Emissions, Fuel Economy, and Sound Reduction Improvements for the 2017 Arctic Cat ZR 3000

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ABSTRACT

The University of Minnesota Duluth's Clean Snowmobile Team re-engineered a 2017 Arctic Cat ZR 3000 snowmobile for entry in the 2017 SAE International Clean Snowmobile Challenge. The extensive design work was done with the goals of emissions reduction, improved fuel economy, and better performance. An engine relatively new to the snowmobiling industry, the 700cc parallel twin from Kymco featured in the Arctic Cat ZR chassis, fit the bill perfectly for the 2017 build. Coupled with a Garrett turbocharger and an advanced cooled exhaust gas recirculation (EGR) system, both efficiency and performance were achieved in ideal harmony. Due to the ethanol based fuel used in the 2017 challenge, flex fuel capabilities were added, as well as sophisticated engine calibration based on ethanol content utilizing a Haltech 2500 Elite electronic control unit. Progressing with last year's rear exiting exhaust system, a Heraeus catalyst specifically designed for the Kymco engine characteristics keeps emissions low and a custom designed muffler keeps sound to a minimum. Utilizing a new chassis sound testing dynamometer, drivetrain sound emissions were systematically decreased. With an emphasis on accurate, reliable testing, numerous dynamometer upgrades were made, including a computer controlled auto-load servo to ensure repeatable testing. The finished product is a reliable 85-horsepower class snowmobile that meets the industry leading 'Best Available Technology' standards while coming to market at a competitive price.

INTRODUCTION

Since their invention in the 1960s, snowmobiles have been a means of transportation, a work vehicle, and a fun pastime in the northern United States and Canada. They have revolutionized the way people travel across snow-covered terrain, and allowed exploration of new areas during the long winter months. One of the areas that saw increased snowmobile exploration was Yellowstone National Park. Over the years, however, unrestricted snowmobile traffic has had detrimental effects on the wildlife, air quality, and serenity of the United States oldest National Park [1].

The SAE Clean Snowmobile Challenge was founded in 2000 as a response to the demand for more environmentally friendly snowmobiles. The Challenge puts teams of college and university students against one another in friendly competition in an effort to create clean, quiet, and practical alternatives to the current snowmobiles on the market. The demands of a successful CSC entry are simple: take a production snowmobile, clean up the emissions and reduce sound levels while maintaining a high level of performance. This, however, is much easier said than done.

For the 2017 CSC competition, the team has prepared an entry with extensive improvements across the board. From the precision-tuned, turbocharged, flex fuel engine to the ultra-clean exhaust, the brand new 2017 Arctic Cat ZR 3000 Turbo is a big step forwards for the snowmobiling industry. The improvements detailed herein will make snowmobile riding in the National Parks a reality for future generations.

MARKET ANALYSIS

The goal of the competition is to modify a snowmobile to be more fuel efficient and achieve better emissions. The ultimate goal, however, 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 fuel economy. The 85-horsepower class is the entry level class of trail performance snowmobiles. The three snowmobiles in this class are the Arctic Cat ZR4000, Yamaha Phazer 500, and the Ski-Doo 900 ACE. The Arctic Cat features a rather outdated 500cc twin 2-stroke, which sacrifices emissions and fuel economy for the sake of performance. The Yamaha and Ski-Doo are at the opposite end of the spectrum, having lower performance with their heavier 4-stroke technology, but achieving much better fuel economy and emissions. The 2017 Arctic Cat ZR 3000 Turbo built by the UMD Clean Snowmobile Team bridges this gap, offering excellent emissions while maintaining enjoyable, turbocharged performance.

ENGINE IMPROVEMENTS

Fuel economy and emissions are two pillars of this competition. While the goal to improve both dramatically was held at great importance, it was decided by the team that it would not be at the cost of drivability and performance. As the 3000 Turbo engine package received the Award for Best Engine Design last year, we moved forward and made a number of improvements. Through an advanced design, a 60 kW snowmobile could be built with fuel economy that matches snowmobiles with half the power, while maintaining a performance oriented machine that can easily be manufactured and brought to market.

Engine Package Design

The transition to small displacement, forced induction engines is already commonplace in the automotive market. While it was mostly in small, economy cars to start, engine designs such as Ford's 'EcoBoost' and Chevrolet's 'EcoTec' have brought this technology into every market, including the light duty pickup truck. In looking at past Clean Snowmobile Challenge events, the formula of a small displacement four cycle engine with forced induction has seen great success. The logic of the engine design is sound as well. It has the ability to have dual purpose characteristics. In no to low boost, or positive manifold pressure produced by the turbocharger, the power can be kept low, resulting in a minimal amount of fuel being burned. When a high throttle position and engine speed is reached, the compressed air from the turbocharger delivers a strong power curve and great performance that riders desire. This engine design takes it to the next level through its efficient use of cooled Exhaust Gas Recirculation (EGR) system, combined with a 3-way catalytic converter and advanced engine tuning. The engine package is capable of running any fuel from 87 octane gasoline to e85 ethanol. The control logic allows for the adjustment of ignition timing, fueling, manifold pressure, and EGR mass flow based upon fuel content. The same Kymco 700cc parallel twin engine is used in this year's build, providing an ideal foundation for our package. [2]

Table 1. Kymco 700i Specifications

Engine	Kymco 700i
Displacement (cc)	700
Configuration	Inline Twin
Valve Layout	Dual Overhead Camshaft
Fueling	Full Sequential Port Fuel Injection
Compression Ratio	11:1
Bore x Stroke (mm)	76.9x75.3
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 48 kW of power. In-house dyno testing resulted in 40 kW and 51 newton-meters (N·m) of torque. The stock engine and exhaust system also underwent the same five-mode emissions test as at competition and produced an estimated eScore of 191.

