# Emissions, Fuel Economy, and Sound Reduction Improvements to the 2016 Arctic Cat Pantera 3000

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## ABSTRACT

The University of Minnesota Duluth's Clean Snowmobile Team reengineered a 2016 Arctic Cat Pantera 3000 snowmobile for entry in the 2016 SAE International Clean Snowmobile Challenge (CSC). The extensive design work was done with the goals of emissions reduction, improved fuel economy, and better performance. An engine brand new to the snowmobiling industry, the 700cc parallel twin from Kymco featured in the Arctic Cat Pantera chassis, fit the bill perfectly for the 2016 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 2016 challenge, flex fuel capabilities were added, as well as sophisticated engine calibration based on ethanol content utilizing a Haltech 2500 Elite Electronic Control Unit (ECU). Progressing with last year's rear-exiting exhaust system, a Heraeus catalyst specifically designed for the Kymco's engine characteristics keeps emissions minimal, and a custom designed five-chamber muffler makes it quiet. 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 2016 CSC competition, the team has prepared an entry with extensive improvements across the board. From the precision-tuned, turbocharged, flex fuel motor to the ultra-clean exhaust, the brand new 2016 Arctic Cat Pantera 3000 Turbo is a big step forward for the snowmobiling industry. The improvements detailed herein will make snowmobile riding in our 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, 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 important, as well as emissions, fuel economy, and sound. In the past, the effort to achieve the most fuel economy and lowest emissions has yielded some incredible results, however it is always at the sacrifice of power. 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 economy and emissions. The 2016 Arctic Cat Pantera 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 dramatically improve both was held at great importance, it was decided by the team that it would not be at the cost of drivability and performance. Through an advanced design, a 65 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

Having run the Yamaha Genesis 130FI the last season to a successful 4$^{th}$ place finish, the limits of that engine had been reached. Being a high revving, big displacement triple, there are inherent sound and fuel economy disadvantages of the engine design. Taking a cue from the automotive industry, it was decided that the move to a smaller displacement engine with the addition of a turbocharger was the best design. Virtually every automotive market has seen the transition from naturally aspirated, large displacement engines to smaller, turbocharged units. The choice to use a smaller, turbocharged engine lies in its ability to have dual purpose characteristics. In areas where there is negative manifold pressure (vacuum) or low positive manifold pressure (boost), the power can be kept low, resulting in a minimal amount of fuel being burned. When a high throttle position and revolutions per minute (RPM) is reached, the compressed air from the turbocharger delivers a strong power curve and great performance that the rider desires. Continuing on last year’s design, an EGR and 3-way catalytic converter were implemented. A Haltech Elite 2500 ECU and electronic throttle control (drive-by-wire) provided precision control and driveability. The new 3000 series 700cc parallel twin 4-stroke engine from Kymco featured in the Arctic Cat Pantera provided a great foundation to build on.

*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* | Aluminium |

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 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.

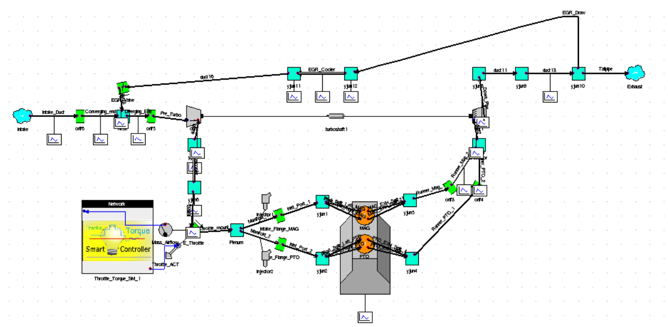

*Figure 1. Turbocharged engine with EGR modeled in Ricardo WAVE*

## 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 65 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. An inline water-to-air intercooler provides cooling for the turbocharger system, utilizing a heat exchanger under the tunnel.

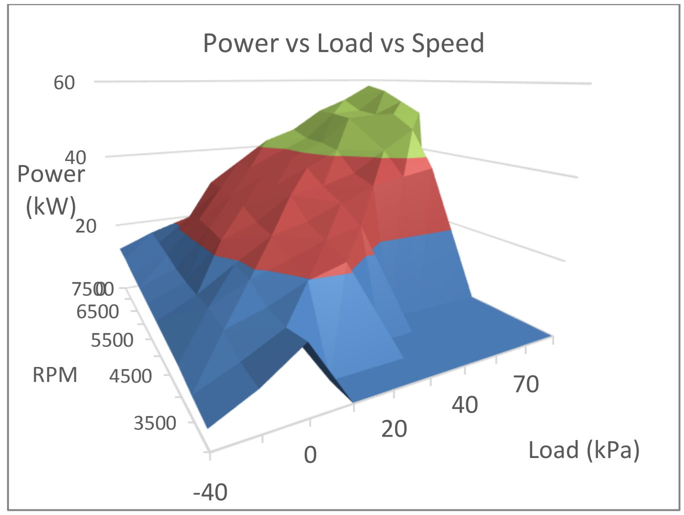


*Figure 2. Graph of RPM vs. Load vs. Speed of final engine package, with a peak power of 63 kW.*

