Figure 13. SolidWorks model of the clutch cover.

The clutch cover is bolted to the bulkhead on one end, and a removable pin on the other. This keeps the cover well secured, while allowing the clutch cover to be easily removed for servicing the belt.

Steering System

The larger size of the 4-stroke engine was also problematic for the steering system, as it was quickly realized that the entire system would have to be redesigned completely. After various designs, a double universal joint (U-joint) was chosen. It provided the angles required for proper steering operation. The double U-joint system allowed for use of the factory tie rods, lower steering assembly, and upper steering mounts.

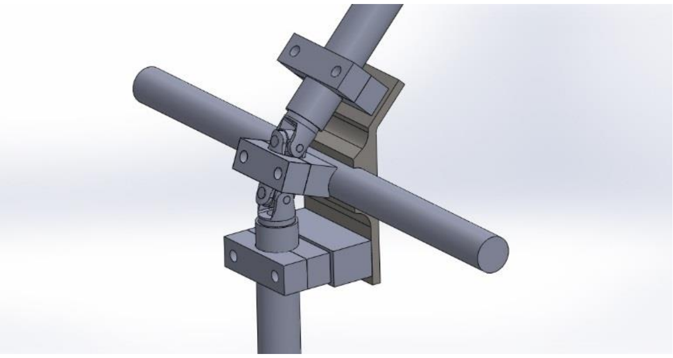

Figure 14. A SolidWorks drawing of the steering assembly.

The upper steering post, lower steering post, and the midsection of the double U-joint all share a mounting plate. This mounting plate ties into the front engine mounting system, providing enough strength for the application. Using an aluminum clamp system, the shafts were rigidly fixed to the mounting plate, while still able to rotate smoothly. Small collars were welded to the shaft on either side of the upper stock clamp mount, keeping the shaft from moving up and down.

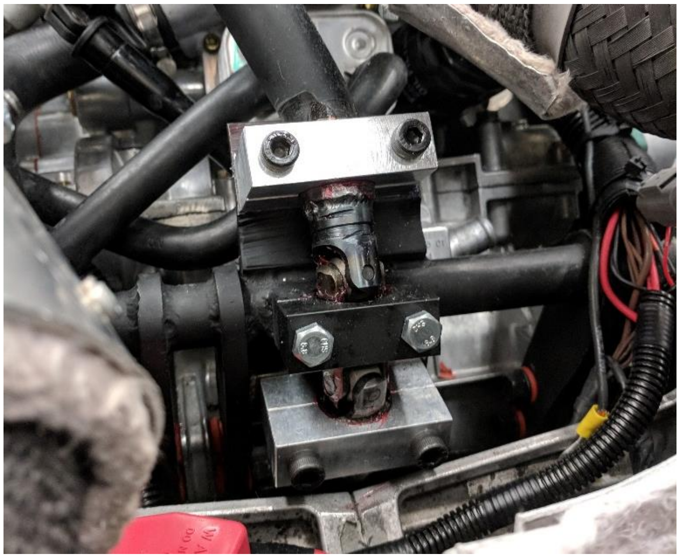

Figure 15. The steering assembly fixed to the chassis.

Sound Improvements

Sound is an incredibly important part of the competition, and the team had lots of room for improvement over the stock snowmobile. This season, a great emphasis was placed on legitimate research and design of the entire machine, not just the exhaust, as a good portion of sound comes from the intake, track, and chassis components.

Chassis

Although the primary source of sound emissions is the engine, the chassis and drivetrain produce substantial noise as well. With an emphasis on drivetrain sound emissions this season, a suitable and reliable testing method was needed. To accomplish that, the water dynamometer was retrofitted to fit our needs. The water dynamometer measured chassis efficiency using an electric motor as a control, and won the 2015 and 2017 Award for Innovation.

The process for testing was the same principle as the water dyno. Utilizing a ten horsepower electric motor with a pulley in place of the primary clutch, the power would transfer through the entire drivetrain down to the track. The track was set on a stainless-steel table that was built to sit in the bottom of the large metal tank. This would allow the weight to rest on the track, much like when it sits on the ground. With the table acting as the boundary condition, load was placed on the rear suspension system, drive sprockets, idler wheels, and axle wheels, all in an effort to accurately measure the simulated sound levels of riding on snow. In order to keep the track and skid properly lubricated, an external water pump was used to provide a constant layer of soapy water on the table.