In an effort to maximize efficiency of the engine package design before it was even constructed, a full Ricardo WAVE simulation was created. This simulation allowed for many different combinations of turbocharger and EGR set-ups to be tested without having to physically construct them. This was crucial to the success of the build. Knowing that the turbo and EGR specifics were chosen correctly and would work well with the engine is invaluable, as it was both a cost and time-saving provision.

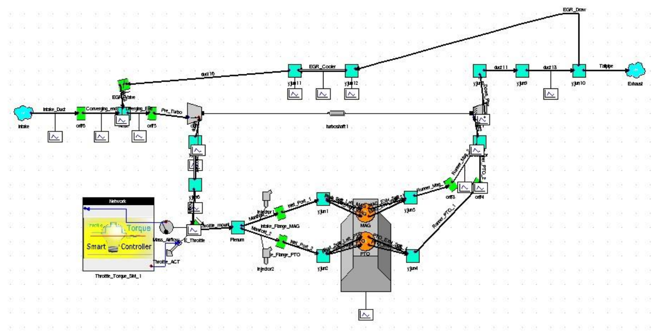

Figure 1. Turbocharged engine with EGR modeled in Ricardo WAVE

Turbocharger

The turbocharger chosen was a Garrett MGT1238. This was chosen due to the fact that a turbo capable of producing the desired power at less than a 2.0 pressure ratio was needed. This concern arose out of the high compression of the engine, as well as the internals not designed for turbo use. The turbo also needed to be small enough where response time could be nearly instantaneous. Using Ricardo WAVE, it was accurately determined that 83 kilopascals (kPa) of boost pressure would produce 63 kW of power while using EGR. Using electronic boost control, the boost curve was tailored to fit the clutch loading and achieve maximum economy and performance with little compromise.

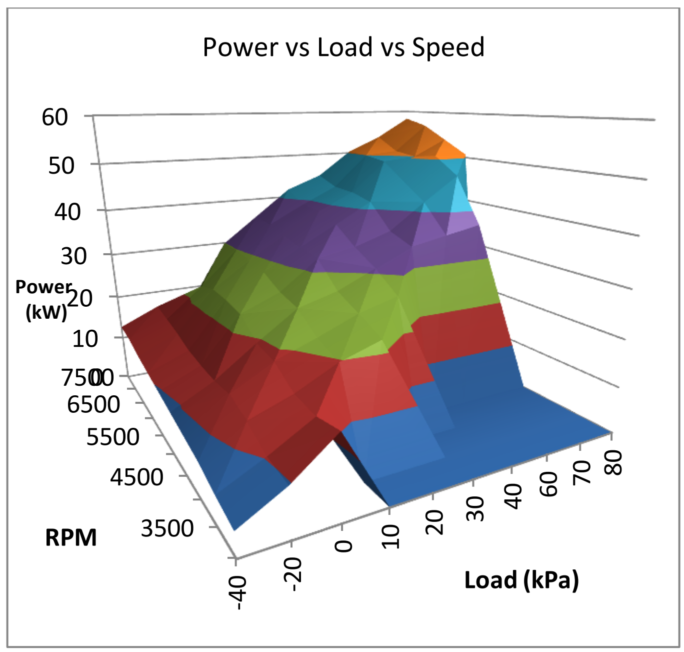

Figure 2. A power sweep graph showing a maximum power of 58 kW.

Intercooler

One component of last year’s design that had a lot of potential for improvement was the intercooler system. The previous design was a cylinder shaped water to air intercooler. It was bulky and very inefficient for its size. This year, a major goal was to downsize the intercooler while increasing the efficiency. Again looking to the OEM’s for established designs, the intercooler design of the Polaris RZR Turbo was the starting point. The Polaris RZR Turbo is a side-by-side off road vehicle that is a factory turbocharged 4-stroke. The water to air intercooler is packaged inside the plenum of the air intake system. This allowed for a great space savings in the engine bay, where the previous intercooler was placed, as well as a greatly reduced length of the cooling loop for better packaging.