## Exhaust Gas Recirculation System

Last year, the naturally aspirated three cylinder engine run by the team had the best Hydrocarbon (HC) + Oxides of Nitrogen (NOx) score among all competitors. This was mostly due to the EGR system, and also the catalytic converter and richer fuel mixture, as a richer fuel mixture produces less NOx. [2]. The rich mixture led to a smooth power delivery and safe combustion temperatures, however, the Carbon Monoxide (CO) emissions were too high. In order to alleviate these problems, a stoichiometric fuel mixture was used in combination with a new EGR design and catalyst. The catalyst was designed by Heraeus, specifically built for the engine's predicted emissions, with the information coming again from the WAVE model. Also derived from our software simulations, a cooled EGR system was developed. A combination of liquid-to-air cooler, vacuum operated valve, and venturi were utilized.

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.

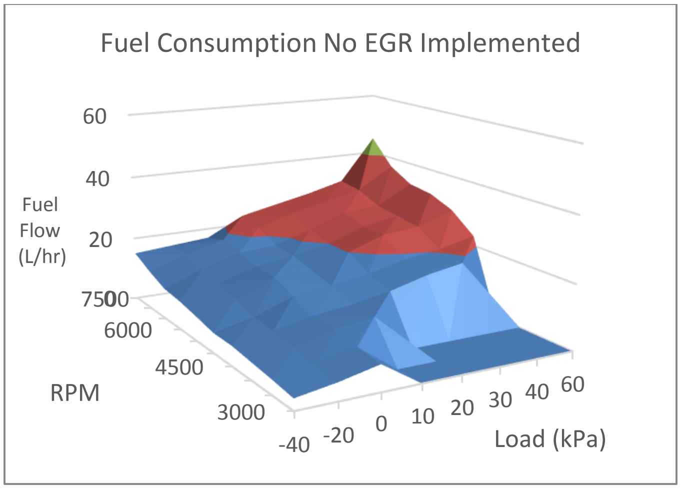


*Figure 3. Fuel consumption sweep of final engine build with EGR valve shut.*

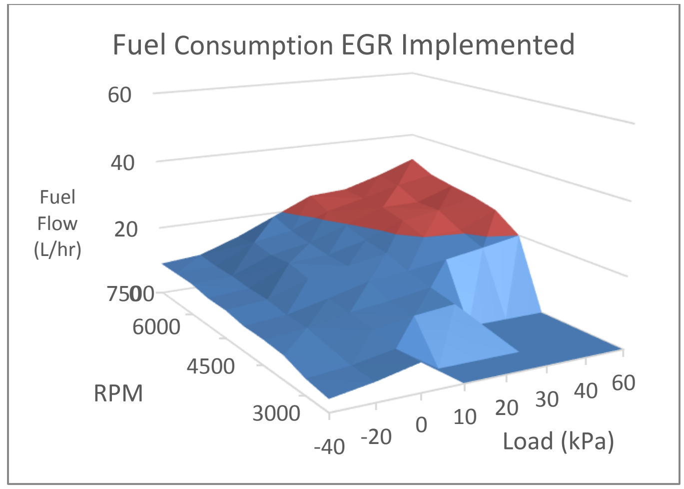


*Figure 4. Fuel consumption sweep of final engine build with full EGR, showing an 18.4% decrease in fuel flow.*

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 Economy (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 run a leaner fuel mixture, the emissions of CO and 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.

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 RPM range, with the control of flow dictated entirely by the vacuum-operated EGR valve. Through many Ricardo WAVE simulations and design evolutions, a 12mm diameter valve was used for ample flow and excellent control, along with a liquid-to-air cooler.

NOx emissions are the primary benefit of the EGR, and this year's design lowered NOx levels by 70.6% over stock. This incredible reduction of NOx is due to the cooling effect of EGR. The cooling process is critical for keeping intake charge temperatures low, resulting in reduced cylinder pressure and the inherent NOx emissions. Running a rich fuel mixture also reduces NOx by lowering combustion temperatures, however at the cost of fuel economy. The cooled EGR system allows the best of both [3].