The room that housed the sound dyno was a closed room that had no other sound inputs during testing. While it wasn't as ideal as a full OEM-quality quiet room for testing, it was very consistent for a University level club. The dyno was placed along one wall, and the sound meter was placed in two marked positions 6 feet away. The electric motor was run at three distinct speeds: 30, 50, and 70 hertz while sound levels were recorded at each position.

New for this year, a contour map of sound was made recording sound across a grid. A contour map of sound is essentially a simpler rendition of an acoustic camera. Acoustic cameras have been used in a variety of industries to isolate vibration and noise sources. This technology, however, is not economically feasible for a University level team. To accommodate, a net grid was placed at a set distance from the water dyno and a sound meter recorded sound in each square of the grid. The water dyno needed further modification to accurately display the sound sources. First, the water tank had to be trimmed to expose the full length of the track. Also, additional sound dampening was used around the test location, and vibration dampening was used under the water tank in an effort to mitigate outside sound or reverberation.

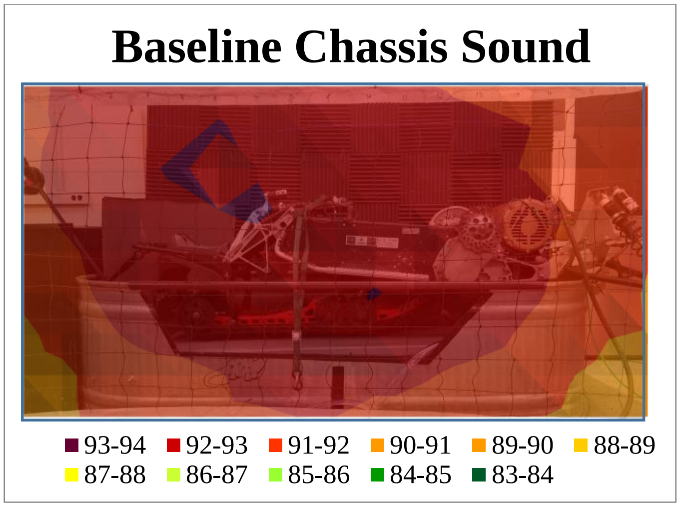

Figure 16. The baseline sound grid test. The colors corelate to observed sound, measured in dBa.

Using the results of the baseline, areas were targeted that had the highest observed sound. These areas were the front of the skid assembly, and the upper mounting location of the rear suspension.

Table 2. The order of added components during testing.

Test 1:	Stock baseline
Test 2:	Removed all Idler Wheels
Test 3:	Add additional support and mounting hardware to factory plastic shields
Test 4:	Applied 'Lizard Skin' tunnel coating
Test 5:	Installed shroud around rear of the track
Test 6:	Installed anti-stab wheel kit

Test 1 is a baseline test of the drivetrain in stock form. For Test 2, all idler and bogey wheels were removed. This greatly reduced sound, but would leave the hyfax open to premature wear. In an OEM application, that is unacceptable. Ultimately, a hyfax from DuPont was used. In addition to the typical plastic, it featured DuPont Vespel graphite inserts to prolong life, allowing for no idler wheels. The hyfax has seen great results in a few seasons of racing and performed well on last year's machine. In Test 3, the snowmobiles rear plastics were fastened more securely. The Polaris Rush chassis features a pivoting rear tunnel suspension with plastic covering the track and coolers. These plastics were able to vibrate and rattle. Test 4 saw the application of a sound deadening coating called Lizard Skin. Applied much like a bed liner in a pickup truck, it adhered well to the underside of the aluminum tunnel. The echo effect created by the tunnel was greatly reduced, and the coating showed no signs of fatigue during on snow testing. Lizard Skin was implemented on last year's entry as well, and performed well. Test 5 added a shroud in an attempt to cover and deflect the sources of sound as much as possible. The Polaris Rush suspension includes a large amount of exposed track and moving parts. In an attempt to combat that, portions of the rear were skirted. Test 6 saw the installation of an Anti-Stab kit. An Anti-Stab kit is an axle with four small roller wheels that mounts at the front of the rail tips. As the idler and bogey wheels were removed, there was a lot of ‘track slap’ present. The track does not maintain uniform tension while rotating around the skid frame and driveshaft, and this can cause the track to make an audible ‘slap’ against the rails. The addition of these rollers smoothed this out greatly, reducing track noise as well as extending track life.