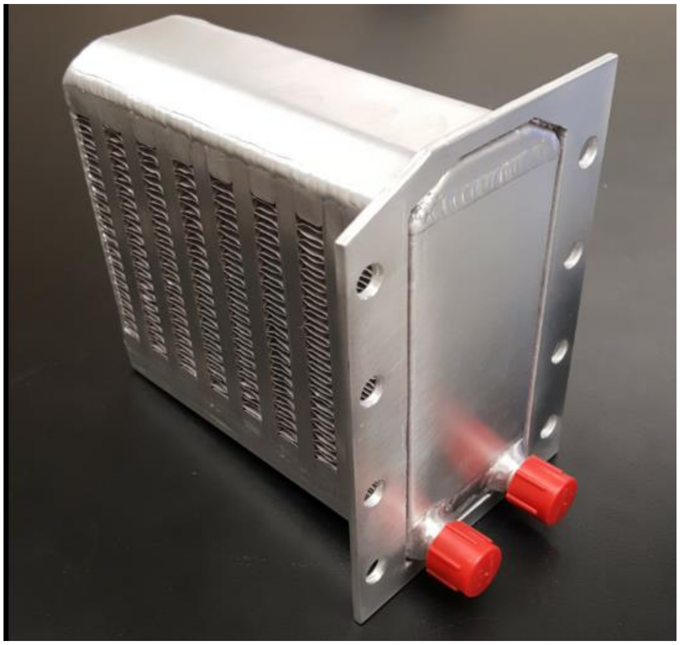

Figure 3. Intercooler

As the stock location of the plenum is between the engine block and the gas tank, a custom plenum was built specifically to fill the cavity. Using Ricardo WAVE and Solidworks, multiple design iterations were created before actual fabrication. With the model complete, Bell Intercoolers worked with the team to build a custom water-to-air intercooler specifically for the application. The end result is a well packaged and easy to manufacture solution. Intake temperatures are decreased through the efficient intercooler, and more space is available in the engine bay.

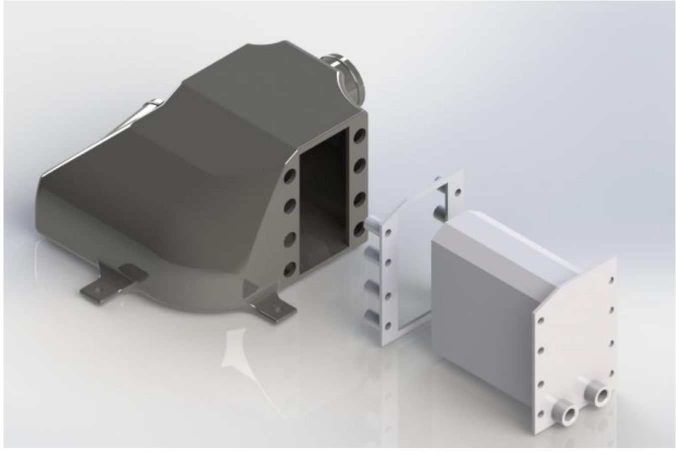

Figure 4. An exploded Solidworks CAD model of the plenum and intercooler.

Exhaust Gas Recirculation System

Last year, the cooled EGR system employed on the 700cc turbocharged twin was able to reduce Oxides of Nitrogen (NOx) emissions by 70.6% and aided to decrease fuel consumption by up to 18.4%. Cooled EGR reduces NOx emissions by cooling the combustion temperatures. The use of EGR also allows for control over torque generation and can be used to improve fuel economy while at cruising speeds. It also allows for the reduction of fuel enrichment in high load conditions such as boosting where enrichment is typically required for component longevity.

The design of the system employed last year relied solely on the pressure differential between the exhaust gas and the intake tract. Since the design employed utilizes the EGR pickup post-catalyst, the exhaust system pressure is quite low; 106 kilopascals (kPa) as determined from engine modeling. The low pressure differential, in conjunction with an EGR valve that severely restricted the EGR loop flow rate, lead to the requirement of fuel enrichment from stoichiometric during Mode 1 of the EPA Ramp Modal Emissions Test.

The EGR valve was also limited in its resolution during calibration, making some throttle transitions very unstable, leading not only to a perception of poor run quality, but also transient engine knock. Engine knock being sudden and unexpected high cylinder pressures. The knock was caused by unstable EGR flow during these transitions. This was due to that fact that the EGR demand may change as the engine speed changes, and the poor resolution often would deliver too much or too little EGR during these transients than what the ignition system was calibrated for. In instances where the EGR flow was less than expected, the engine would knock because additional ignition timing is required when EGR is burned due to the reduction in flame propagation speed. [3]

To solve these issues, a new valve would be required, and the system loop redesigned. The simplest solution for the flowrate through the EGR loop would be to increase the backpressure in the main exhaust system, thus generating a greater pressure delta across the EGR circuit. The downsides to increasing exhaust system backpressure include a reduction in engine torque (more pumping losses) and resistance to turbo spooling, hindering throttle response. With the understanding that 1) we have failed the sound tests for the past two years and 2) that the muffler would have to exist in an even smaller package than last year, it was determined that a more restrictive muffler would provide the necessary exhaust backpressure increase, and offer increased performance in the sound tests.

The EGR valve would need to have an increased flow capability, as well as improved control. The choice of a stepper motor controlled valve would allow for fine resolution and more precise control. Working with Ford Motor Company, we were able to source an EGR valve that not only could deliver the flow required in the worst cases, but also had 57 steps for unparalleled control. The use of this valve, in combination with the increased exhaust system pressure, allowed for stoichiometric fueling to be employed in all areas of the map while maintaining a safe (less than 1200 K) exhaust gas temperature, including conditions seen during Mode 1 of the emissions test. The optimization of this system allowed for smooth throttle transitions and also increased the NOx reduction abilities of the system. NOx was reduced an additional 17.6% for an overall average reduction of 88.2%.

When comparing the fuel flow of the engine with 65% ethanol fuel (E65) when running EGR and no EGR, there is a significant reduction in fuel consumption.