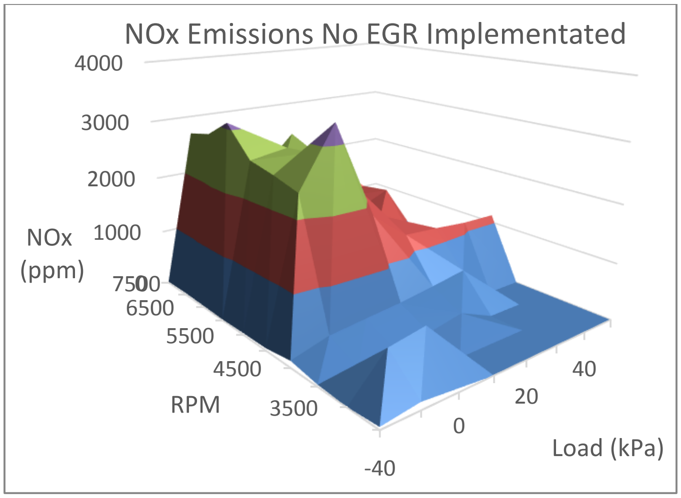


*Figure 5. NOx emissions in parts per million with no EGR.*

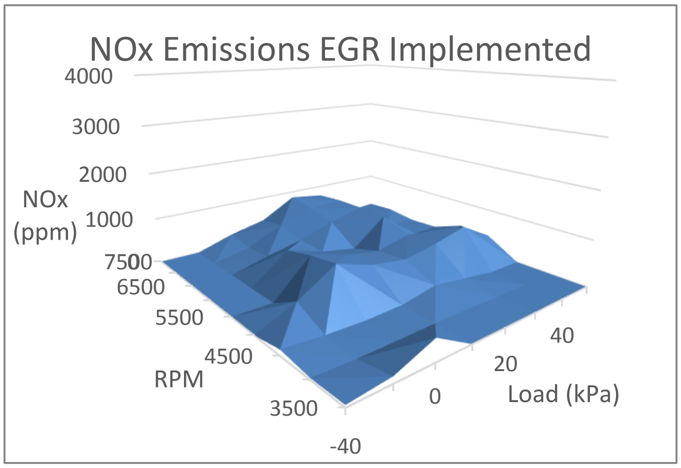


*Figure 6. NOx emissions in parts per million with EGR. This graph is a 70.6% decrease overall from Figure 5.*

As Figure 5 above displays, when a leaner mixture is used, NOx rises dramatically. With the cooled EGR and turbocharging, a stoichiometric mixture is used throughout, as shown in Figure 6. The graph shows much lower values, with even air fuel ratios yielding even NOx.

The addition of a properly designed catalyst 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 and low level. As the EGR was extremely effective, the CO emissions went down as well, with the CO emissions being reduced 96% over stock values. 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 exactly as predicted by the Ricardo WAVE model, if not better. A 57% increase in horsepower, 18% reduction in fuel flow, and an 10 point increase to produce an eScore of 201, all in a reliable, safe, enjoyable engine package.

## Engine Tuning and Testing

The engine package was constructed in the bulkhead of the snowmobile to optimize our timeline and resources. 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 tuning. This year the Engine Control Unit (ECU) was upgraded to 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 damping, unnecessary fueling in transient zones is eliminated, thus increasing fuel economy.

The engine package spent over 150 hours of run time on the dyno this year. Having an abundance of dyno time allowed for a full validation of the design. Many small issues arose, as expected with a first year engine package. A scavenge pump and inline pressure reducer were implemented to correctly oil the turbocharger. The exhaust manifold design was also redesigned several times, with the final design being a dual flex joint, V-band design. After complete dyno validation, the snowmobile was put on the snow for real world miles and testing. Incorporating the new engine, turbocharger, cooled EGR, drive-by-wire throttle, and new ECU proved to be challenging, however the extensive tuning process netted excellent results.

Since 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 in check, 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 20 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 remain high, 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 nearly in half 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, and the clutching and gearing of the snowmobile, dictated that 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, that is 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. By this point, the sled can nearly achieve its calculated top speed of 81 mph, so the additional boost and throttle is present for acceleration purposes only. 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.