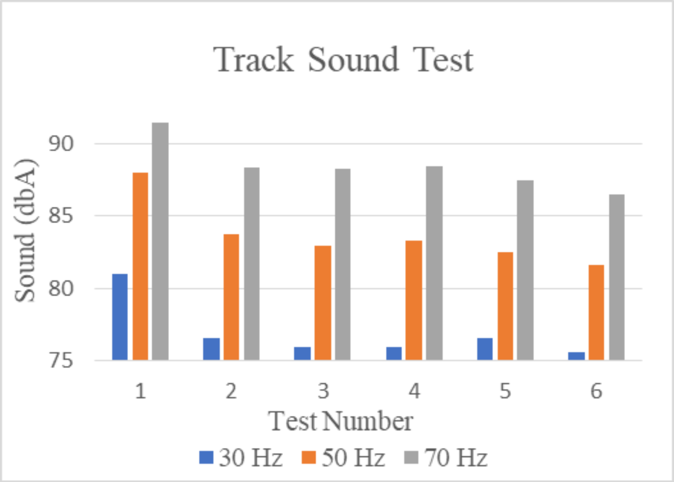

Figure 17. A graph of sound levels per the Test ordinal in Table 2.

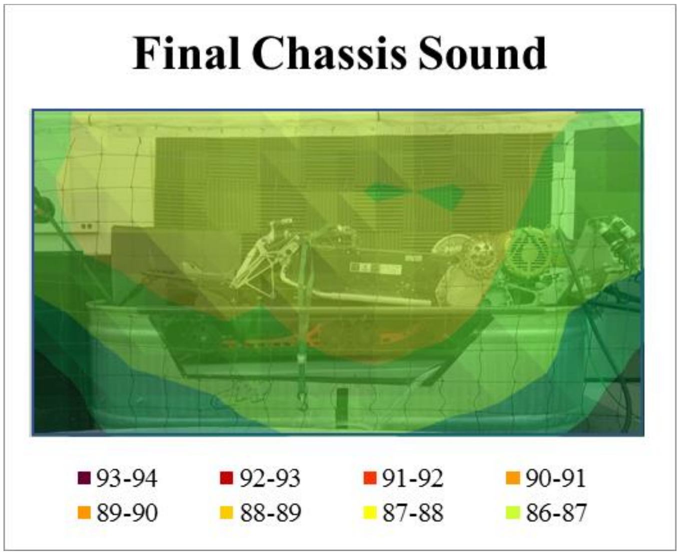

Figure 18. The final grid sound test. The colors corelate to observed sound, measured in dBa.

Using the grid testing to focus the improvements, the sound levels were reduced from 87 to 81 dBa. This level of sound emissions reduction is already substantial, and the engine package is yet to be implemented.

Exhaust

The primary source of sound emitted from a snowmobile is the engine exhaust. The alternating exhaust strokes of a 4-cycle engine generate large pressure pulsations through exhaust gases. These alternating pressure levels create the loud sounds heard from an engine. A muffler serves to counteract these pressure imbalances.

In an effort to design the muffler around the specific characteristics of the engine, a series of initial tests were conducted to find the dominate frequencies of the engine. This would provide specific wavelengths to target for the muffler. A 3M Sound-Pro sound meter was used to measure the sound pressure levels relative to their frequencies. Using data-logging software, each dominate frequency was recorded with its correlating Decibel level.

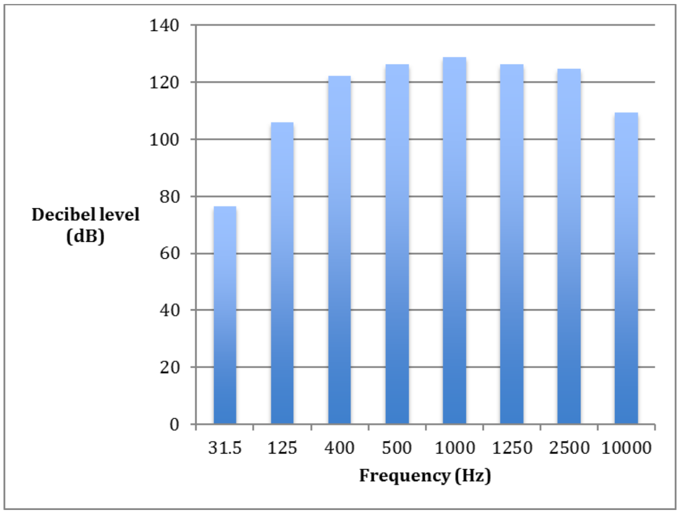

Figure 19. The eight dominate frequencies and their correlating Decibel level.