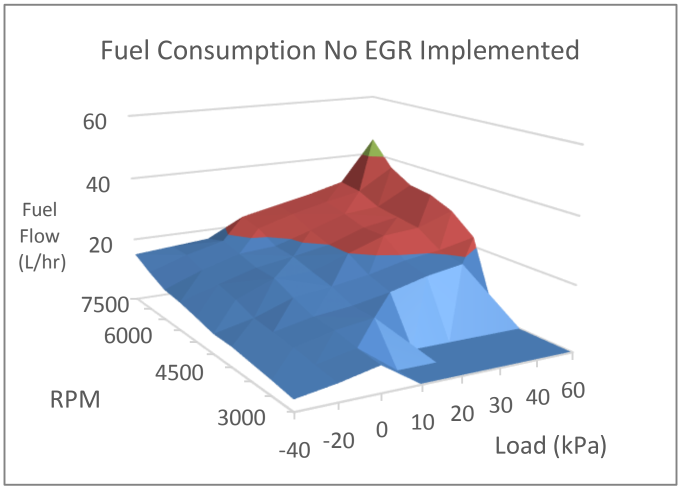

Figure 5. Fuel consumption sweep of final engine build with EGR valve shut.

When the engine is in vacuum, fuel flow is decreased due to EGR by 18.4%. This 'cruise' region of -40 to 0 kPa is incredibly important. This region accounts for a majority of time on the trail, as it is driving at a relatively steady speed. While power decreased in this region by 8.2%, the decrease in Brake Specific Fuel Consumption (BSFC) and increase in fuel economy outweighed the power loss. In the boosted regions reserved for high speed and acceleration, the EGR allowed for the air fuel ratio to be held at a stoichiometric mixture while still achieving safe exhaust gas temperatures. Due to the ability to use a stoichiometric fuel mixture, the emissions of Carbon Monoxide (CO) and Hydrocarbons (HC) were greatly reduced, while fuel economy increased yet again. From 0 to 60 kPa, fuel flow decreased an average of 13.6% through the use of EGR while power was down only 12.7%. Although there is a slight drop in power due to EGR, a majority of the power was recovered through higher boost pressures.

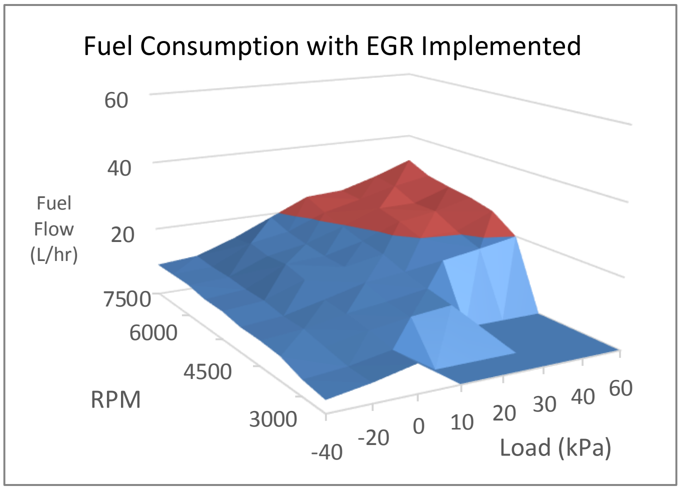

Figure 6. Fuel consumption sweep of final engine build with full EGR, showing an 18.4% decrease in fuel flow.

The system utilizes a low pressure EGR loop. The low pressure (long route) system draws the exhaust gas after the catalyst, passes it through a cooler, and then into the intake tract before the turbo in order to be pressurized with the intake air. Typically, a second throttle in the intake tract is used to create a low pressure region where the exhaust gasses are reintroduced into the intake. This assists in drawing gasses from the EGR into the intake. With already running a drive-by-wire electronic throttle, the complexity of another electronic throttle was deemed too much. Using Ricardo WAVE and SolidWorks flow simulation, a venturi was designed to ensure that flow would be sufficient in every desired revolutions per minute (RPM) range, with the control of flow dictated entirely by the EGR valve.

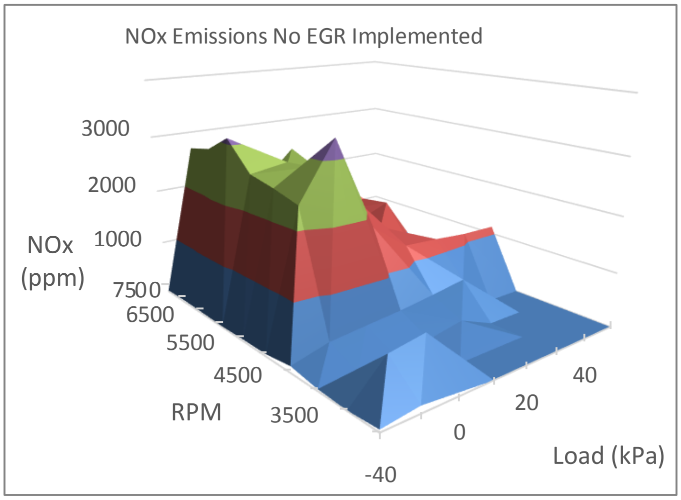

Figure 7. NOx emissions in parts per million with no EGR.