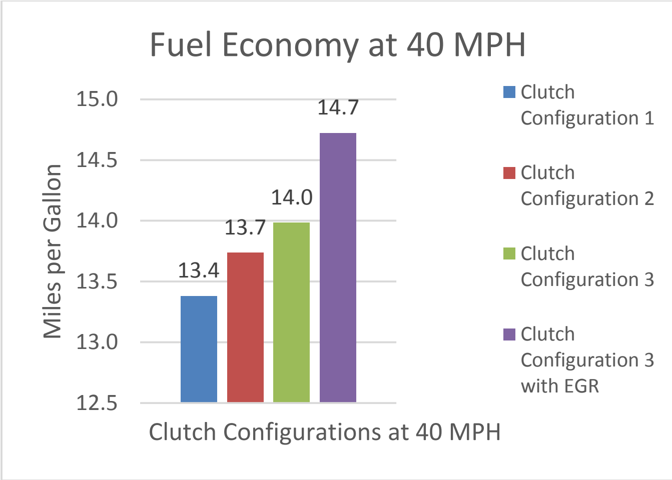


*Figure 7. Fuel economy at 40 mph.*

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 tuning was crucial, as it resulted in an incredibly smooth snowmobile. It is smooth of 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.

## 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.

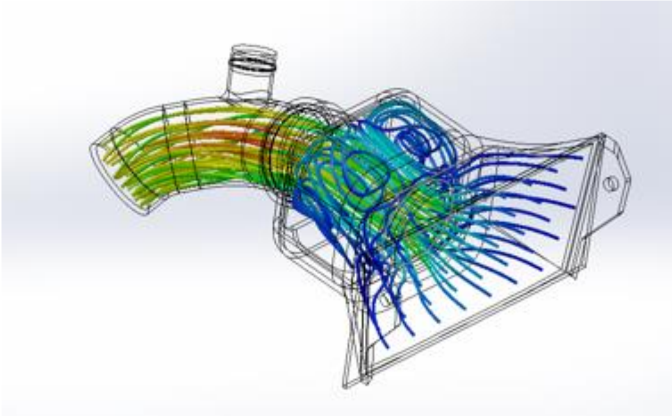

*Figure 8. SolidWorks flow simulation of intake.*

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 filled Nylon 11. This created a lightweight, but strong intake.

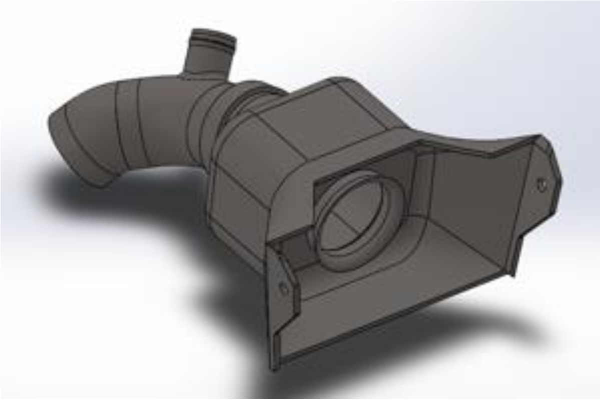

*Figure 9. SolidWorks rendering of intake*.

# 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 a density increase of gases, resulting in decreasing exhaust velocities and pressure wave amplitude [5].

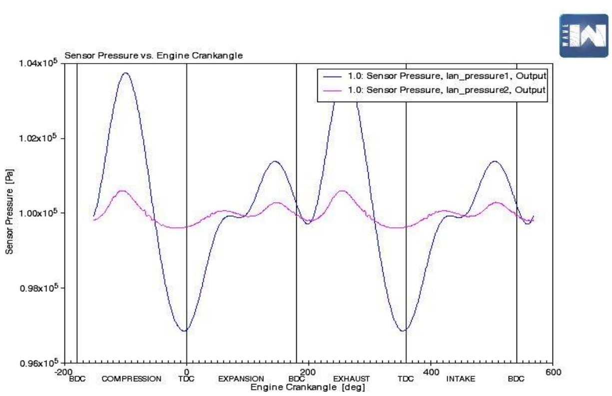


*Figure 9. The line with more amplitude is stock, the lower amplitude line is with modified muffler.*

The muffler was designed in SolidWorks, allowing the design to have various studies run before starting the physical build. It is composed of two main chambers and three rerouting chambers. The first chamber reroutes the exhaust gasses from an upward velocity towards the first main chamber. The first main chamber was designed to target a variety of frequencies using geometric surface angles that enhance deconstructive interference without restricting exhaust flow. The purpose of the angled baffles is to reflect pressure pulses from the engine into each other, thus creating destructive interference. As displayed in Figure 9, the reduction of wave amplitude with respect to crankshaft angle is shown versus a straight section of pipe. This chamber also has fiberglass packing material to reduce vibration. After this, the next chamber is a second rerouting chamber that directs flow from the main chamber into the end of a perforated pipe, which is the start of the secondary main chamber. The second main chamber consists of a pipe capped at both ends. This allows lower frequencies to bounce back, generating more destructive interference, much like the inline resonator on the intake tract.