After writing a program in Visual Basic, each quarter wavelength was identified. The baffles of the muffler were designed using this information, using destructive wave interference to cancel and diminish waves.

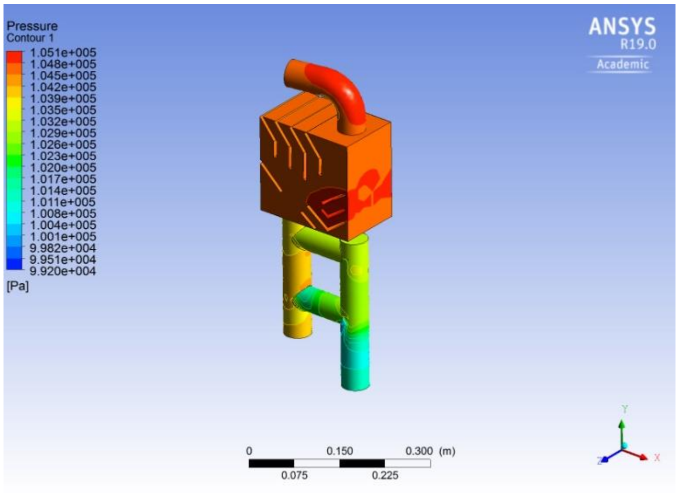

Figure 21. ANSYS flow simulation. Exhaust enters in the red section, and the pressure drops throughout to the blue.

This muffler is a 2-stage expansion chamber design. The first chamber is reactive and reflective, designed around the principles of destructive wave interference. Destructive wave interference results in a reduction in sound levels, targeting frequencies from 31.5 Hertz (Hz) to 1250Hz. Exhaust pressure waves enter the first chamber at the top of the muffler. This chamber is lined with rigid baffles that reflect the pressure waves to create destructive interference. When the initial sound waves enter the first chamber, they are reflected back by placed baffles and create destructive interference with incoming sound waves. The first chamber is also designed to have a direct path for exhaust gases to flow. It acts as an ideal expansion chamber and throughout is over 1.5 times larger than the cross-sectional area of the exhaust pipe. This gives the muffler lower backpressure and provides a greater space for attenuation. The inlet and outlet tubes of the first chamber are offset by seven inches. Utilizing a dual wall design, there is a 0.5” barrier of packing material placed between the boundaries of the first chamber and the shell of the muffler.

The second chamber of the muffler is a sound absorbing design. The chamber is designed to provide attenuation for the higher frequency levels ranging from 2000Hz to 10000Hz. Perforated pipe is surrounded by ceramic high-density packing material. A 2-inch outer diameter perforated pipe with an open area of over 20% was used. This prevents the packing material from being dislodged from and also allows the sound pressure waves to escape the intended exhaust flow path the muffler. The packing material absorbs the sound pressure waves passing through the open area of the perforated pipe and the fibers of the packing material dissipate the sound energy as thermal energy. Designed to provide pressure waves with the longest possible path in an H-style path design for the greatest attenuation.

Figure 22. The muffler mounted in the snowmobile, with heat shields.

As the engine is not offered in a production snowmobile, there was no baseline to measure against. Through a very scientific approach, the muffler design has been effectively and thoroughly designed for the engine package. Using the SAE J1161 sound test, the snowmobile registered 71.8 dBa.

Conclusion

The UMD Clean Snowmobile Team’s entry for the 2018 Clean Snowmobile Challenge is packed with effective, marketable improvements for emissions, fuel economy, and sound. The finished product looks professional and stock. This results in a machine that features drastically reduced emissions, quieter than stock sound levels, and enhanced rideability, delivering at a competitive MSRP of $11,766.

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