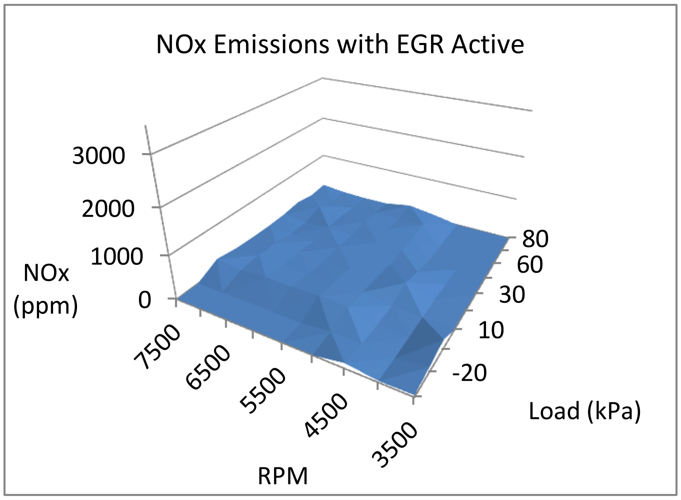

Figure 8. NOx emissions in parts per million with EGR. This graph is an 88.2% decrease overall from Figure 7.

The addition of a properly designed catalyst from Heraeus allowed for a substantial reduction in constituents over the stock engine with no aftertreatment [4]. Since the NOx emissions are effectively handled by the cooled EGR, the focus was on HC and CO emissions. As a rich air/fuel mixture leads to the rapid production of CO emissions, effective EGR was very important to keep the mixture stoichiometric while holding exhaust gas temperatures at a safe level. As the EGR was extremely effective, the CO emissions went down as well, with the CO emissions nearly 100 times less than stock especially in high load regions which historically ran fuel rich. The catalyst also helped reduce HC emissions by 79% over stock.

All of these engine improvements were designed from the beginning to work in perfect accord. The results were accurately predicted by the Ricardo WAVE model. A 32% increase in horsepower, 18% reduction in fuel flow, and an 10 point increase to produce an estimated eScore of 201, all in a reliable, safe, enjoyable engine package.

Engine Calibration and Testing

The engine package was constructed and calibrated in the bulkhead to expedite the process. While building it inside the snowmobile was a tedious task, fitment of every part was ensured at every step of the way. After complete fabrication, the bulkhead was placed in the dyno for calibration. This year the Engine Control Unit (ECU) is a Haltech Elite 2500. This ECU allowed for much more customization, as well as increased tuning capabilities. In an effort to allow for fine tuning and control, an electronic drive-by-wire throttle system was from Ski-Doo was adopted. In conjunction with the Haltech, the drive-by-wire allows for a custom throttle characteristics. Through dampening, unnecessary fueling in transient zones is eliminated, thus increasing fuel economy.

The engine package spent over 75 hours of run time on the dyno this year, in addition to 150 hours in development last year. Having an abundance of dyno time allowed for a full validation of the design. Last year, this engine package had issues with oiling the low mounted turbo. This led to oil escaping past the oil seals and into the intake and exhaust tract. Developments last year, including the addition of a scavenge pump solved this issue. However, there was still an unacceptable oil buildup in the intake. It was determined that this was due to improper positive crankcase ventilation (PCV). Many solutions were attempted to alleviate this issue, which is very harmful to the turbocharger, valves, pistons, and HC emissions, which included utilizing a larger breather line, an inline catch can, and different venting locations. In the end, a temporary fix of the addition of a pump to return the excess oil from the catch can back to the oil pan was employed. The root cause is threefold: 1) The pistons rise and fall together, displacing the full 700cc volume to the crankcase in one pulse 2) Inadequate labyrinth volume and 3) The addition of boost. Further development will yield a more permanent, less costly solution in the future.

The goal this year was to produce a snowmobile with minimal compromises, a turbocharged setup running a stoichiometric mixture was ideal. This is difficult to achieve with a moderate level of boost pressure as the compressed air in the cylinders increases the cylinder pressure and exhaust gas temperatures. This also induces detonation (knock) tendencies; parts can be damaged in the engine and turbo due to the intense heat. Typically, lambda (air-to-fuel ratio) values used were below 1.00 to keep the temperatures safe, however this increases the amount of unburned fuel. This leads to higher emissions and decreased fuel economy. EGR solves this problem. Since the addition of EGR cools combustion temperatures, a stoichiometric mixture can be used and exhaust gas temperatures will remain safe. In order to compensate for the slower combustion reaction caused by EGR implementation, ignition timing must be added (up to 36 degrees of advance depending on EGR content and knock presence in a zone). If ignition timing is not added, BSFC will increase and exhaust gas temperatures will increase, as an overly retarded ignition timing increases exhaust gas temperatures. Maximum Brake Torque (MBT) timing was used everywhere possible, whether using EGR or not. Once boost was added, on 87 octane fuel, ignition timing had to be cut in order to avoid knock, especially at higher boost where stoichiometric mixtures were used. While EGR implementation helped to add more advanced timing in these areas, the real benefit of ethanol based fuel was witnessed in areas previously prone to knocking. With the extra knock resistance of ethanol fuel, as well as its cooling effect, ignition timing could be advanced closer to MBT and immediate gains in power were seen in boost regions.

The wastegate, a pressure relief valve in the exhaust tract, is set to a low 20 kPa. Due to this low pressure, as well as clutching and gearing of the snowmobile, the boost control would not engage until 40% throttle. With the camshafts in this engine, the stock engine's peak torque is nearly off clutch engagement, or when the engine and primary clutch engage the secondary clutch. This allows for good engine performance in areas off boost, while still reducing fuel flow in these areas. The leaning of fuel mixtures (slightly above stoichiometric) and addition of EGR allowed for calibration changes, which minimized the amount of power produced at given cruise speeds. Utilizing the electronic throttle, which allows for customizable throttle curves (a non-linear relationship between throttle blade position and lever position on the handlebars) the throttle response and performance below the boost control region is smooth, predictable, and offers good acceleration. This also allows for a reduction of response time to decrease the instances of transient fueling for acceleration. Above 40% throttle, boost control initiates. Due to these turbocharging characteristics, this snowmobile can achieve 65-horsepower class fuel economy while still accelerating and performing much like an 85-horsepower class snowmobile. Based on ethanol content, air temperature, coolant temperature, and elevation, boost is adjusted to maintain maximum performance and safety for the engine. In some areas where NOx emissions were high, EGR was added and supplemented by boost to keep the power delivery smooth. After the calibration of the engine package was complete, the driveline could be calibrated.