*Figure 10. SolidWorks rendering of the muffler*

A large portion of the perforated pipe is situated in the second main chamber where any outlying frequencies are absorbed by fiberglass packing material surrounding the pipe. At the ends of this pipe, the perforations are increased as this is to reduce back pressure. Finally there is a third rerouting chamber that receives the exhaust gases and directs them through the downward exit pipe. As the muffler is located under the tunnel, heat management was critical. The entire box is covered in high temperature Aerogel, which has an extremely low thermal conductivity. This protects the utility box from the heat generated.

To test the design, a scale model of the internal baffles of the muffler was constructed in a tub of water. Water pulses, or waves, were used to represent the way pressure pulses from the engine propagate through the first main muffler chamber. Water pulses were created by generating waves of varying sizes and frequencies through the model and observing wave heights with floats. The test proved the model successful as the wave heights at the inlet were much higher than the wave height at the exit port. This reinforced the concept of geometric deconstructive interference.

*Figure 11. Model of internal baffles used for water testing.*

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 12 shows the pressure drop as the exhaust gasses move throughout the muffler.

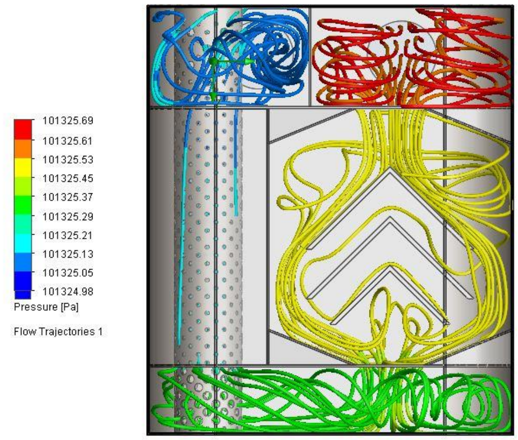


*Figure 12. SolidWorks flow simulation. Exhaust enters in the red section, and the pressure drops throughout to the blue.*

The next simulation run was velocity trajectories. The simulation revealed that the baffling system in the first main chamber worked. As shown in Figure 13, a large portion of the flow moved freely while still allowing pressure waves to reflect.

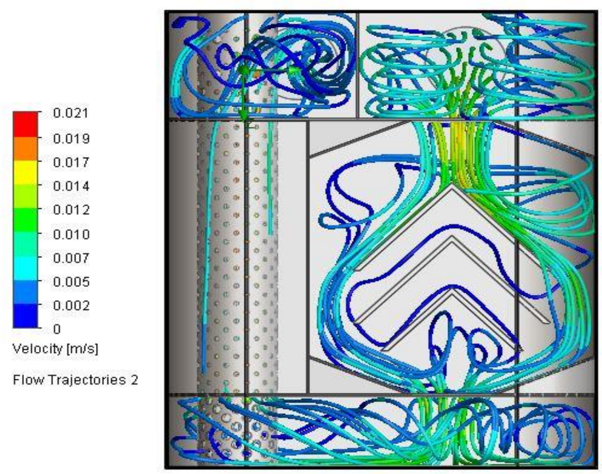


*Figure 13. Velocity simulation of muffler.*

Once the build was completed, another J1161 test was run. The test produced an average of 69.45 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. It is a very quiet, effective design that is easily marketable on a production snowmobile.

## Conclusion

The UMD Clean Snowmobile Team's entry for the 2016 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 panels. This results in a machine that features:

- Turbocharged engine with a 57% gain in power over stock, resulting in 63 kW
- Cooled Exhaust Gas Recirculation system
- 70.6% decrease in NOx emissions
- 96% decrease in CO emissions
- 70.9% decrease in HC emissions
- eScore of 201
- Rear-exiting exhaust with a 2.5 dBa decrease in sound levels over stock
- Calculated MSRP of $12,692.42

The 2016 Arctic Cat Pantera 3000 Turbo is a solution that will continue snowmobiling into future generations. It is clean, quiet, and marketable. It is packed with cutting edge technology that greatly reduces its environmental impact, while still being a performance-oriented machine customers desire.

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