Through the use of the Haltech's data logging software, fuel economy could be measured using fuel consumption and distance traveled. Using this software, the continuously variable transmission (CVT) clutches could be calibrated and tuned to match the characteristics of the engine, netting peak fuel economy in a 40 mph trail environment. The engine and clutches were optimized at this speed as it is the standard cruising speed on the trails. Testing was completed on a plowed, flat, straight course. The snowmobile accelerated to 40 mph, held at the constant speed, then slowed to a stop. Each clutch configuration completed five runs to eliminate outliers and create reliable data. The testing was completed using E65 fuel, as it is the standard available at the pump during the winter months. This reading was taken by the Haltech fuel composition sensor.

While the net fuel economy gain was only measured at 6.6%, the intangibles that cannot be represented in statistics were far greater. The new set up allows the entire power band of the engine to be used while still maintaining great fuel economy. The snowmobile is quick to respond to throttle input, smooth on acceleration, and has sufficient top speed. The on-snow calibration was crucial, as it resulted in an incredibly smooth snowmobile. It is smooth off clutch engagement, and the turbocharger response time is nearly instantaneous.

Sound Improvements

Sound is an incredibly important part of the competition, and the team had lots of room for improvement over the stock snowmobile. The transition this season to a smaller displacement engine has paid great dividends in sound levels. 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 other chassis components.

Using the new sound test for the Clean Snowmobile Challenge, the J1161, baseline sound data was taken on the snowmobile in stock form. After four runs, the average sound level was found to be 72 dBa. This level in stock trim meant that Best Available Technology (BAT) compliance was only a few decibels away.

Chassis

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

The process for testing was the same principle as the water dyno. With 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. This would put the standard load 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 three 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.

Test 1:	Stock baseline
Test 2:	Added 6 idler wheels
Test 3:	No idler wheels
Test 4:	Added new Track and Hyfax
Test 5:	Added 'Lizard Skin' tunnel coating

Table 2. The order of added components during testing. Results are shown in Figure 9.

Test 1 is a baseline test of the drivetrain in stock form. For Test 2, 6 more idler wheels were added in addition to stock in an effort to reduce track ballooning and slap, which is when the track has room to move and slaps against the rails and drivers, thus creating more noise. As evidenced by Figure 9, that wasn't the case. Moving then to Test 3, 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 new-to-market 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 have seen great results in a few seasons of racing, and our initial tests show the same. Test 4 saw the addition of the hyfax, as well as a new Camso track. It is the Cobra lug design, which is a softer, paddle style lug. The original Hacksaw track design features a sawtooth-cut lug design, with much stiffer rubber. While the track did reduce sound levels, there wasn't enough clearance with the tunnel mounted exhaust to use the track. This is another area to explore going forward. Test 5 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.

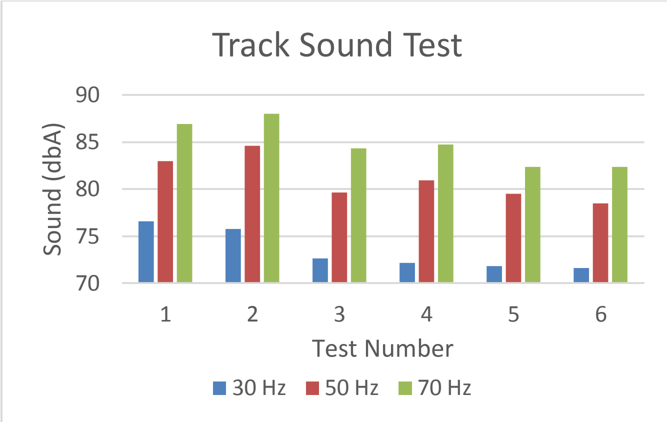

Figure 9. A graph of sound levels per the Test ordinal in Table 2.

Throughout all of the changes and additions to the drivetrain of the snowmobile, sound levels were reduced from 82 to 77 dBa. This level of sound emissions reduction is already substantial, and the engine package is yet to be implemented.

Intake

The intake tract of the snowmobile was completely analyzed and reengineered with numerous improvements. A new intake system was designed to direct air from the front of the snowmobile into the turbocharger effectively. SolidWorks was used extensively, as ample, clean air flow was required for the turbocharger and engine. As the venturi for the EGR sits inline with the intake and turbo as well, the intake needed to provide unimpeded flow.

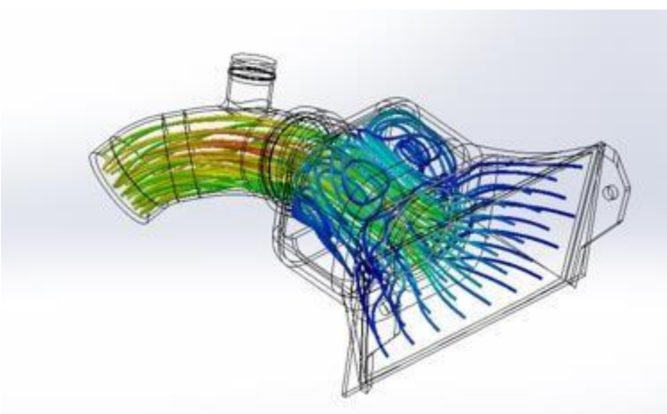

Figure 10. SolidWorks flow simulation of intake.

The flared entrance to the initial intake pipe, as opposed to a sharp edge, provides a lower loss of pressure. Minimizing intake pressure drops maintained mass flow rate, and was critical to the success of the EGR and turbo. A resonating chamber was integrated inline in the intake tract to improve sound characteristics, which allows the pulsating pressure waves created by the turbo's compressor blades to cancel themselves. The destructive interference resulted in a reduction in sound without affecting air flow. The intake was then 3D printed using Carbon Fiber reinforced Nylon 11. This created a lightweight, but strong intake.

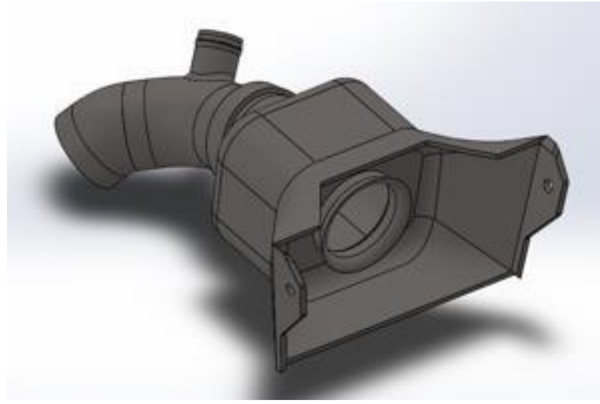

Figure 11. SolidWorks rendering of intake.

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. This alternating pressure levels creates the loud sounds heard from an engine. A muffler serves to counteract these pressure imbalances.

The muffler design used was the same concept as last year's design. A rear-exiting exhaust that would exit at the rear of the tunnel provided ample space for the turbocharger and EGR by moving the muffler from the engine bay. This longer exhaust has numerous benefits. It relocates the heat load outside the envelope of the hood, and allows an increase in exhaust gas density, resulting in decreased exhaust velocities and pressure wave amplitude [5].

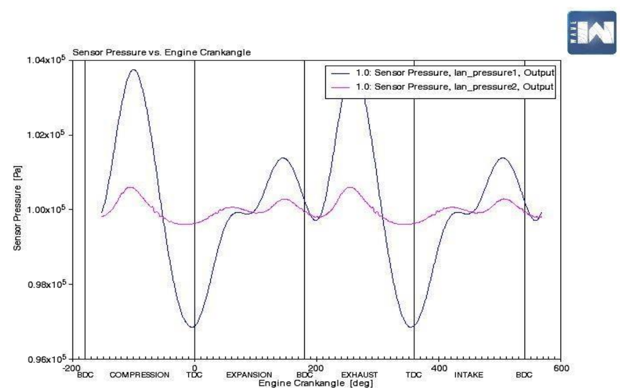

Figure 12. The line with more amplitude is stock, the lower amplitude line is with modified muffler.

The muffler was designed in SolidWorks, allowing the design to have various studies run before starting the physical build. Internally, there are 3 chambers which reduce sound emission while directing the exhaust gasses toward the ground. The first chamber mixes and slows the exhaust gases by using a perforated pipe. The second chamber is designed to reduce the majority of the engine noise. Packing material and linear wedges cover the surface of the walls absorbing sound. The wedges are designed to capture sound waves and reflect them back into themselves. Aerogel was placed on the reflective surfaces of the wedges to absorb some of the sound waves. Similar sound cancelling wedges can be found in anechoic chambers made for sound reduction. The packing material covers the inner surfaces of the muffler that do not have linear wedges. The last chamber has a single linear wedge and the outlet pipe. The outlet pipe is wrapped in a dense fiberglass packing to reduce any extraneous sound. The outlet is perpendicular to the track directing the pressure waves and exhaust gases downward onto the track. While in motion, the moving track also helps dissipates sound emissions.

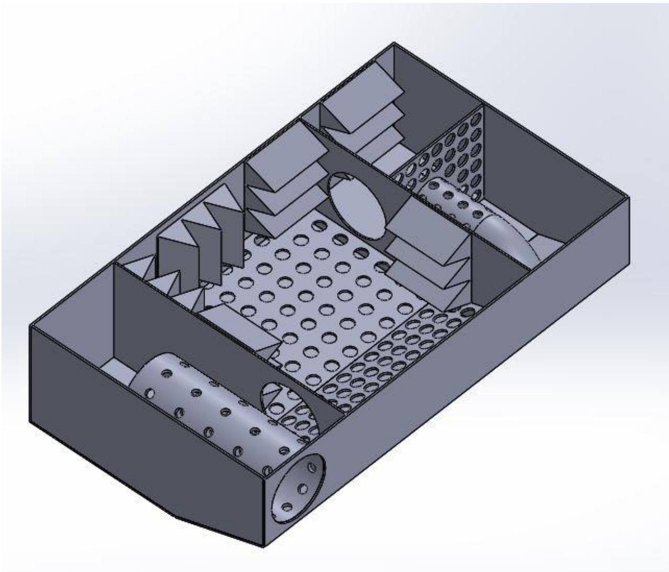

Figure 13. SolidWorks rendering of the muffler

Progressing with last year's muffler design, wedges were placed inside the primary resonating chamber of the muffler in an effort to geometrically cancel sound pressure waves. The geometry and wave reflection of these wedges is a principle component of the design. Due to the constraints of the packaging design, the muffler couldn't be as large as it ideally would be. Therefore, a solution would have to be found that worked in a small area. Aerogel is a product that was introduced last year to a great result. It is a fabric material that is typically used to insulate against heat, however the hypothesis was formed that it could work well as a sound deadening material as well. It is proven to be heat resistant, and is denser than fiberglass, the traditional muffler packing material.

A test was conducted using a small, enclosed test chamber. The walls were lined with the steel linear wedges of the muffler design. One test was with the wedges at 30 degrees, and the other at 45 degrees. Wedges made of bare steel and aerogel covered steel were tested at both angles. A speaker sent a sine wave at 120 Hz and then 150 Hz. The sound level was measured with a sound meter at the outlet of the test chamber.

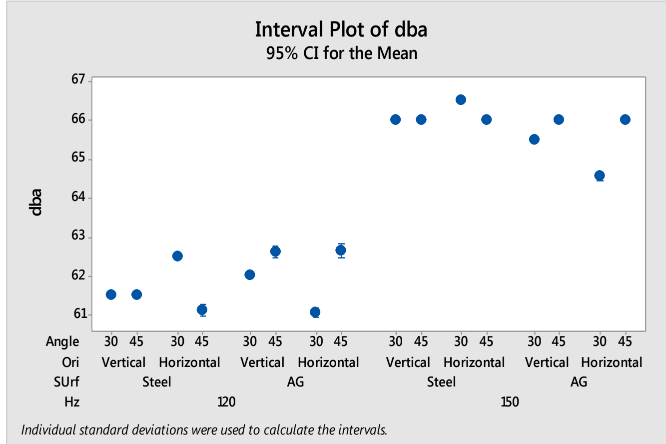

Figure 14. A data plot of the aerogel covered steel wedges in the muffler.

As evidenced in the data plot above, the Aerogel (abbreviated as AG) did lower the sound emissions over bare steel. 30 degrees performed better than 45 degrees, but was impossible to manufacture with the resources available. The aerogel was riveted onto the steel, and required more space behind the wedge than 30 degrees allowed.

The muffler is attached to the tunnel with a sheet of aerogel in between acting as an insulator. By using aerogel the muffler conducts substantially less heat to the tunnel. The pipe and muffler system are cooled by snow and cool air convection when the snowmobile is in motion. After 40 hours or run time on the dyno and 150 miles of on-snow testing, the muffler was removed and analyzed. None of the steel components, aerogel, or welds showed any sign of fatigue or wear.

To ensure the accuracy of the water wave model, a full SolidWorks flow simulation was designed. Based on the average mass flow rate gathered from Ricardo WAVE, the simulation shows the theoretical flow trajectories through the model. Figure 15 shows the pressure drop as the exhaust gasses move throughout the muffler.

Figure 15. SolidWorks flow simulation. Exhaust enters in the red section, and the pressure drops throughout to the blue.

The next simulation run was velocity trajectories. As shown in Figure 13, a large portion of the flow moved freely while still allowing pressure waves to reflect.

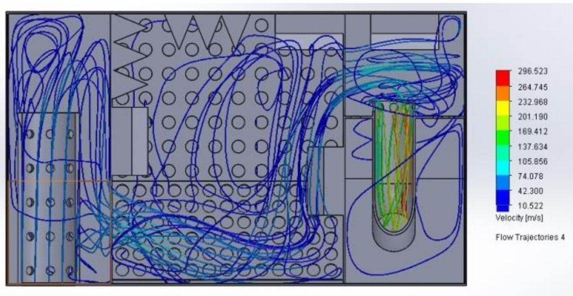

Figure 16. Velocity simulation of muffler.

Once the build was completed, another J1161 test was run. The test produced an average of 68 dBa. This test was done in non-ideal environment, as it was windy with hard snow pack. In a more suitable environment, BAT compliance at 67 dBa is certainly attainable. This was the goal from the beginning, and it was achieved. The intake and exhaust design fits entirely inside the stock snowmobile panels and tunnel, and provides significant gains over the stock snowmobile.

Conclusion

The UMD Clean Snowmobile Team's entry for the 2017 Clean Snowmobile Challenge is packed with effective, marketable improvements for emissions, fuel economy, and sound. The finished product looks professional and stock. Every modification and improvement fits inside the factory hood and panels. This results in a machine that features:

- Turbocharged engine with a 32% gain in power over stock, resulting in 63 kW
- Cooled Exhaust Gas Recirculation system
- 88.2% decrease in NOx emissions
- Drastic reductions in CO.
- 79% decrease in HC emissions
- Estimated eScore of 201
- Rear-exiting exhaust with a 4 dBa decrease in sound levels over stock
- Calculated MSRP of $10,707

The 2017 Arctic Cat ZR 3000 Turbo is a solution that will continue snowmobiling into future generations. It is clean, quiet, and marketable. It's packed with cutting edge technology that greatly reduces its environmental impact, while still being a performance-oriented machine that customer's desire.

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